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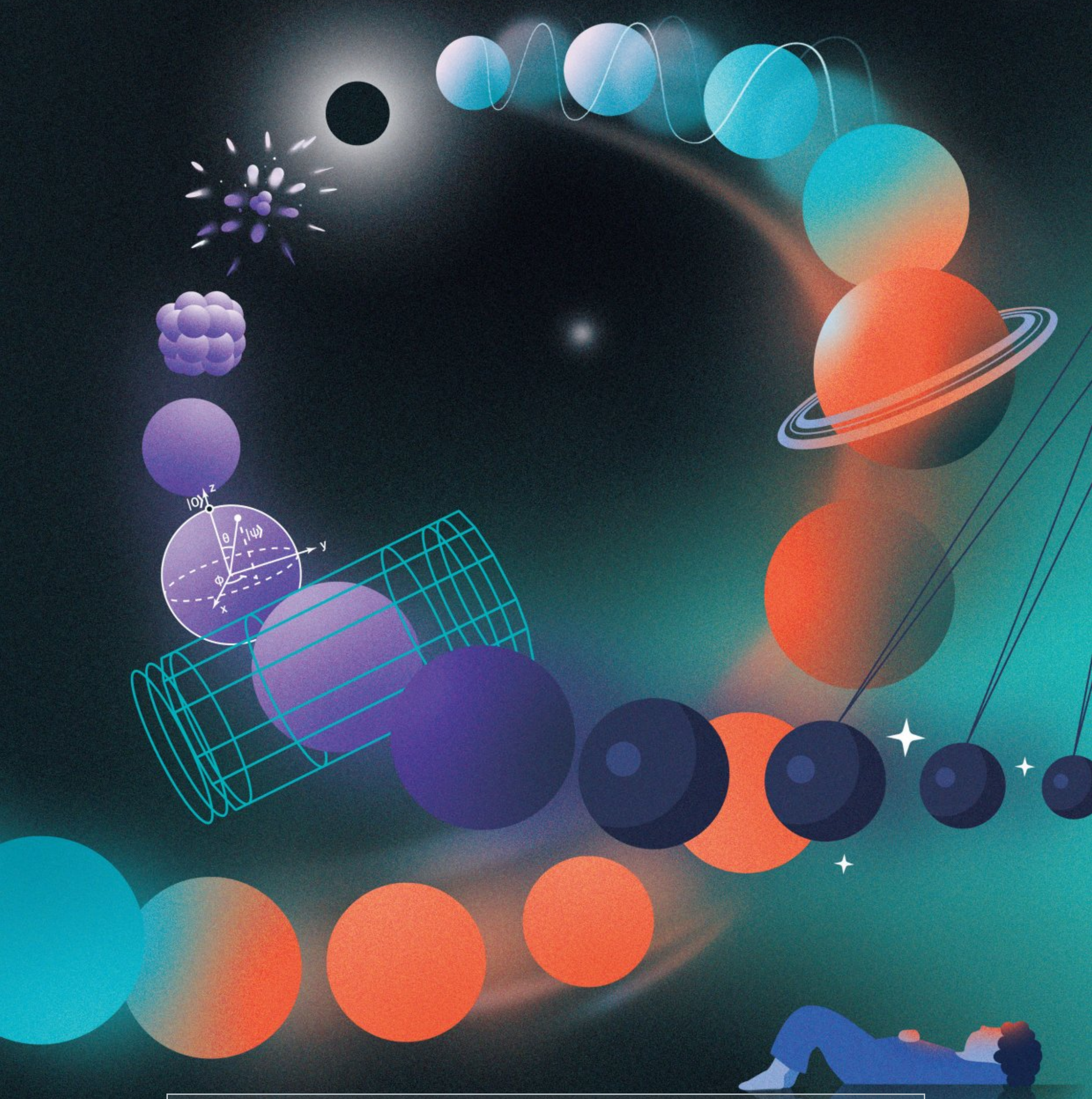
VCE PHYSICS

Units 3 & 4



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VCE PHYSICS

Units 3 & 4

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At Edrolo, we're transforming the way the students learn and teachers teach.
Our mission is simple: to improve education.

Edrolo acknowledges the Traditional Custodians of the land on which this book was created in Naarm (Melbourne). We pay respect to the Wurundjeri and Boon Wurrung / Bunurong peoples whose land we live and work on. We pay respect to their Elders past and present. We also recognise the deep connections of the past and present that Aboriginal peoples and Torres Strait Islander peoples have and continue to maintain.

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Features of this book

Edrolo's VCE Physics Units 3 & 4 textbook has the following features.

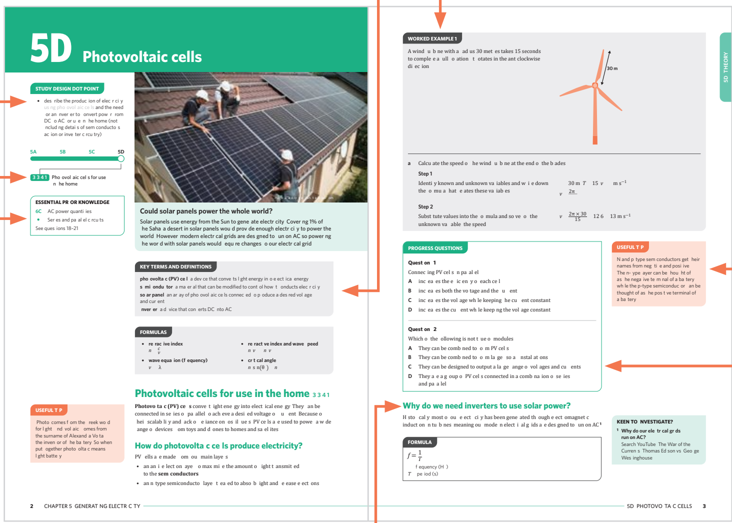
Theory

Study design dot points provide explicit links between the content covered in each lesson and the VCAA study design.

Key terms are defined and highlighted to support learning

Worked examples apply content to exam-style questions with strategies, full working and explanations of each step in the process.

Key knowledge units break down the theory into smaller chunks that help navigate the corresponding theory lesson videos on the Edrolo online platform.



Explore boxes include misconceptions, useful tips, and keen to investigate boxes.

Progress questions test if students can remember bite-sized chunks of theory and overcome common misconceptions early in the learning journey. They are stepping stones between the content and exam-style questions.

Essential prior knowledge questions are designed to break down any misconceptions and highlight prerequisite knowledge from previous lessons that is 'essential' to understanding the lesson's content.

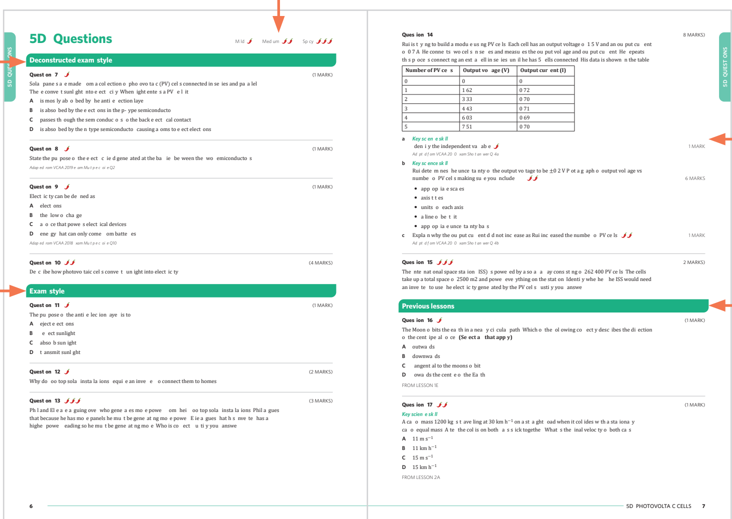
Guiding questions focus and simplify the key knowledge required by the VCAA study design.

Questions

Spiciness ratings measure the difficulty of the questions, and can be used to differentiate students and teach to their level.

Deconstructed questions provide prompts for students to piece together the steps needed to answer an exam-style question.

Exam-style questions reflect the style of questions presented in end-of-year exams.



Key science skill questions develop the key science skills students require to undertake their own investigations and evaluate the research of others.

Questions from previous lessons combine key knowledge from previous lessons to develop a deeper understanding of concepts.

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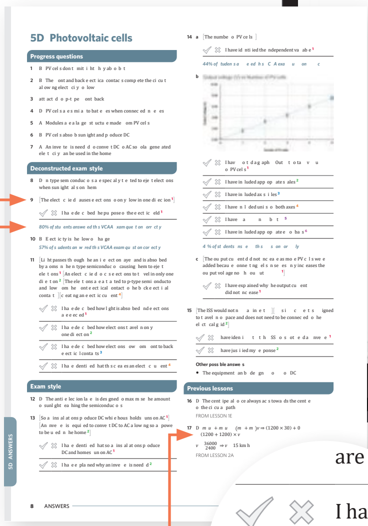
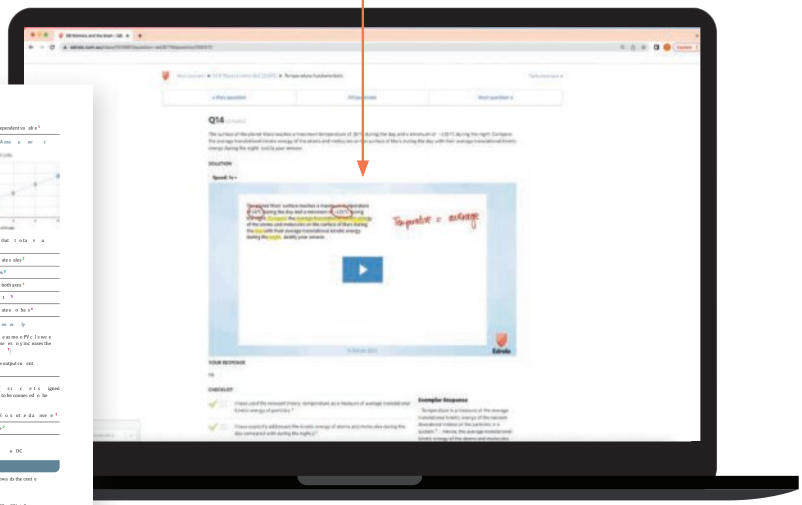
Answers

Video solutions provide extra guidance on how to answer questions.

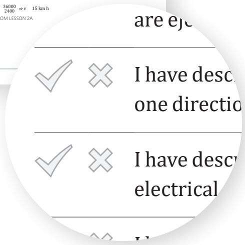
Worded and visual responses include exemplar answers to all questions to show what a full mark response looks like.





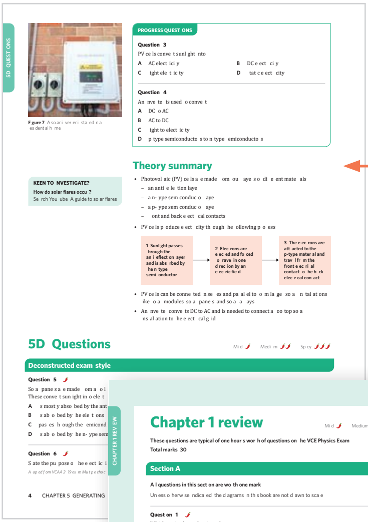
VCAA exam stats show the percentage of students who answered the question correctly in the VCAA exam.

Calculation responses show full working along with mark allocations to help students form good habits and to provide more detailed guidance for students.



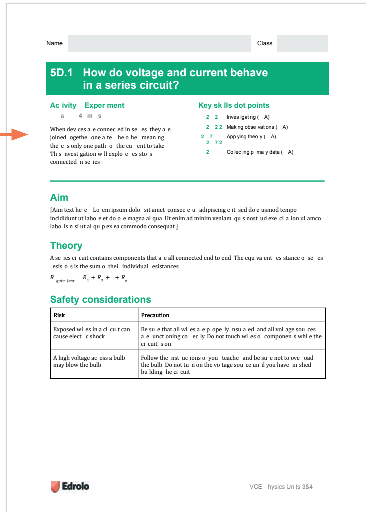
Checklists are provided for all worded answers with more than 1 mark. They explain what is required for each part of a full mark answer and help scaffold student's responses to exam questions.

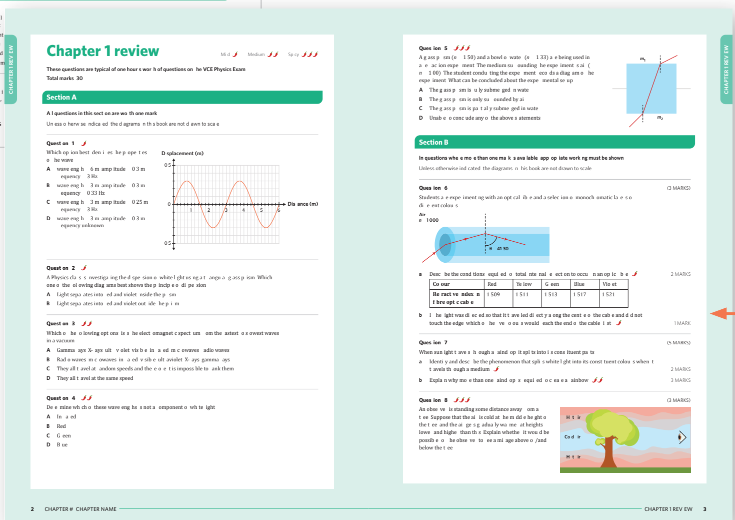
Theory summaries, reviews, and activities



Theory summaries provide a summary of the key takeaways from each lesson.

Activities are downloadable and editable from your Edrolo account. They can be used as assessments, engagement opportunities, and to enhance content understanding.





Chapter and AOS reviews consist of end-of-year exam-style questions that cover content from that chapter or area of study. They are structured into two sections: multiple choice, and short answer questions.

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UNIT 3

How do fields explain motion and electricity?

In this unit students use Newton's laws to investigate motion in one and two dimensions. They explore the concept of the field as a model used by physicists to explain observations of motion of objects not in apparent contact. Students compare and contrast three fundamental fields – gravitational, magnetic and electric – and how they relate to one another. They consider the importance of the field to the motion of particles within the field. Students examine the production of electricity and its delivery to homes. They explore fields in relation to the transmission of electricity over large distances and in the design and operation of particle accelerators.

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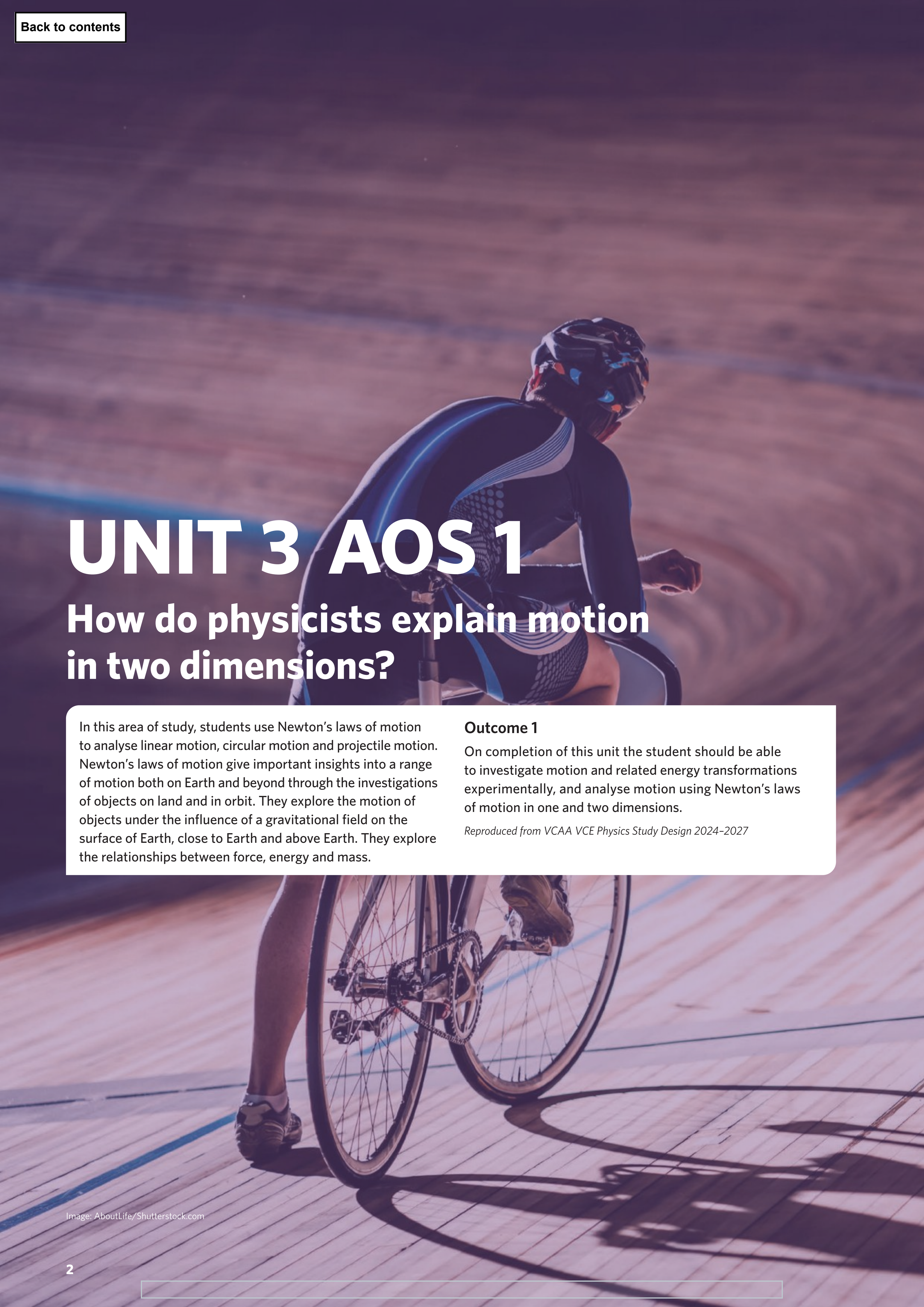

UNIT 3 AOS 1

How do physicists explain motion in two dimensions?

In this area of study, students use Newton's laws of motion to analyse linear motion, circular motion and projectile motion. Newton's laws of motion give important insights into a range of motion both on Earth and beyond through the investigations of objects on land and in orbit. They explore the motion of objects under the influence of a gravitational field on the surface of Earth, close to Earth and above Earth. They explore the relationships between force, energy and mass.

Outcome 1

On completion of this unit the student should be able to investigate motion and related energy transformations experimentally, and analyse motion using Newton's laws of motion in one and two dimensions.

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CHAPTER 1

Force and motion

STUDY DESIGN DOT POINTS

- investigate and apply theoretically and practically Newton's three laws of motion in situations where two or more coplanar forces act along a straight line and in two dimensions
- investigate and analyse theoretically and practically the uniform circular motion of an object moving in a horizontal plane: $\left(F_{net} = \frac{mv^2}{r}\right)$, including:
  - a vehicle moving around a circular road
  - a vehicle moving around a banked track
  - an object on the end of a string
- model natural and artificial satellite motion as uniform circular motion
- investigate and apply theoretically Newton's second law to circular motion in a vertical plane (forces at the highest and lowest positions only)
- investigate and analyse theoretically and practically the motion of projectiles near Earth's surface, including a qualitative description of the effects of air resistance
- investigate and apply theoretically and practically the laws of energy and momentum conservation in isolated systems in one dimension

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LESSONS

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1A Kinematics recap

STUDY DESIGN DOT POINT

- There are no study design dot points for this lesson.

ESSENTIAL PRIOR KNOWLEDGE

- Rearranging equations

See question 1.

How can an athlete's average velocity be zero?

Although they share similarities, there is a big difference between distance and displacement. When it comes to athletes in swimming, track sports or even motorsports, this can be the difference between having a record breaking average speed or an average velocity of zero. We will explore the concepts of distance, displacement, speed and velocity, as well as acceleration, further in this lesson.

KEY TERMS AND DEFINITIONS

scalar a quantity that has only magnitude (size)

vector a quantity that has magnitude (size) and direction

distance the total length of a given path between two points (scalar)

speed the rate of change of distance per unit time (scalar)

displacement the change in position of an object (vector)

velocity the rate of change of displacement per unit time (vector)

acceleration the rate of change of velocity per unit time (vector)

FORMULAS

- **average speed**
  $v = \frac{d}{t}$
- **average velocity**
  $v = \frac{\Delta s}{\Delta t}$
- **average acceleration**
  $a = \frac{\Delta v}{\Delta t} = \frac{v - u}{\Delta t}$
- **the constant acceleration equations**
  $v = u + at$
  $s = ut + \frac{1}{2}at^2$
  $s = vt - \frac{1}{2}at^2$
  $v^2 = u^2 + 2as$
  $s = \frac{1}{2}(v + u)t$

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Vectors and scalars 2.1.1.1

A **scalar** quantity only has magnitude. A **vector** quantity has both a magnitude and an associated direction.

How can we differentiate between scalars and vectors?

Scalar quantities are given as magnitudes, meaning they represent measures of a quantity. Examples of scalar quantities include:

- **distance**
- **speed**
- time
- money
- temperature
- mass

Vector quantities on the other hand are defined by both magnitudes and directions. Examples of these include:

- **displacement**
- **velocity**
- **acceleration**
- force

Vector quantities are often represented visually as arrows, which we call vectors, where the length of the arrow represents the magnitude of the quantity, and the arrow is pointing in the direction associated with the vector quantity (Figure 1).

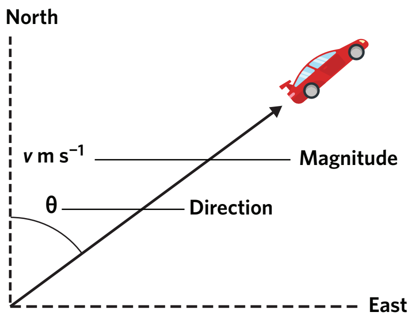

Figure 1 The red car is travelling with a velocity of v m s^{-1} at an angle of θ° east of north, as represented by the vector.

An example of a scalar and a vector quantity is distance and displacement respectively (Figure 2).

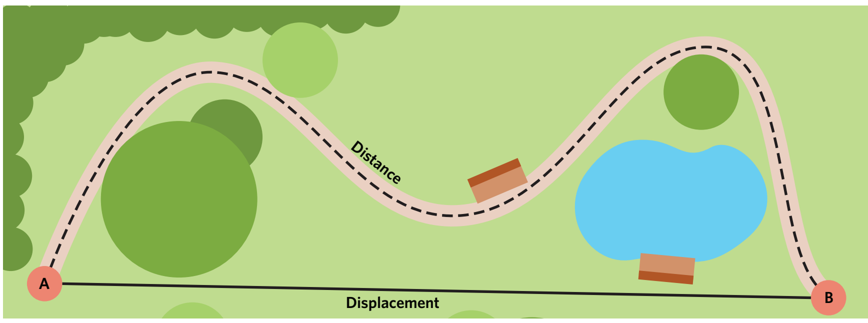

Figure 2 The difference between distance travelled and displacement

- Distance is the total length of a path travelled between two points. It is a scalar quantity.
- Displacement, in comparison, is the shortest path between two points. It is the distance "as the crow flies". Displacement is a vector quantity, so it always has an associated direction.[1]
- The SI unit for distance and displacement is metres (m).

Figure 3 shows the motion of a swimmer as they swim two laps of a 25 m long swimming pool. In this case, we are taking to the right as the positive direction.

USEFUL TIP

The direction component of a vector can be expressed in a variety of ways, such as stating a direction in words (like 'left' or 'east') or applying sign conventions. The most common sign convention is to assign one direction as positive and the opposite as negative. In problems involving vectors, it is generally best to define one direction in the y-axis (generally 'upwards') and one direction in the x-axis (generally 'to the right') as positive, so the opposite directions are negative.

KEEN TO INVESTIGATE?

1 **How can we visualise the difference between distance and displacement?**
Search YouTube: Distance and displacement classroom

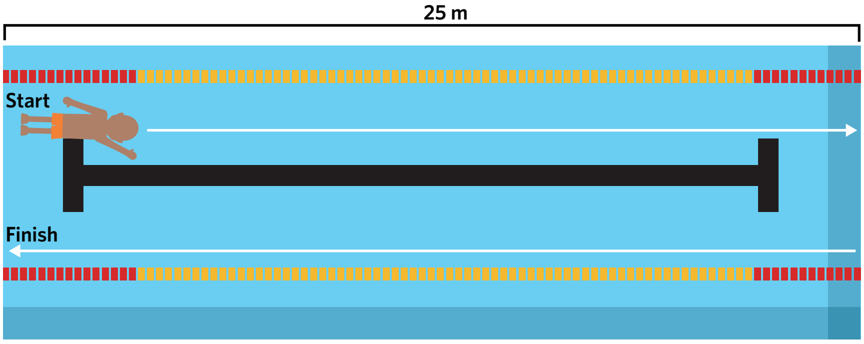

Figure 3 A swimmer swims two laps of a pool

- The distance travelled by the swimmer is given by $25 + 25 = 50$ m.
- However, the displacement of the swimmer is given as the distance between the swimmer's starting and finishing position, which in this case is 0 m because $25 + (-25) = 0$.
  - Note that the first 25 m swam is a positive value, as it was travelled in the positive direction (to the right), and the 25 m swam on the second lap is treated as negative as it is going in the negative direction (to the left).

PROGRESS QUESTIONS

Question 1

A scalar is best represented by

A. a direction.

B. a magnitude.

C. a magnitude with direction.

D. a countable number of objects in a given space.

Question 2

An example of a vector is

A. the acceleration of the train leaving the station.

B. how much money is needed to buy a new phone.

C. the distance travelled to get to school in the morning.

D. the temperature today as measured using a thermometer.

Quantities of motion 2.1.2.1 & 2.1.2.2

Speed and velocity provide information about the rate at which the object's position changes. They are derived from distance and displacement respectively. Acceleration measures the rate at which an object's velocity changes.

What are the similarities and differences between speed and velocity?

We can measure the rate at which distance or displacement is travelled with respect to time using either speed or velocity.

- Speed is the rate of change of distance with respect to time. It is a scalar.
- Velocity is the rate of change of displacement with respect to time. It is a vector.
- Both speed and velocity have the SI unit of metres per second (m s^{-1}).

The average speed of an object can be calculated using the following formula:

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FORMULA

$$v = \frac{d}{t}$$

v = average speed (m s^{-1})
d = distance travelled (m)
t = time (s)

USEFUL TIP

The capital Greek letter delta, Δ, is often used to denote a change in a value. This is always calculated by subtracting the initial value from the final value.
For example, Δt denotes a change in time, which would be calculated using $t_2 - t_1$.

The magnitude of the average velocity of an object can be calculated using the following formula:

FORMULA

$$v = \frac{\Delta s}{\Delta t} = \frac{s_2 - s_1}{\Delta t}$$

v = average velocity (m s^{-1})
Δs = change in displacement (m)
Δt = change in time (s)
s_1 = final displacement (m)
s_2 = initial displacement (m)

USEFUL TIP

In questions involving speed and velocity, we may need to work with either metres per second or kilometres per hour (Figure 4).

To convert from m s^{-1} to km h^{-1}, multiply by 3.6.

To convert from km h^{-1} to m s^{-1}, divide by 3.6.

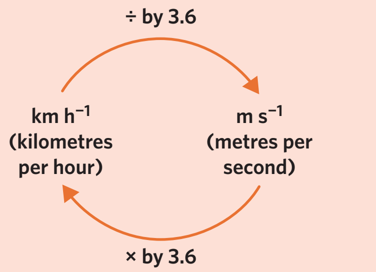

Figure 4 Converting between km h^{-1} and m s^{-1}

The velocity of an object for any given motion is not necessarily constant – it can speed up, slow down, and/or change direction throughout the motion of an object. Therefore there are differences between instantaneous velocity/speed and average velocity/speed (Figure 5).

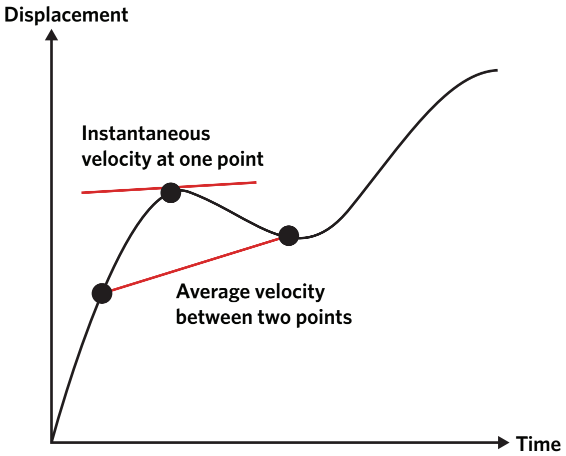

Figure 5 The difference between instantaneous velocity and average velocity

- Instantaneous velocity describes the velocity at an instant in time.
- The direction of the instantaneous velocity is referred to as the direction of motion.
- Instantaneous speed is always equal to the magnitude of the instantaneous velocity.
- Average velocity describes the constant velocity that an object would have in order to travel between two points in a given time.
- An object's average speed will be equal to the magnitude of its average velocity only if the direction of motion does not change.
- The instantaneous velocity can be calculated using the formula for average velocity if the velocity is constant.

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WORKED EXAMPLE 1

David runs one lap around a circular track with a circumference of 400 m in 90 s.

a. Calculate David's average speed.

Step 1

Identify known and unknown variables and write down the formula that relates these variables.

$d = 400$ m, $t = 90$ s, $v = ?$

$v = \frac{d}{t}$

Step 2

Substitute the values into the formula and solve for David's average speed.

$v = \frac{400}{90} = 4.44 = 4.4 \text{ m s}^{-1}$

b. Calculate the magnitude of David's average velocity.

Step 1

Identify known and unknown variables and write down the formula that relates these variables.

Note that as one full lap is completed, David ends up back where he started, so his displacement is 0 m.

$\Delta s = 0$ m, $\Delta t = 90$ s, $v = ?$

$v = \frac{\Delta s}{\Delta t}$

Step 2

Substitute the values into the formula and solve for David's average velocity.

$v = \frac{0}{90} = 0 \text{ m s}^{-1}$

c. If this track was now a straight 400 m section in the easterly direction, what would David's average velocity be?

Step 1

Identify known and unknown variables and write down the formula that relates these variables.

Note that the displacement is 400 m in this case, as the distance between the start and the end points is a straight line of length 400 m.

$\Delta s = 400$ m, $\Delta t = 90$ s, $v = ?$

$v = \frac{\Delta s}{\Delta t}$

Step 2

Substitute the values into the formula and solve for David's average velocity.

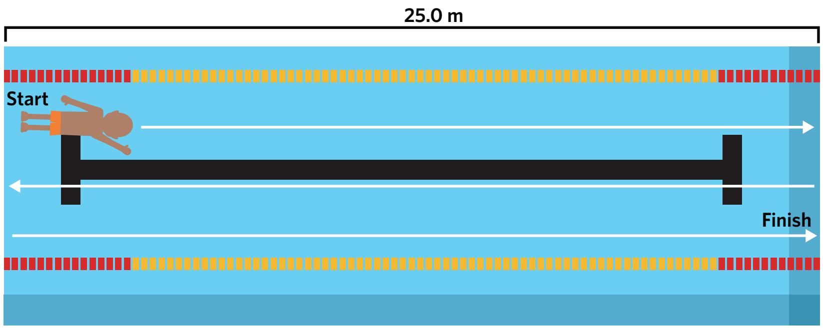
$v = \frac{400}{90} = 4.44 = 4.4 \text{ m s}^{-1}$

$v = 4.4 \text{ m s}^{-1}$ in the easterly direction.

PROGRESS QUESTIONS

Use the following information to answer questions 3 and 4.

Jodie is swimming laps of a 25.0 m swimming pool. She swims 3 laps in 144 s.



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Question 3

What is Jodie's average speed?

A. 0.50 m s^{-1}

B. 0.52 m s^{-1}

C. 1.90 m s^{-1}

D. 1.92 m s^{-1}

Question 4

What is the magnitude of Jodie's average velocity?

A. 0.17 m s^{-1}

B. 0.20 m s^{-1}

C. 5.66 m s^{-1}

D. 5.76 m s^{-1}

How can we understand and calculate acceleration?

Acceleration is the rate of change of velocity per unit of time. The SI unit for acceleration is m s^{-2}.

We will only consider cases of constant acceleration in this lesson.

Acceleration can be calculated using the following formula:

FORMULA

$$a = \frac{\Delta v}{\Delta t} = \frac{v - u}{\Delta t}$$

a = acceleration (m s^{-2})
Δv = change in velocity (m s^{-1})
Δt = change in time (s)
v = final velocity (m s^{-1})
u = initial velocity (m s^{-1})

USEFUL TIP

Acceleration can be thought of as how quickly the velocity of an object is changing (including both the magnitude and direction of the object's motion).[2]

KEEN TO INVESTIGATE?

[2] **How can we visualise the relationship between displacement, velocity and acceleration?**
Search: Uniform acceleration in one dimension simulation

If an object has an acceleration that is in the opposite direction to its motion, the velocity may reverse direction over time. For example, a ball thrown initially upwards will slow down, stop instantaneously and eventually begin to fall downwards, caused by the acceleration due to gravity acting in the downwards (negative) direction.

The point at which the velocity is zero indicates the position where the object is momentarily stationary, just before it starts travelling in the opposite direction. Figure 6 illustrates a constant negative acceleration (gravity), and the effect it has on the velocity of the object (in this case, a ball initially travelling upwards).

- At t_1, the velocity is positive but decreasing in magnitude.
- At t_2, the velocity is instantaneously zero.
- At t_3, the velocity is increasing in magnitude in the negative direction.

USEFUL TIP

It is important to note that if the direction of an object's motion changes, the velocity changes as well (even if the speed is constant). Therefore, there must be an acceleration present.

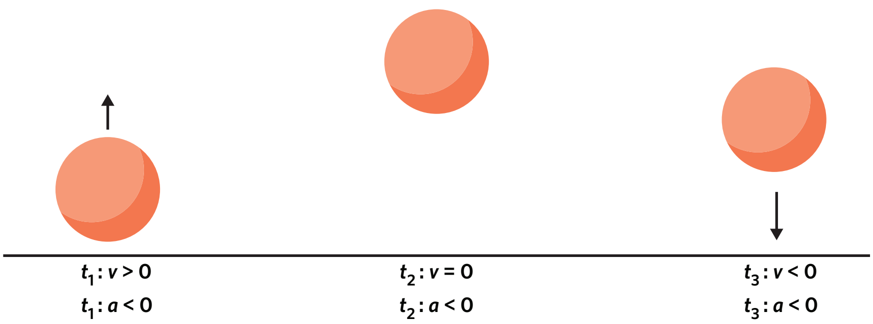

Figure 6 The effect a negative acceleration has on an object initially travelling with a positive velocity

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MISCONCEPTION

'Deceleration is the same as acceleration in the negative direction.'

Deceleration is a term used to describe acceleration that acts in the opposite direction of the velocity, leading to a decrease in the magnitude of the velocity. This is regardless of the direction of the velocity.

On the other hand, negative acceleration refers to acceleration in the negative direction within the chosen coordinate system.
This means, for an object travelling in the defined negative direction:

- A negative acceleration would increase the magnitude of the velocity, as the object is speeding up in the negative direction.
- A deceleration would decrease the magnitude of the velocity, causing the object to slow down regardless of the direction it is travelling in.

WORKED EXAMPLE 2

Matt is riding on a tram that brakes over a duration of 3 s as it approaches a pedestrian crossing. The initial velocity of the tram is 11 m s^{-1} north and the final velocity is 2 m s^{-1} north. What is the acceleration of the tram over this time? Take north as the positive direction.

Step 1

Identify known and unknown variables and write down the formula that relates these variables..

$u = 11 \text{ m s}^{-1}, v = 2 \text{ m s}^{-1}, \Delta t = 3 \text{ s}, a = ?$

$a = \frac{\Delta v}{\Delta t} = \frac{v - u}{\Delta t}$

Step 2

Substitute the values into the formula and solve for the acceleration of the tram.

Note that the acceleration is negative because it acts in the opposite direction to the velocity (which is taken to be in the positive direction). Hence, the acceleration could also be described as 3 m s^{-2} south.

$a = \frac{2 - 11}{3} = -3 \text{ m s}^{-2}$ north.

PROGRESS QUESTIONS

Question 5

A ferry starts from rest and accelerates uniformly, taking 20 seconds to reach a velocity of 10 m s^{-1}. What is the magnitude of the ferry's acceleration?

A. 0.050 m s^{-2}

B. 0.50 m s^{-2}

C. 2.0 m s^{-2}

D. 20 m s^{-2}

Question 6

Sidra is riding her motorcycle. She begins to decelerate. What does this tell us about her motion?

A. Sidra's speed is decreasing.

B. Sidra's speed is increasing quickly.

C. Sidra's acceleration is momentarily zero.

D. Sidra's speed is increasing in the negative direction.

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Constant acceleration equations 2.1.2.3

The constant acceleration equations are used to determine an unknown quantity of motion of an object accelerating at a constant rate, where multiple other quantities are known.

How can we calculate quantities of motion for constant acceleration situations?

In analysing motion with constant acceleration, there are several equations which form a 'toolbox' that allow us to solve for either the

- displacement (s),
- initial velocity (u),
- final velocity (v),
- acceleration (a), or
- time (t).

These are commonly known as the 'SUVAT' equations because of these variables. The derivation of these equations is not required for VCE Physics, but can be done using the equations already given in this chapter.

FORMULA

$$v = u + at$$
$$s = ut + \frac{1}{2}at^2$$
$$s = vt - \frac{1}{2}at^2$$
$$v^2 = u^2 + 2as$$
$$s = \frac{1}{2}(v + u)t$$

s = displacement (m)

u = initial velocity (m s^{-1})

v = final velocity (m s^{-1})

a = acceleration (m s^{-2})

t = time (s)

Each constant acceleration equation is missing a different variable. The method of solving for the unknown variable is to apply the equation which uses variables provided in the question or found in earlier parts. Table 1 lists these equations in terms of the missing variable.

USEFUL TIP

In a situation where we end up with a quadratic equation containing t^2, we can instead try using $v^2 = u^2 + 2as$ to solve for v, and the use $v = u + at$ to solve for t.

Table 1 The constant acceleration equations in terms of their missing variables

Constant acceleration equation	Missing variable
$v = u + at$	s
$s = ut + \frac{1}{2}at^2$	v
$s = vt - \frac{1}{2}at^2$	u
$v^2 = u^2 + 2as$	t
$s = \frac{1}{2}(v + u)t$	a

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WORKED EXAMPLE 3

In each of the following problems, use the constant acceleration equations to solve for the required variable.

---

a. Peter runs with an initial velocity of 2.00 m s^{-1} east and accelerates at –0.0800 m s^{-2} east. Calculate how far Peter runs in 16.0 s.

Step 1

Identify known and unknown variables and write down the formula that relates these variables.

Note that we are using $s = ut + \frac{1}{2}at^2$ as this equation includes our 3 known variables and our unknown variable. Also, in this scenario, we will take east as the positive direction.

$u = 2.00$ m s^{-1}, $a = -0.0800$ m s^{-2}, $t = 16.0$ s, $s = ?$

$s = ut + \frac{1}{2}at^2$

Step 2

Substitute the values into the formula and solve for Peter's distance travelled.

Note that direction is not required for a distance.

$s = 2.00 \times 16.0 + \frac{1}{2} \times (-0.0800) \times 16.0^2$

$s = 21.76 = 21.8$ m

---

b. Jodie walks with an initial velocity of 1.70 m s^{-1} north and accelerates at 0.100 m s^{-2} south until reaching a velocity of 0.100 m s^{-1} north. Calculate how far Jodie walked.

Step 1

Identify known and unknown variables and write down the formula that relates these variables.

In this scenario, we will take north as the positive direction.

$u = 1.70$ m s^{-1}, $a = -0.100$ m s^{-2}, $v = 0.100$ m s^{-1}, $s = ?$

$v^2 = u^2 + 2as$

Step 2

Substitute the values into the formula and solve for Jodie's distance travelled.

Note that direction is not required for a distance.

$0.100^2 = 1.70^2 + 2 \times (-0.100) \times s$

$s = \frac{0.100^2 - 1.70^2}{2 \times (-0.100)} = 14.4$ m

---

c. Christopher has an initial velocity of 7.20 km h^{-1} to the right but slows uniformly to a final velocity of 0.500 m s^{-1} to the right over a time of 10.0 s. Calculate Christopher's final displacement.

Step 1

Identify known and unknown variables and write down the formula that relates these variables.

In this scenario, we will take to the right as the positive direction.

Note that the 7.20 km h^{-1} value has been converted to m s^{-1} by dividing by 3.6.

$u = \frac{7.20}{3.6} = 2.00$ m s^{-1}, $v = 0.500$ m s^{-1}, $t = 10.0$ s, $s = ?$

$s = \frac{1}{2}(v + u)t$

Step 2

Substitute the values into the formula and solve for Christopher's final displacement.

$s = \frac{1}{2} \times (0.500 + 2.00) \times 10.0 = 12.5$

$s = 12.5$ m to the right.

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PROGRESS QUESTIONS

Use the following information to answer questions 7 and 8.

A train travelling at 20 m s^{-1} takes 140 m to come to a complete stop.

Question 7

Which formula is best suited to calculate the time taken for the train to come to a stop?

A. $v = u + at$

B. $v^2 = u^2 + 2as$

C. $s = vt - \frac{1}{2}at^2$

D. $s = \frac{1}{2}(u + v)t$

Question 8

How long does it take the train to come to a stop?

A. 11 s **B.** 12 s **C.** 13 s **D.** 14 s

Theory summary

- Scalar quantities only have magnitude while vector quantities have both magnitude and direction.
- Displacement and distance provide information about the path an object has travelled.
  - Displacement is a vector quantity, which means it has a magnitude and direction, whereas distance is scalar, so it only has a magnitude.
- Velocity and speed measure how an object moves.
  - Velocity is a vector quantity, which means it has a magnitude and direction, whereas speed is scalar, so it only has a magnitude.
  - Average velocity can be calculated using: $v = \frac{\Delta s}{\Delta t} = \frac{s_2 - s_1}{\Delta t}$
  - Average speed can be calculated using: $v = \frac{d}{t}$
- Acceleration measures the rate of change of an object's velocity.
  - Acceleration is a vector quantity, meaning it has a magnitude and direction.
  - Acceleration can be calculated using: $a = \frac{\Delta v}{\Delta t} = \frac{v - u}{\Delta t}$
- Displacement, velocity, acceleration and time are linked by the constant acceleration equations, which can be used to solve kinematic problems.
  - The constant acceleration equations are:
  - $v = u + at$
  - $s = ut + \frac{1}{2}at^2$
  - $s = vt - \frac{1}{2}at^2$
  - $v^2 = u^2 + 2as$
  - $s = \frac{1}{2}(v + u)t$

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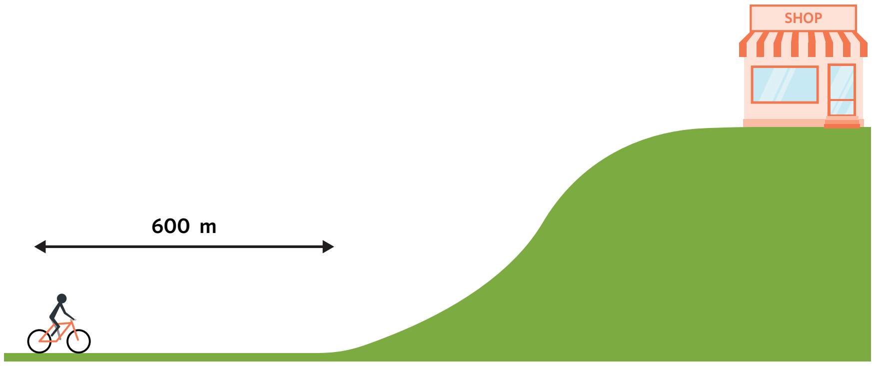
1A Questions

Mild 🌶 Medium 🌶🌶 Spicy 🌶🌶🌶

Deconstructed exam-style

Use the following information to answer questions 9–12.

Rose's journey to the corner store is mostly flat but involves one hill at the end. The flat section has a length of 600 m and the path up the hill is 20 m long.



Question 9 🌶 (1 MARK)

Rose is riding at a constant speed of 2.5 m s^{-1}. Calculate how long it takes her to travel the flat section.

Question 10 🌶 (1 MARK)

Rose slows down at a rate of 0.10 m s^{-2} as she rides up the hill. Show that Rose's speed at the top of the hill is 1.5 m s^{-1}.

Question 11 🌶 (1 MARK)

How much time does Rose take to ride up the hill?

Question 12 🌶🌶 (4 MARKS)

Calculate the total time it takes for Rose to ride to the store.

Exam-style

Question 13 🌶 (1 MARK)

A swimmer swims one length of a 50 m pool with a constant velocity. If they take 20 s to swim its length, what is the magnitude of their velocity?

A. 0.40 m s^{-1}

B. 2.5 m s^{-1}

C. 5.0 m s^{-1}

D. 10 m s^{-1}

Question 14 🌶 (2 MARKS)

A car accelerates from 0 km h^{-1} to 36 km h^{-1} in 2.0 s. Calculate the magnitude of the acceleration of the car in m s^{-2}.

Question 15 🌶 (2 MARKS)

Donna is initially driving a taxi at 4.0 m s^{-1}, and accelerates at 0.50 m s^{-1} in the direction of motion for 30 m. Calculate the final speed of the taxi.

Adapted from 2016 VCAA Exam Section A Q1a

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Question 16 (2 MARKS)

A toy car accelerates at 0.30 m s^{-2} over 6.0 s. If the toy car has a final speed of 2.0 m s^{-1}, how far has the car travelled?

Question 17 (2 MARKS)

Martha rides her bike down a hill, trying to go as fast as she can. She starts at an initial speed of 3.0 m s^{-1}, ends at a speed of 17 m s^{-1} and covers a distance of 30 m. How long does her descent take?

Question 18 (4 MARKS)

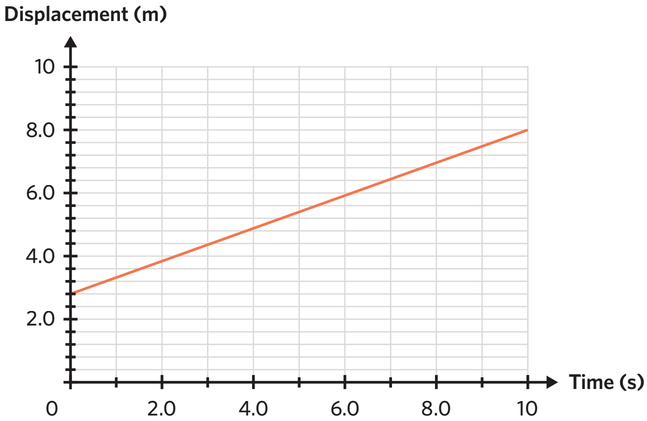
Amy sleds down a hill. She starts at rest and accelerates at 3.0 m s^{-2}. It takes Amy 4.0 seconds to get to the bottom of the hill.

a. Calculate the length of the path she travelled. 2 MARKS

b. Calculate Amy's final speed at the bottom of the hill. 2 MARKS

Question 19 (5 MARKS)

Rory records his displacement versus time as he walks a distance of 5.0 m to the south and plots the following graph.



a. *Key science skill*
Calculate the gradient of the trendline. 2 MARKS

FROM LESSON 12E

b. *Key science skill*
Explain the physical interpretation of the gradient of the trendline. 2 MARKS

FROM LESSON 12E

c. What is the magnitude and direction of Rory's velocity? 1 MARK

Question 20 (2 MARKS)

Calculate the initial speed of a truck that speeds up to 60 km h^{-1} over 3.6 s and a distance of 50 m. Give your answer in km h^{-1}.

Question 21 (5 MARKS)

Yasmin and Bill are trying to see who can slide further on a polished wood floor after taking a run-up. Yasmin's initial speed is 1.70 m s^{-1} while Bill's is 1.60 m s^{-1}. Yasmin decelerates with a magnitude of 0.500 m s^{-2} whereas Bill decelerates at 0.400 m s^{-2}.

Who travels further? Justify your answer with calculations.

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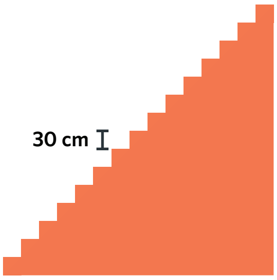
Question 22 (3 MARKS)

Clara takes 10 s to run up 15 steps. Each step is 30 cm tall.



She slows down over the 10 s so that she is stationary when she gets to the top of the stairs.
Calculate the magnitude of Clara's average vertical acceleration.

Question 23 (4 MARKS)

Ryan starts jogging at 1.0 m s^{-1} and accelerates at a rate of 0.30 m s^{-2} over a distance of 10 m.

Graham starts slower, jogging at 0.80 m s^{-1}, and accelerates at a rate of 0.40 m s^{-2} over 5.0 s.

Who ends up running at a faster pace? Justify your answer.

Question 24 (2 MARKS)

A shark accelerates at 2.0 m s^{-2} from its initial swimming speed of 1.5 m s^{-1}. It is hunting a stationary fish 10 m away. The fish intends to dart into a nearby cave (out of the shark's reach) 2.0 s after the shark starts accelerating. Can the shark catch the fish?

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1B Forces recap

Image: Natursports/Shutterstock.com

How can we work out which direction the ball will go?

There are multiple forces acting on a soccer ball when it's in the air, including the force due to gravity and air resistance. By analysing all the forces acting on the ball, Newton's laws of motions can be used to determine the resultant force and therefore the direction the ball will go. This lesson revises our understanding of vectors and the study of forces, including Newton's laws of motion, the net force, and other common types of forces. Understanding vectors and forces is fundamental to understanding motion and kinematics.

STUDY DESIGN DOT POINT

- investigate and apply theoretically and practically Newton's three laws of motion in situations where two or more coplanar forces act along a straight line and in two dimensions

1A 1B 1C 1D 1E 1F 1G 1H

- 3.1.1.1 Force vectors
- 3.1.1.2 The net force
- 3.1.1.3 Newton's laws of motion
- 3.1.1.4 Types of forces

ESSENTIAL PRIOR KNOWLEDGE

- Trigonometry
- Vector quantities

See questions 2–3.

KEY TERMS AND DEFINITIONS

force a push or a pull with an associated magnitude and direction (vector)

net force the vector sum of all forces acting on an object

Newton's first law of motion an object in motion will remain in motion unless acted upon by a net external force

force due to gravity the force experienced by an object due to the gravitational field of another object

normal force the contact force that acts at right angles to the surface the object is resting on

tension a pulling force that acts through an object connecting two bodies

frictional force a force that resists the relative motion of two surfaces in contact

FORMULAS

- **Newton's second law of motion**
  $F_{net} = ma$
- **force due to gravity**
  $F_g = mg$
- **Newton's third law of motion**
  $F_{A\ on\ B} = -F_{B\ on\ A}$

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Force vectors 3.1.1.1

Force, *F*, is a vector quantity, which means it has both a magnitude (size) and direction. A force is a push or a pull, and causes an object to accelerate. The SI unit for force is the newton, N.

How can we add and subtract vectors in one dimension?

Figure 1 Force vectors with magnitude *F* in the negative (left) and positive (right) directions. Here the positive direction has been defined as to the right.

In order to add and subtract vectors in one dimension, the direction of a force can be assigned as either positive or negative for arithmetic purposes (Figure 1). The definition of which direction is positive should be explicitly stated in the working out, if it is not already defined in the question. Positive direction is often defined as upwards or to the right.

To add or subtract one dimensional force vectors we add or subtract the magnitude of all the forces, making sure to include signs to indicate direction.

WORKED EXAMPLE 1

Add two force vectors shown. Take to the right as the positive direction.

Step 1

Identify known and unknown variables and write down the formula that relates these variables.

$F_1 = -8$ N, $F_2 = 14$ N

$F_{addition} = F_1 + F_2$

Step 2

Substitute values into the formula and solve for the addition of the two forces.

$F_{addition} = -8 + 14$

$F_{addition} = 6$ N

The addition of the two forces is 6 N to the right.

How can we add and subtract vectors in two dimensions?

The direction of a two dimensional force vector can be defined by the angle from an axis, or a direction such as 'north-west'.

- In order to add vectors algebraically in two dimensions, we can resolve (break down) each force into two components (often this is the horizontal, x, and vertical, y, directions).
- The components forming a two dimensional force can be either positive or negative, depending on the definition of which directions are positive.

USEFUL TIP

The directions of the force components depend on the context of the question, but it is often easiest to choose the directions parallel (in the same or opposite direction) to and perpendicular (at right angles) to the motion of the object being considered.

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We can use Pythagoras' theorem and trigonometry to determine the one dimensional components of a two dimensional force and vice versa (Figure 2).

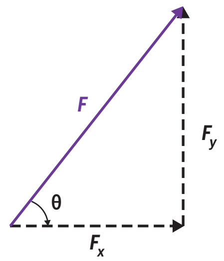

Figure 2 A force can be broken up into its perpendicular components.

For a force applied at an angle, θ:

- The force vector, F, can be resolved into:
  - a horizontal component, F_x

    $$F_x = F\cos(\theta)$$

  - a vertical component, F_y

    $$F_y = F\sin(\theta)$$

- The magnitude of F can be related to its components using Pythagoras' theorem:

  $$F = \sqrt{{F_x}^2 + {F_y}^2}$$

- The angle, θ, can be related to the horizontal and vertical components:

  $$\theta = \tan^{-1}\left(\frac{F_y}{F_x}\right)$$

STRATEGY

To add or subtract two dimensional force vectors:

1. Choose the directions that the forces will be resolved in.
2. Resolve each vector into its one dimensional components in each direction chosen.
3. Add or subtract all of the individual components in each direction to form two new one dimensional components.
4. Calculate the magnitude and angle of the overall two dimensional vector from its two components.

We can add and subtract vectors graphically[1] using the tip-to-tail method. The tip and tail of a vector are shown in Figure 3.

KEEN TO INVESTIGATE?

[1] **How do we add forces graphically?**
Search: Graphical vector addition

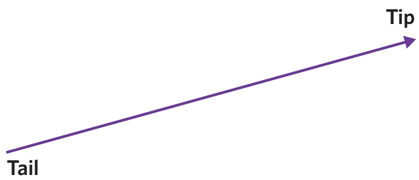

Figure 3 The tip and tail of a vector

Consider the vectors A and B shown in Figure 4. The tip of the first vector, A, is connected to the tail of the second vector, B, and the addition of the vectors, C, is drawn from the tail of A to the tip of B. This principle applies to the addition of any number of vectors.

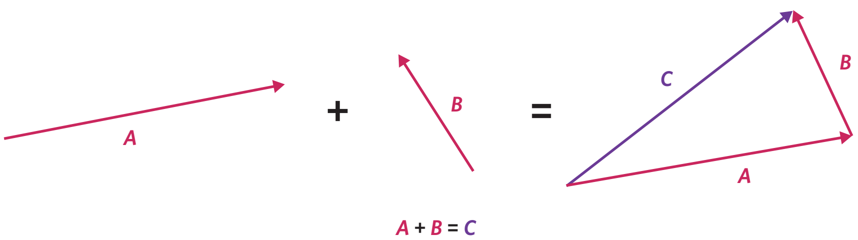

Figure 4 The graphical addition of vectors A and B, using the tip-to-tail method

The negative of a vector has the same magnitude but acts in the opposite direction to the original, meaning the tip and tail will flip. To graphically subtract vectors, such as $A - B$, we take vector A and add it to the negative of vector B, so $A - B$ becomes $A + (-B)$, as shown in Figure 5.

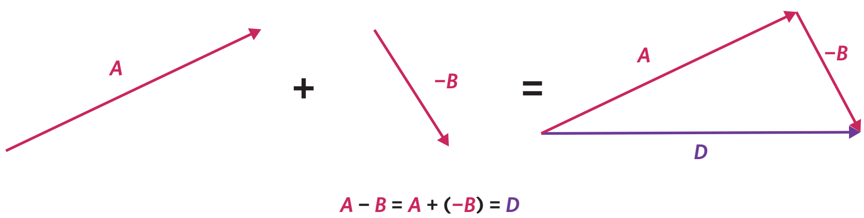

Figure 5 The graphical subtraction of vector *B* from vector *A*, using the tip-to-tail method

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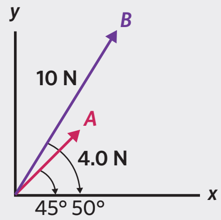
WORKED EXAMPLE 2

Add vector A and vector B. Take upwards and to the right as the positive directions.



Step 1

Resolve both forces into components in the x- and y-directions.

$A_x = 4.0 \times \cos(45°) = 2.83$ N

$A_y = 4.0 \times \sin(45°) = 2.83$ N

$B_x = 10 \times \cos(50°) = 6.43$ N

$B_y = 10 \times \sin(50°) = 7.66$ N

Step 2

Identify known and unknown variables and write down the formula that relates these variables.

$A_x = 2.83$ N, $A_y = 2.83$ N, $B_x = 6.43$ N, $B_y = 7.66$ N, $F_x = ?$, $F_y = ?$

$F_x = A_x + B_x$

$F_y = A_y + B_y$

Step 3

Substitute values into the formula and solve for the addition of the two forces in each direction.

$F_x = 6.43 + 2.83 = 9.26$ N

$F_y = 7.66 + 2.83 = 10.49$ N

Step 4

Identify known and unknown variables relating to the overall vector and write down the formulae that relates these variables.

$F_x = 9.26$ N, $F_y = 10.49$ N, $F = ?$, $\theta = ?$

$$F = \sqrt{(F_x)^2 + (F_y)^2}$$

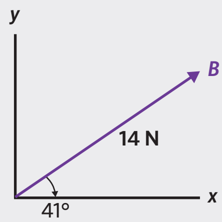
$$\theta = \tan^{-1}\left(\frac{F_x}{F_y}\right)$$

Step 5

Substitute values into the formulae and solve for the magnitude and angle of the overall force.

$$F = \sqrt{(9.26)^2 + (10.49)^2} = 14.0 = 14 \text{ N}$$

$$\theta = \tan^{-1}\left(\frac{9.26}{10.49}\right) = 41.4 = 41°$$



PROGRESS QUESTIONS

Question 1

Which single vector best represents the sum of the vectors x and y?

A. 

B. 

C. 

D. 

Continues →

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Question 2

A force of 4.5 N is applied at an angle of 60° to the positive horizontal axis. Which of the following are components of the force in the x- and y- direction?

A. $F_x = 2.3$ N, $F_y = 2.3$ N

B. $F_x = 2.3$ N, $F_y = 3.9$ N

C. $F_x = 3.9$ N, $F_y = 2.3$ N

D. $F_x = 3.9$ N, $F_y = 3.9$ N

The net force 3.1.1.2

The **net force** acting on an object is the vector sum of all forces acting on that object.

How can we find the net force acting on an object?

The net force, sometimes referred to as the resultant force, can be found by adding all of the forces acting upon an object (Figure 6). The net force is often denoted as F_{net}.

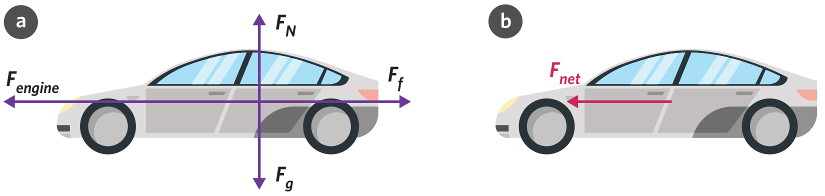
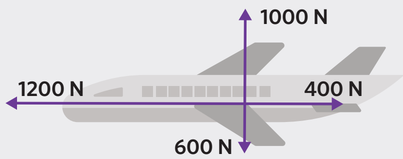


Figure 6 **(a)** The forces acting on a car and **(b)** the net force on a car

WORKED EXAMPLE 3

The forces acting on a model plane are shown in the diagram.
Determine the net force acting on the model plane.
Take upwards and to the left as the positive directions.



Step 1

Identify known and unknown variables and write down the formula that relates these variables.

$F_{x,1} = 1200$ N, $F_{x,2} = -400$ N,
$F_{y,1} = 1000$ N, $F_{y,2} = -600$ N

$F_{x,net} = ?$, $F_{y,net} = ?$

$F_{x,net} = F_{x,1} + F_{x,2}$

$F_{y,net} = F_{y,1} + F_{y,2}$

Step 2

Substitute values into the formula and solve for the components of the net force in each direction.

$F_{x,net} = 1200 + (-400) = 800$ N

$F_{y,net} = 1000 + (-600) = 400$ N

Step 3

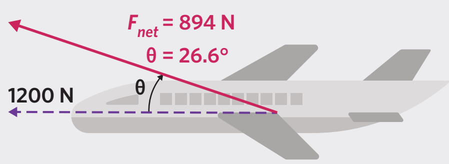
Find the magnitude and angle of the net force from its x and y components.

$F_{net} = \sqrt{(F_{x,net})^2 + (F_{y,net})^2}$

$F_{net} = \sqrt{(800)^2 + (400)^2} = 894.4 = 894$ N

$\theta = \tan^{-1}\left(\frac{400}{800}\right) = 26.57° = 26.6°$

The net force has a magnitude of 894 N, at 26.6° from the left (positive) horizontal axis.



PROGRESS QUESTIONS

Question 3

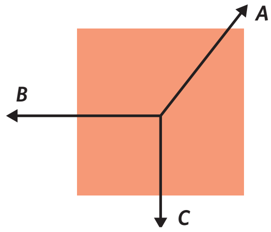
Three forces A, B, and C act on a block. Which of the forces contribute to the net force on the block?

A. Just forces A and B.

B. Just forces B and C.

C. All the forces A, B, and C.

D. There are no net forces acting on the block.



Question 4

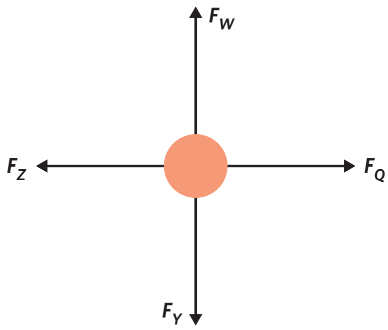
Four students are pulling on ropes in a four-person tug of war. The relative sizes of the forces acting on the various ropes are $F_W = 200$ N, $F_Q = 240$ N, $F_Y = 180$ N, and $F_Z = 210$ N. The situation is shown in the diagram below. Which one of the following best gives the magnitude of the resultant force acting at the centre of the tug-of-war ropes?

A. 28.3 N

B. 30.0 N

C. 36.1 N

D. 50.0 N



Adapted from VCAA 2018 exam Multiple choice Q5

Newton's laws of motion 3.1.1.3

Newton's laws of motion can be used to predict and describe the motion of objects.

How can we apply Newton's three laws of motion?

Newton's first law of motion

Newton's first law states that an object in motion will remain in motion unless acted on by a net external force. An important conclusion of the law is that an object can be moving even if there is no force being applied.

For example, an object may slide across a frictionless surface until there is an external force applied to change its velocity. If the net force acting on an object is zero, it will remain moving at a constant velocity.

Newton's second law of motion

Newton's second law states that the net force applied to an object is equal to its mass multiplied by its acceleration. This gives the equation:

FORMULA

$$F_{net} = ma$$

F_{net} = net force (N)
m = mass (kg)
a = acceleration (m s^{-2})

USEFUL TIP

When one vector quantity, like a, is multiplied by a scalar quantity, m, the resulting vector is in the same direction as the original vector quantity.

It is important to note that both the net force, F_{net}, and the acceleration, a, are vector quantities, and point in the same direction.

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Newton's third law of motion

Newton's third law states that for every 'action' force applied there is a 'reaction' force applied of equal magnitude and opposite direction. If an object A applies an action force on an object B, the reaction force is applied by object B on object A.

$$F_{A\ on\ B} = -F_{B\ on\ A}$$

Consider the motion of a rocket. The rocket applies a force on the gases, to the right. The reaction force is the force the gases apply on the rocket, to the left (Figure 7).

USEFUL TIP

The designation of which force is the action and which force is the reaction force is arbitrary, as both forces are applied at the same time.

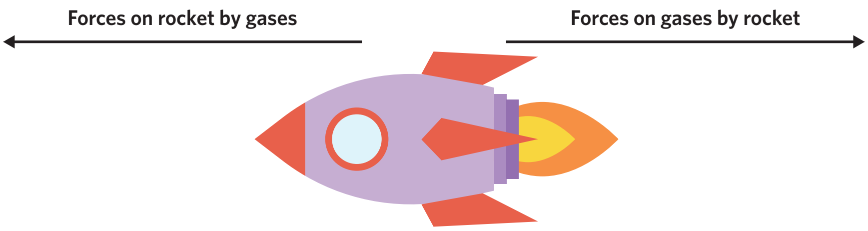
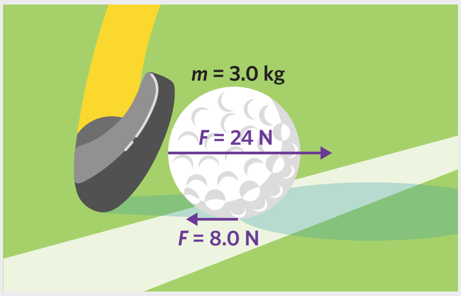


Figure 7 The action and reaction forces causing a rocket to accelerate in space

WORKED EXAMPLE 4

A ball of mass 3.0 kg is being pushed along the grass by a player's stick with a 24 N force, as shown in the diagram. The grass applies a constant 8.0 N frictional force. Take to the right as the positive direction.



a. Find the acceleration of the ball.

Step 1

Identify known and unknown variables and write down the formula that relates these variables.

$F_{net} = 24 - 8.0 = 16$ N, $m = 3.0$ kg, $a = ?$

$F_{net} = ma$

Step 2

Substitute values into the formula and solve for the net force in each dimension.

$16 = 3.0 \times a$

$a = 5.33 = 5.3$ m s^{-2}

The acceleration of the ball is 5.3 m s^{-2} to the right.

b. Identify and describe the reaction force to the force the stick applies to the ball.

Breakdown

Identify the action force.

The action force is the force of the stick on the ball, which is 24 N to the right.

Using $F_{A\ on\ B} = -F_{B\ on\ A}$, describe the reaction force.

The reaction force is the force of the ball on the stick, which is 24 N to the left.

c. When the ball is travelling at 9.0 m s^{-1} it slides onto a portion of frictionless ice, and the person stops applying force to the ball. Describe the motion of the ball as it slides along the ice.

Breakdown

Apply Newton's first law to the motion of the ball.

Newton's first law states the ball in motion will remain in motion until it is acted upon by a net external force.

Describe the motion of the ball when sliding along the ice according to Newton's first law.

The ball will continue to travel at 9.0 m s^{-1} to the right, since no net external force is applied to it.

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PROGRESS QUESTIONS

Question 5

The acceleration of an object is

A. always to the right.

B. always in the horizontal direction.

C. opposite in direction to the net force acting on it.

D. in the same direction as the net force acting on it.

Question 6

Which of the following is true about action-reaction force pairs?

A. The action and reaction forces involve different objects.

B. The action and reaction forces act in the same direction.

C. The action and reaction forces involve the same objects.

D. The action and reaction forces are different in magnitude.

Question 7

An object is moving at 4.0 m s^{-1} along a frictionless flat surface. Which of the following best describes its motion?

A. It will come to a stop in 12 s.

B. It will come to a stop in 16 s.

C. It will come to a stop, but after a long period of time.

D. It will only come to a stop when an external net force is applied to it.

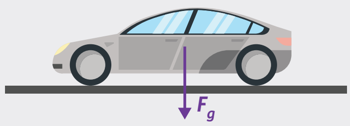
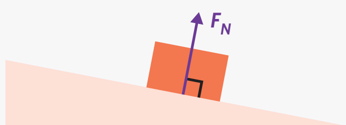
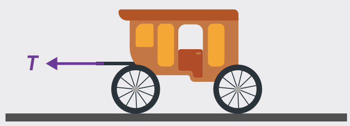
Types of forces 3.1.1.4

There are many different common types of forces we will encounter in VCE physics, which each have their individual properties and conventions.

What are some common types of forces?

Table 1 summarises some common types of forces.

Table 1 Common types of forces

Type of force	Symbol	Definition	Point of application	Direction	Diagram
Gravitational force (weight), $F_g = mg$	F_g	The force experienced by an object due to the gravitational field of another object.	Centre of mass	Towards the centre of the mass exerting the gravitational force	 A gravitational force acting on a car
Normal force	F_N	The contact force that acts between two objects at right angles to the surfaces in contact.	Point of contact between two objects	Perpendicular to the surface of contact between the two objects	 The normal force acting on a block, perpendicular to the surface
Tension	T	A pulling force that acts along a string, rope or other connector between two objects	In the connection between two objects	Along the connection between the two objects	 The tension force acting on a carriage

Continues →

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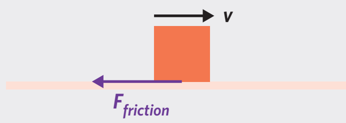
Table 1 Continued.

Type of force	Symbol	Definition	Point of application	Direction	Diagram
Frictional force	F_f	A force that resists the relative motion of two surfaces in contact	Contact between two surfaces	Opposing the direction of the relative motion of each object	 The frictional force acting on a mass moving to the right

PROGRESS QUESTIONS

Question 8

The normal force is

A. always acting directly up.

B. never greater in magnitude than the gravitational force.

C. the reaction force to the gravitational force acting on an object.

D. the reaction force to the force an object applies to the surface it is located on.

Question 9

A gravitational force on a mass

A. always has the same magnitude.

B. always acts directly downwards.

C. always acts towards the centre of the mass exerting the gravitational force.

D. is always greater in magnitude than the frictional force acting on an object.

MISCONCEPTION

'Mass and weight are the same.'

Mass, m, refers to the amount of matter an object has, whereas weight refers to the gravitational force acting on an object, $F_g = mg$. The mass of an object does not vary with location, but the weight of an object does depending on the strength of the gravitational field.

Theory summary

- Forces are vector quantities with the SI unit of newtons, N.
- Vectors in one dimension can have a positive or negative direction.
  - We add or subtract one dimensional vectors using their direction signs.
- Vectors in two dimensions can be broken down into two one dimensional components.
  - We use one dimensional components to add or subtract two dimensional vectors.
  - We can use the tip-to-tail method to add these vectors graphically.
- Newton's three laws of motion are:
  - Newton's first law of motion: an object in motion will remain in motion unless acted by a net external force.
  - Newton's second law of motion: the acceleration of an object by a net force is equal to the net force divided by the mass of the object, $F = ma$.
  - Newton's third law of motion: every action force has an equal and opposite reaction force, $F_{on\ A\ by\ B} = -F_{on\ B\ by\ A}$.
- Different forces are applied at different positions on objects and act in particular directions, depending on the type of force and the motion of the object.

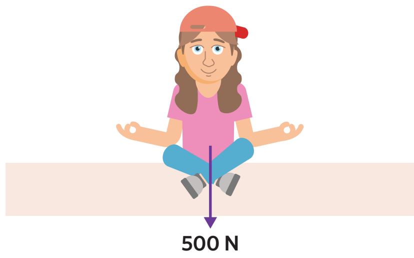
1B Questions

Mild 🌶 Medium 🌶🌶 Spicy 🌶🌶🌶

Deconstructed exam-style

Use the following information to answer questions 10–13.

Liesel, a student of yoga, sits on the floor in the lotus pose, as shown in the following figure. The action force, F_g , on Liesel due to gravity is 500 N down.



Question 10 🌶 (1 MARK)

The action force, F_g, is the force of

A. the Earth on Liesel.

B. Liesel on the Earth.

C. the ground on Liesel.

D. Liesel on the ground.

Question 11 🌶 (1 MARK)

The reaction force to the action force, F_g, is the force of

A. the Earth on Liesel.

B. Liesel on the Earth.

C. the ground on Liesel.

D. Liesel on the ground.

Question 12 🌶 (1 MARK)

State the direction of the reaction force to the action force, F_g.

Question 13 🌶🌶 (3 MARKS)

Identify and explain what the reaction force is to the action force, F_g.

Adapted from VCAA 2021 exam Short answer Q4

Exam-style

Question 14 🌶 (1 MARK)

Two force vectors are shown.

The addition of the two forces is

A. 5.0 N, left.

B. 5.0 N, right.

C. 17.0 N, left.

D. 17.0 N, right.

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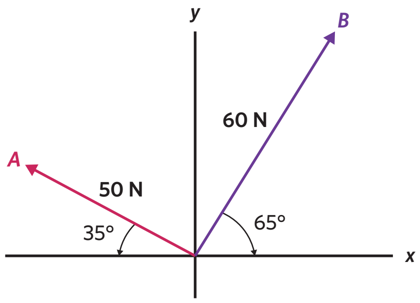
Question 15 (5 MARKS)

Two forces, *A* and *B*, are shown. Take to the right and upwards as the positive directions.



a. Determine the components of the two vectors *A* and *B* in the *x* and *y* direction. 2 MARKS

b. Find the addition of forces *A* and *B*. A direction is not required. 3 MARKS

Question 16 (6 MARKS)

A force of 70 N to the right pushes a 30 kg stone. It is moving to the right on a horizontal, frictionless surface. Take to the right as the positive direction.

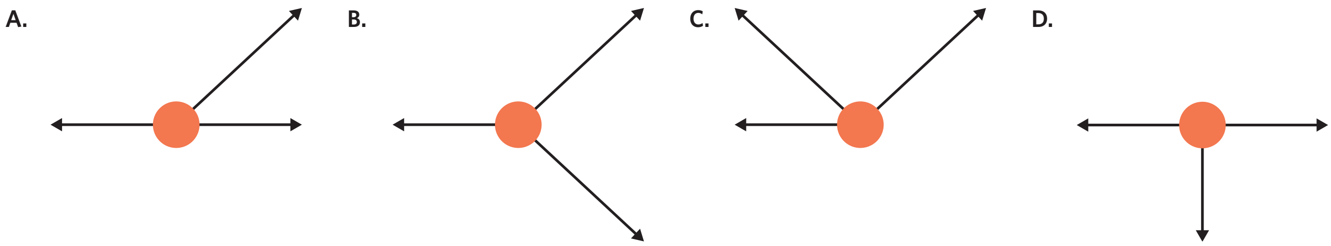
a. Draw and label all the forces acting on the stone. The magnitudes of the forces are not required. 3 MARKS

b. Assuming there is no friction, determine the magnitude of the acceleration of the stone. 1 MARK

c. The stone slides onto a different surface, where its acceleration is now 1.5 m s^{-2} to the left. A force of 70 N to the right is still being applied. Determine the magnitude of the frictional force acting on the stone. 2 MARKS

Question 17 (1 MARK)

A metal ring has three forces acting on it. Identify which of the following arrangements could hold the ring so that it is not accelerating.



Adapted from VCAA 2012 exam Short answer Q3

Question 18 (8 MARKS)

Four forces are acting on a 1000 kg boat being towed behind a car. The boat is not accelerating in the vertical direction. Take to the right and upwards as the positive directions. Assume friction forces and air resistance are negligible

a. What is the magnitude and direction of the gravitational force acting on the boat? 2 MARKS

b. What is the magnitude of the normal force acting on the boat? 2 MARKS

c. Why is there a normal force present in this scenario? 2 MARKS

d. The tow bar that is pulling the boat snaps when the boat is travelling at 65 km h^{-1}. Explain the motion of the boat after the tow bar snaps. 2 MARKS

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1B QUESTIONS

Question 19 (1 MARK)

Two blocks of mass 5 kg and 10 kg are placed in contact on a frictionless horizontal surface, as shown in the diagram below. A constant horizontal force, F, is applied to the 5 kg block. Both blocks accelerate to the right at 2.0 m s^{-2}.

Which one of the following statements is correct?

A. The net force on each block is the same.

B. There is no net force acting on either block.

C. The magnitude of the net force on the 5 kg block is half the magnitude of the net force on the 10 kg block.

D. The magnitude of the net force on the 5 kg block is twice the magnitude of the net force on the 10 kg block.

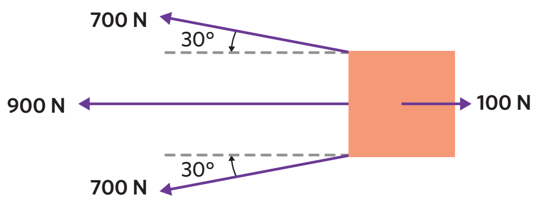
Adapted from VCAA 2020 exam Multiple choice Q9

Question 20 (2 MARKS)

Explain how the gases expelled by a rocket engine in one direction accelerate the rocket in the opposite direction.

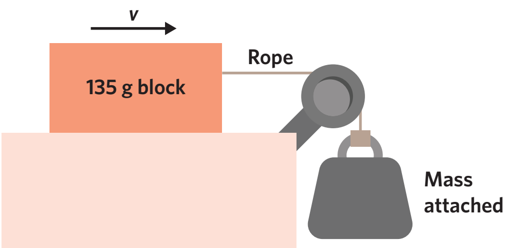
Question 21 (4 MARKS)

Three friends are pulling a 70 kg esky full of kombucha along the ground. The diagram shows the horizontal forces acting on the esky, as seen from the top. This is a constant friction force of 100 N. Determine the esky's acceleration. Take to the left as the positive direction.



Question 22 (7 MARKS)

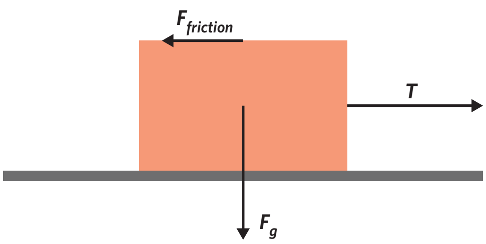
Students are investigating the acceleration of a 135 g block across a rough (non-frictionless) surface when a constant force is applied. They attach a mass to a pulley, so that the force pulling the object has the same magnitude as the gravitational force of the mass attached.



a. Identify the type of force that is causing the block to accelerate. 1 MARK

b. *Key science skill*

The students draw a diagram of the forces acting on the block. Evaluate the students' drawing of the forces. 2 MARKS



FROM LESSON 12A

c. *Key science skill*

The students have been told that the frictional force acting on an object is μF_N, where μ is the coefficient of friction of a surface. Determine the coefficient of friction of the surface, if the block accelerates at 3.6 m s^{-2} when 120 g of mass is attached to the end of the pulley system. 4 MARKS

FROM LESSON 12A

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Previous lessons

Question 23 (1 MARK)

Identify which of the following people has the same magnitude of average speed and average velocity.

A. A person who swims a lap up and back in a pool.

B. A person who runs a 100 m race in a straight line.

C. A person who runs a 400 m race around an oval path.

D. A person who rides a bike around a circular velodrome track.

FROM LESSON 1A

Question 24 (2 MARKS)

A race car is able to accelerate from rest to 200 km h^{-1} in just 6.6 s. Determine the magnitude of the acceleration of the race car. Assume the acceleration of the race car is constant.

FROM LESSON 1A

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1C Inclined planes

STUDY DESIGN DOT POINT

- investigate and apply theoretically and practically Newton's three laws of motion in situations where two or more coplanar forces act along a straight line and in two dimensions

1A 1B 1C 1D 1E 1F 1G 1H

3.1.1.6 Inclined planes

ESSENTIAL PRIOR KNOWLEDGE

1A Constant acceleration equations

1B Resolving forces in two dimensions

1B Newton's laws of motion

See questions 4–6.

Image: Amy Johansson/Shutterstock.com

Why do ski racers try to stay in constant contact with the slope?

Ski racers want to move as fast as possible parallel to the hill to reach the finish line. Lifting their skis from the slope would decrease their acceleration in the direction of the finish line. Many physical situations involve objects on a surface that is not completely horizontal. This lesson applies Newton's laws of motion to situations where objects sit on planes that are inclined from the horizontal, and shows how this can affect their motion.

KEY TERMS AND DEFINITIONS

inclined plane a flat surface that is at an angle to the horizontal plane

angle of inclination the angle between the flat surface of an inclined plane and the horizontal plane

friction a force that resists the relative motion of two surfaces in contact

FORMULAS

- **Newton's second law of motion**

  $F_{net} = ma$

- **components of gravity on inclined planes**

  $F_{g\parallel} = mg\sin(\theta)$

  $F_{g\perp} = mg\cos(\theta)$

Inclined planes 3.1.1.6

For an object on an **inclined plane**, the normal force will act perpendicular to the plane and the gravitational force will act vertically downwards. The component of the gravitational force parallel to the plane will act down the plane.

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How can we analyse forces and motion on inclined planes?

An inclined plane is a flat surface at an angle to the horizontal – this angle is referred to as the **angle of inclination**. When an object is placed on an inclined plane, such as a ball resting on a hill, it will tend to accelerate down that surface if it is able to overcome **friction**. There are two forces which will always act on an object on an inclined plane:

- The force due to gravity, which acts vertically down.
- The normal force, which acts perpendicular (at a 90° angle) to the inclined plane.

There may also be a friction force which acts parallel to (up or down) the plane and opposite to the direction of motion of the object. For example if the object is sliding down the plane then the friction force acts up the plane (Figure 1a). If the object is sliding up the plane, then the friction force acts down the plane (Figure 1b).

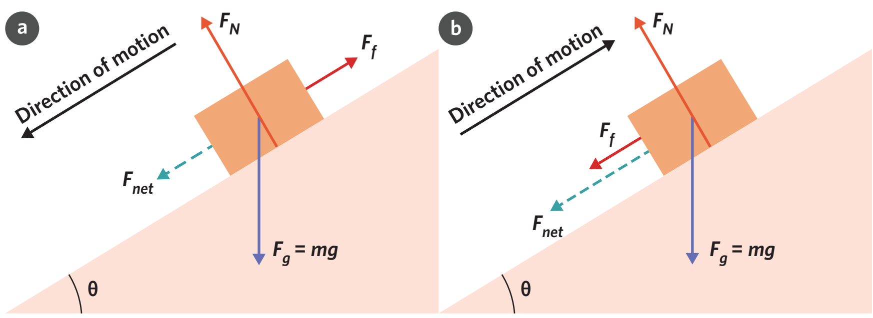

Figure 1 The forces that act on an object sliding **(a)** down and **(b)** up an inclined plane

All these forces, when added together, result in a net force which acts parallel to the plane. However, before we can add them together, the gravitational force needs to be resolved (separated) into two components: one perpendicular and one parallel to the inclined plane (Figure 2).

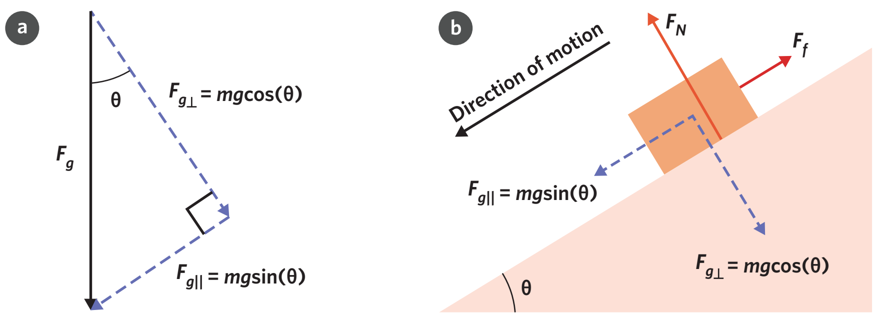

Figure 2 **(a)** Resolving the gravitational force into components. **(b)** These components drawn on an inclined plane diagram.

FORMULA

$$F_{g\parallel} = mg\sin(\theta)$$
$$F_{g\perp} = mg\cos(\theta)$$

$F_{g\parallel}$ = component of gravitational force parallel to the inclined plane (N)

$F_{g\perp}$ = component of gravitational force perpendicular to the inclined plane (N)

m = mass of object on the inclined plane (kg)

g = acceleration due to gravity (m s^{-2})

θ = angle of inclination (°)

MISCONCEPTION

'The net force will always point in the direction of motion.'

Because $F_{g\parallel}$ will always point down the plane, regardless of the direction of motion, and F_f will always resist the direction of motion. F_{net} can act up the plane only if there is an additional force on the object that acts up the plane.

USEFUL TIP

The symbol ∥ is used to represent parallel and the symbol ⊥ is used to represent perpendicular. These symbols can be used to label forces and accelerations parallel (up or down) and perpendicular to inclined planes.

MISCONCEPTION

'The normal force and the force due to gravity are equal.'

On an inclined plane, the normal reaction force is equal in magnitude and opposite in direction to the force of the object pushing onto the inclined plane, which has the same magnitude as the perpendicular component $F_{g\perp}$ of the gravitational force on the object.

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STRATEGY

The net force and the components of the gravitational force are only combinations or components of other forces. Therefore if a question asks to draw 'the forces acting on the object' on an inclined plane, do not draw those force arrows unless specifically asked to.

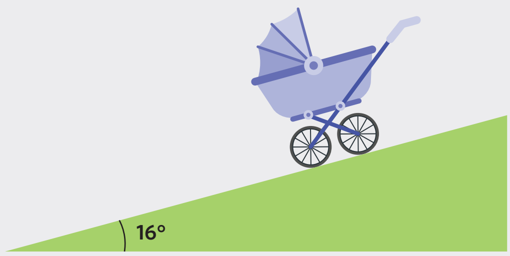
The net force of an object on an inclined plane can be found as follows:

- The net perpendicular force is given by $F_{net\perp} = F_N - mg\cos(\theta)$.
  - F_N and $F_{g\perp}$ are equal in magnitude and opposite in direction to one another (even though they are not an action-reaction pair),
  - therefore perpendicular net force acting on an object on an inclined plane is zero, $F_{net\perp} = 0$.
- The net force acting on an object which is sliding down an inclined plane, or at rest on it, has a magnitude given by $F_{net\parallel} = mg\sin(\theta) - F_f$.
- The net force on an object sliding up the plane is given by $F_{net\parallel} = mg\sin(\theta) + F_f$, since the friction force opposes the direction of motion of the object.

If the angle of inclination is increased, then the component of the gravitational force acting parallel to the plane also increases. This means that the net force down the plane, and hence the acceleration down the plane, will increase.

WORKED EXAMPLE 1

A pram with a total mass of 20 kg is placed on a hill, which is inclined at 16° to the horizontal. The brakes on the pram provide a constant frictional force of 54.0 N up the hill.



a. Draw and label all the forces acting on the pram. Draw the parallel and perpendicular components of the gravitational force as dotted lines.

Breakdown

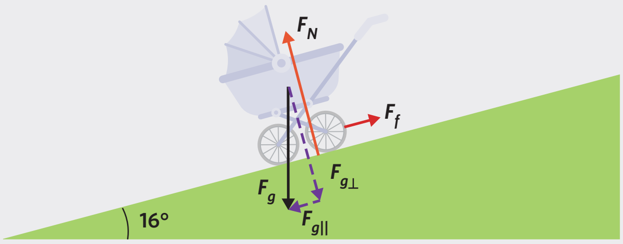
I have drawn an arrow labelled F_g from the middle of the pram pointing downwards.

I have resolved the arrow F_g into its parallel and perpendicular component arrows, and drawn these as dotted lines and tip to tail.

I have drawn an arrow labelled F_N perpendicular to the hill and starting where the pram meets the ground, and this is the same size as the arrow $F_{g\perp}$

I have drawn an arrow labelled F_f pointing up the hill.

Answer



b. Calculate the net force acting on the pram.

Step 1

Identify known and unknown variables and write down the formula that relates these variables.

Note that the net force on the pram will be parallel to the hill.

$m = 20$ kg, $g = 9.8$ m s^{-2}, $\theta = 16°$, $F_f = 54.0$ N, $F_{net} = ?$

$F_{net} = F_{net\parallel} = mg\sin(\theta) - F_f$

Step 2

Substitute values into the formula and calculate the net force.

$F_{net} = 20 \times 9.8 \times \sin(16°) - 54.0$

$F_{net} = 54.0 - 54.0 = 0$ N

Continues →

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c. The brakes on the pram are turned off, reducing the friction force to 24.0 N. Calculate the magnitude of the acceleration of the pram down the hill.

Step 1

Identify known and unknown variables and write down the formula that relates these variables.

$m = 20$ kg, $g = 9.8$ m s^{-2}, $\theta = 16°$, $F_f = 24.0$ N, $F_{net} = ?$

$F_{net} = F_{net\parallel} = mg\sin(\theta) - F_f$

Step 2

Substitute values into the formula and solve for net force.

$F_{net} = 20 \times 9.8 \times \sin(16°) - 24.0$

$F_{net} = 54.0 - 24.0 = 30.0$ N

Step 3

Identify known and unknown variables and write down the formula that relates these variables.

$m = 20$ kg, $F_{net} = 30.0$, $a = ?$

$F_{net} = ma$

Step 4

Substitute values into the formula and solve for the acceleration of the pram.

$30.0 = 20 \times a$

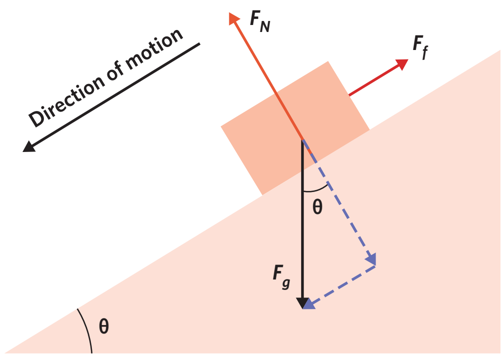
$a = \frac{30.0}{20} = 1.50 = 1.5$ m s^{-2}

PROGRESS QUESTIONS

Question 1

Select the option that correctly gives the equations for the net force acting on an object parallel and perpendicular to an inclined plane. Assume the object is sliding down the plane.

	$F_{net\parallel}$	$F_{net\perp}$
A.	$F_N - mg\cos(\theta)$	$mg\sin(\theta) - F_f$
B.	$mg\sin(\theta) - F_f$	$F_N - mg\cos(\theta)$
C.	$F_N - mg\sin(\theta)$	$mg\cos(\theta) - F_f$
D.	$mg\cos(\theta) - F_f$	$F_N - mg\sin(\theta)$



Question 2

Fill in the blanks in the following paragraph describing the forces acting on an object, and its motion, when on an inclined plane.

An object on an inclined plane will always experience a force due to (gravity / friction) and a normal force. It will also sometimes experience a force due to (gravity / friction). In general it will tend to accelerate (down / up) the plane, and increasing the angle of inclination will (increase / decrease) the magnitude of this acceleration.

Question 3

Select the option that correctly describes why objects on an inclined plane have no net force perpendicular to the plane.

A. The friction force is the reaction force to the gravitational force, so they cancel out.

B. The normal force is the reaction force to the gravitational force, so they cancel out.

C. If there was a net force perpendicular to the plane then the object would float off the plane.

D. The forces acting perpendicular to the plane are the normal force and the perpendicular component of the gravitational force, which are equal and opposite to each other.

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Theory summary

- There are three main forces which may act on an object on an inclined plane:
  - The gravitational force, which acts vertically down.
  - The normal force, which acts perpendicular to the inclined plane.
  - The friction force, which (if applicable) resists motion of the object.
- The gravitational force acting on an object on an inclined plane can be resolved into two components, parallel and perpendicular to the plane.
  - $F_{g\parallel} = mg\sin(\theta)$
  - $F_{g\perp} = mg\cos(\theta)$
- The net force acting on an object on an inclined plane is parallel to the plane, and is given by:
  - $F_{net} = mg\sin(\theta) - F_f$, if the object is at rest on or moving down the plane.
  - $F_{net} = mg\sin(\theta) + F_f$, if the object is moving up the plane.
- The net perpendicular force on an object on an inclined plane, $F_{net\perp}$, is zero.

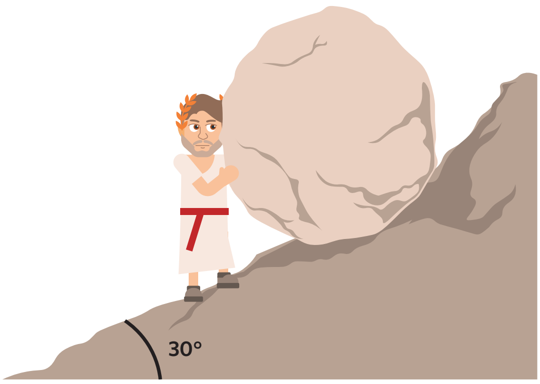
1C Questions

Mild Medium Spicy

Deconstructed exam-style

Use the following information to answer questions 4–7.

Sisyphus is pushing a boulder of mass 200 kg up a mountain with a force F_S. Due to the roughness of the ground, the boulder is subject to a constant frictional force of 120 N. He and the boulder move at a constant speed of 0.50 m s^{-1} up the slope.



Question 4 1 MARK

What is the magnitude of the parallel component of the gravitational force on the boulder?

A. $F_{g\parallel} = 0$

B. $F_{g\parallel} = mg\sin(\theta)$

C. $F_{g\parallel} = mg\cos(\theta)$

D. $F_{g\parallel} = mg\tan(\theta)$

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Question 5 1 MARK

Which of the following equations gives the net force on the boulder parallel to the mountain? Take down the mountain as positive.

A. $F_{net\parallel} = mg\sin(\theta) - F_f - F_S$

B. $F_{net\parallel} = mg\sin(\theta) - F_f$

C. $F_{net\parallel} = mg\sin(\theta) + F_f - F_S$

D. $F_{net\parallel} = mg\sin(\theta) + F_f$

Question 6 1 MARK

If an object is moving with a constant velocity in a certain direction then it is

A. experiencing a net force.

B. exerting a net force on the environment.

C. not experiencing a net force in that direction.

D. experiencing a net force in a different direction.

Question 7 4 MARKS

Calculate the magnitude of F_S.

Exam-style

Question 8 (11 MARKS)

A 1.2 kg block of wood is sliding down an inclined plane as shown in the given diagram. There is a constant frictional force of $F_f = 1.7$ N acting on the block up the plane, opposing its motion.

a. Label the diagram with the forces acting on the wooden block. 3 MARKS

b. The block has a net force of $F_{net} = 2.3$ N down the plane acting on it. Show that the angle of inclination is 20°. 2 MARKS

c. Calculate the magnitude and direction of the normal force on the block. 3 MARKS

d. The block is replaced with a different wooden block of mass 0.50 kg, and placed at rest at a distance of 6.0 m up the plane. It takes 5.0 s to slide to the bottom of the inclined plane. Calculate the magnitude of constant frictional force acting on it while on the plane. 3 MARKS

Adapted from VCAA 2013 exam Short answer Q1b

Question 9 (6 MARKS)

Consider an object remaining at rest on an inclined plane. The formula for the net force parallel to the plane in this situation is given by $F_{net\parallel} = F_{g\parallel} - F_f$.

a. Explain why we have to subtract the friction force from the parallel component of gravitational force in this situation. 3 MARKS

b. Using the net force, explain why the normal force does not affect the motion of the block, even if the block is moving on the plane. Assume that the normal force does not affect friction. 3 MARKS

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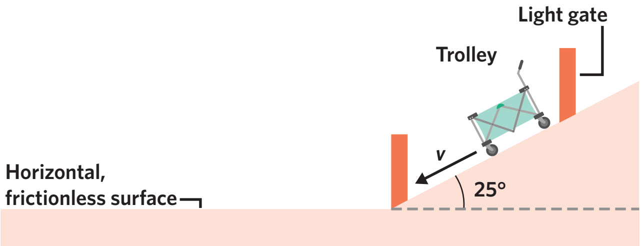
Question 10 (5 MARKS)

Kym and Kelly are experimenting with trolleys on a ramp inclined at 25°, as shown in the diagram. They release a trolley with a mass of 5.0 kg from rest at the top of the ramp. The trolley moves down the ramp, through two light gates and onto a horizontal, frictionless surface. Kym and Kelly calculate the acceleration of the trolley to be 2.7 m s^{-2} using the information from the light gates.



a. Calculate the component of the gravitational force of the trolley down the slope. 1 MARK

b. Assume that on the ramp there is a constant frictional force acting on the trolley and opposing its motion. Calculate the magnitude of the constant frictional force acting on the trolley. 2 MARKS

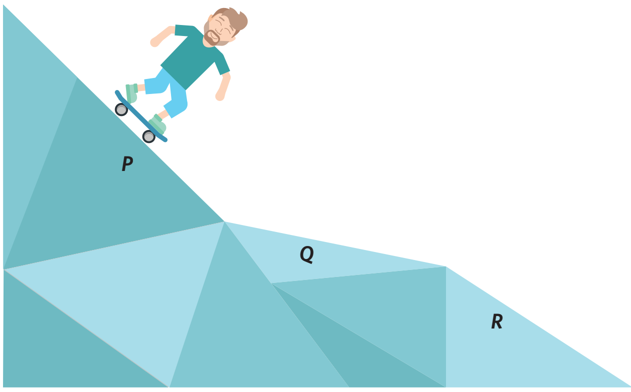
c. ***Key science skill***

Kym and Kelly repeat this experiment a number of times to find an average value for the acceleration measured. Comment on how this process reduces the effect of a type of error, and what type of error this is. 2 MARKS

Adapted from VCAA 2022 exam Short answer Q7

Use the following information to answer questions 11 and 12.

Garrett is skateboarding on a piece of sculptural art that is made up of a number of inclined planes, as shown in the diagram.



Question 11 1 MARK

At which of the given points does Garrett have the greatest normal force acting on them?

A. *P*

B. *Q*

C. *R*

D. The normal force has the same magnitude at all given points.

Question 12 (6 MARKS)

a. Compare the magnitude of Garrett's acceleration at points *P*, *Q*, and *R*. 3 MARKS

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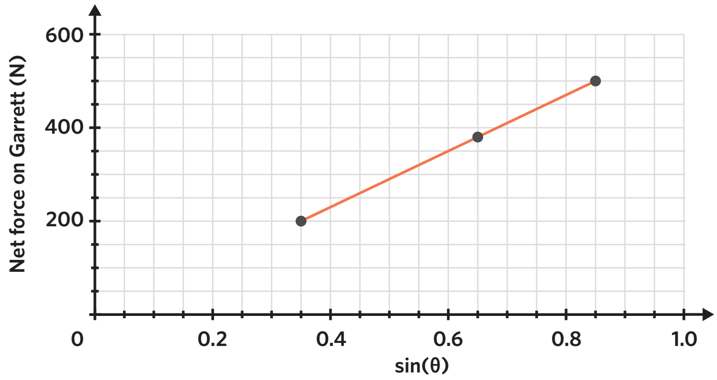
b. *Key science skill*

As Garrett skateboards, their friend Finn collects and graphs the following data comparing the angle of inclination and the net force on Garrett.

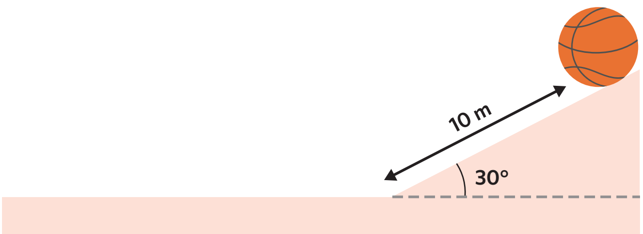


Using the gradient, calculate the total mass of Garrett and their skateboard. Assume there is no friction force. 🌶🌶🌶 3 MARKS

Previous lessons

Question 13 (7 MARKS)

Nim and Michael release a 0.50 kg ball from rest down a 10 m long frictionless hill inclined at 30.0° to the horizontal. The ball experiences a constant acceleration of 4.9 m s^{-2}. Once the ball reaches the bottom of the hill it rolls onto a surface where there is a constant friction force of 0.75 N which stops the ball after a few metres.



a. Show that the speed of the ball when it reaches the bottom of the hill is 9.9 m s^{-1}. 🌶 2 MARKS

b. Calculate the time it takes for the ball to reach the bottom of the hill, without using the value for the ball's displacement. 🌶🌶 2 MARKS

c. Calculate the magnitude of the ball's acceleration as the friction force slows it down. 🌶 2 MARKS

d. When the ball is at rest on the horizontal surface it experiences a normal force which can be described as 'the force on the ball by the ground'. If this is considered the 'reaction force', identify the 'action force' in relation to Newton's third law of motion. 🌶 1 MARK

FROM LESSONS 1A & 1B

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1D Connected bodies

STUDY DESIGN DOT POINT

- investigate and apply theoretically and practically Newton's three laws of motion in situations where two or more coplanar forces act along a straight line and in two dimensions

ESSENTIAL PRIOR KNOWLEDGE

1B Newton's second law of motion

1B Newton's third law of motion

1B Force due to gravity

See questions 7–9.

How does a strongman pull an aeroplane?

Even though a strongman is much lighter than an aeroplane, as long as the force they generate is more than the force resisting the plane's motion, they will cause the aeroplane to move. In this lesson, we will break down the forces between objects in contact with each other or connected by a rope.

KEY TERMS AND DEFINITIONS

connected bodies two or more objects either in direct contact or attached by a string, rope, cable, or stiff rod

FORMULAS

- **Newton's second law of motion**
  $F_{net} = ma$
- **Newton's third law of motion**
  $F_{A\ on\ B} = -F_{B\ on\ A}$
- **force due to gravity**
  $F_g = mg$

Connected bodies in tension 3.1.1.7

When two or more objects are connected by a string (or similar), there is a tension force acting through the string pulling on both sides. We can analyse these objects individually or as a system. These sorts of systems can be referred to as **connected bodies** in tension.

How do we analyse connected bodies in tension?

For connected bodies in tension, there are three forces that we often have to consider (Figure 1):

- T, the tension force. This acts with equal magnitude on both objects in opposite directions.
- F_x, a pulling force. In this case, F_x is pulling the system to the right.
- F_f, some resisting or frictional force. This resists the motion of the system but will not be present in every scenario.

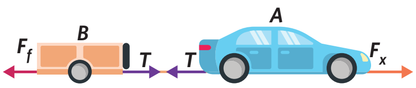

Figure 1 The horizontal forces involved for car, *A*, which is towing a trailer, *B*

USEFUL TIP

In VCE physics:

- The connection will always be considered massless.
- Only include a force due to friction in your calculations when the question requires you to.

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We can apply Newton's second law, $F_{net} = ma$, to any individual object or to the system of connected bodies as a whole. The acceleration of each object will have the same value in all cases. It is important that we correctly consider the relevant forces and masses in each case.

STRATEGY

When analysing the whole system, treat it as a single object:

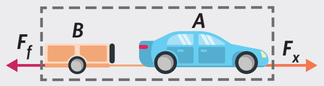
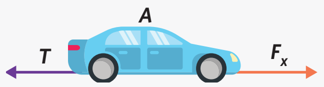
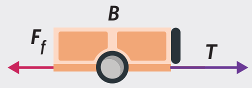
- Ignore the tension forces which are considered 'internal forces'. In this case, because they have the same magnitude in opposite directions, they cancel each other out.
- Use the total mass of the system.

When analysing a single object within the connected system:

- Consider only the forces acting directly on that object, including the tension force.
- Use only the mass of that object.

Taking to the right as the positive direction, Table 1 shows the application of Newton's second law to the different systems described in Figure 2.

Table 1 The formulas extracted from Figure 2. Note that a is the same in all the following equations.

Description	Situation	Formula
The whole system		$F_{net} = F_x - F_f = (m_A + m_B) \times a$
Only the car		$F_{net} = F_x - T = m_A \times a$
Only the trailer		$F_{net} = T - F_f = m_B \times a$

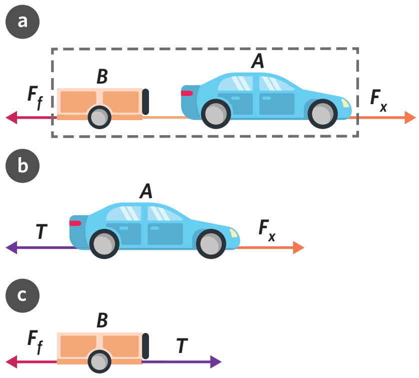
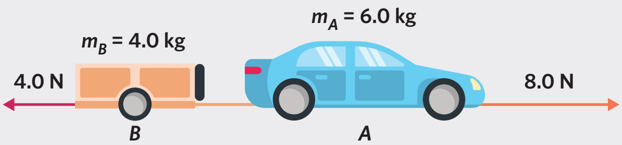


Figure 2 The relevant forces from Figure 1 when we analyse **(a)** the whole system, **(b)** only the car, and **(c)** only the trailer

WORKED EXAMPLE 1

A 6.0 kg remote control car tows a 4.0 kg trailer. The car is propelled by an 8.0 N force and there is a frictional force of 4.0 N acting on the trailer. Take to the right as the positive direction.



a. Show that the magnitude of the acceleration of the car is 0.40 m s^{-2}.

Step 1

Identify known and unknown variables and write down the formula that relates these variables.

$m_A = 6.0$ kg, $m_B = 4.0$ kg, $F_x = 8.0$ N, $F_f = 4.0$ N, $a = ?$

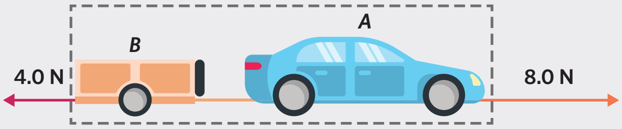
$F_{net} = F_x - F_f = (m_A + m_B) \times a$

Note: the acceleration of the car is equal to the acceleration of the system, we want to use the forces acting on the system.

Continues →

Step 2

Substitute values into the formula and solve for the acceleration.



$F_{net} = F_x - F_f = (m_A + m_B) \times a$

$8.0 - 4.0 = (6.0 + 4.0) \times a$

$a = 0.40$ m s^{-2}, as required.

---

b. Calculate the magnitude of the tension force.

Step 1

Identify known and unknown variables and write down the formula that relates these variables.

Note: that we can analyse either the car or trailer individually to find the magnitude of the tension force.

$m_A = 6.0$ kg, $F_x = 8.0$ N, $a = 0.40$ m s^{-2}, $T = ?$

$F_{net} = F_x - T = m_A \times a$

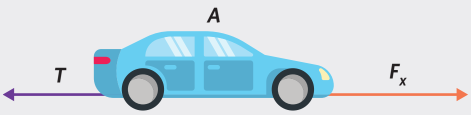
OR

$m_B = 4.0$ kg, $F_f = 4.0$ N, $a = 0.40$ m s^{-2}, $T = ?$

$F_{net} = T - F_f = m_B \times a$

Step 2

Substitute values into the formula and solve for the magnitude of the tension force.

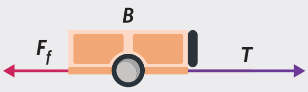


$F_{net} = F_x - T = m_A \times a$

$8.0 - T = 6.0 \times 0.40$

$T = 5.6$ N

OR



$F_{net} = T - F_f = m_B \times a$

$T - 4.0 = 4.0 \times 0.40$

$T = 5.6$ N

We can make similar observations when one of the connected masses is hanging over an edge via a pulley as shown in Figure 3a. The only difference here is that the force due to gravity acting on the hanging mass, F_g, will replace the pulling force, F_x.

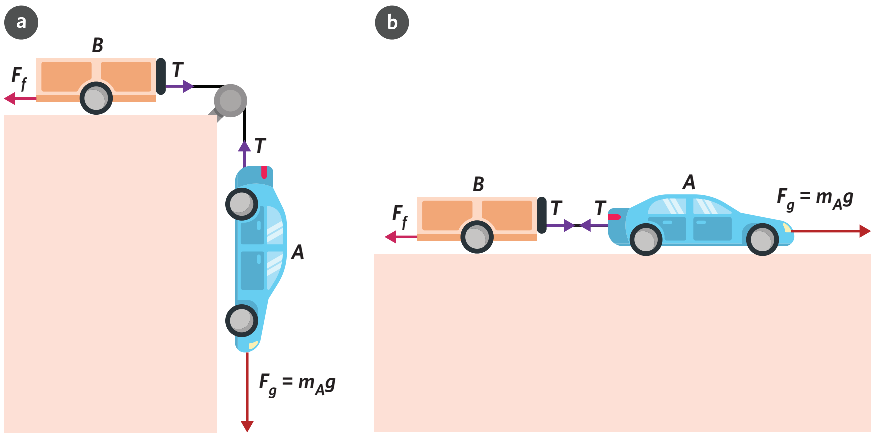


Figure 3 **(a)** A force diagram for a car, hanging over a ledge connected to a trailer. **(b)** This can be modelled with all forces in a horizontal direction in order to simplify calculations.

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PROGRESS QUESTIONS

Question 1

A truck is accelerating while pulling a trailer connected by a cable. The tension force in the cable acts

A. only forward on the trailer.

B. only backward on the truck.

C. forward on the truck and backward on the trailer.

D. backward on the truck and forward on the trailer.

Question 2

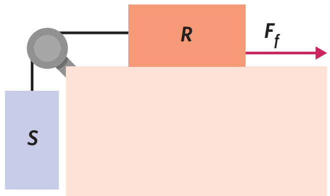
Identify the forces acting on block *S*. **(Select all that apply)**

A. T

B. F_f

C. F_x

D. F_g



Question 3

Sarah, who has a mass of 75 kg, is pulling a sled with a force of 400 N. Sarah and the sled are accelerating at 3.0 m s^{-2}. Considering there is no friction force acting on the sled, the mass of the sled is closest to

A. 5.3 kg.

B. 58 kg.

C. 1.3×10^2 kg.

D. 1.8×10^2 kg.

Connected bodies in contact 3.1.1.8

When two or more objects in direct contact are pushed, they exert contact forces on one another according to Newton's third law. Similar to connected bodies in tension, we can analyse these objects individually or as a system.

How do we analyse connected bodies in contact?

For connected bodies in contact, there are four forces that we may have to consider (Figure 4):

- F_x, a pushing force. In this case, F_x is pushing the system to the right.
- $F_{on\ B\ by\ A}$, the contact force on block *B*.
- $F_{on\ A\ by\ B}$, the contact force on block *A*.
- F_f, some resisting or frictional force. This resists the motion of the system but will not be present in every scenario.

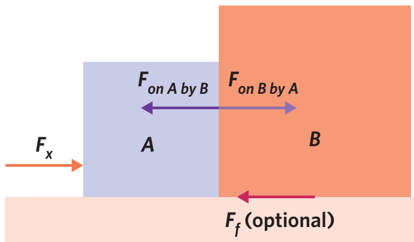


Figure 4 A force diagram for connected bodies in contact. $F_{on\ B\ by\ A}$ and $F_{on\ A\ by\ B}$ are action reaction pairs.

Similarly to connected bodies in tension, we can apply Newton's second law, $F_{net} = ma$, to any individual object or to the system of connected bodies as a whole. The acceleration will have the same value in all cases. It is important that we correctly consider the relevant forces and masses in each case.

STRATEGY

When analysing the whole system, treat it as a single object:

- Ignore the contact forces ($F_{on\ A\ by\ B}$ and $F_{on\ B\ by\ A}$) which are considered 'internal forces' because they have the same magnitude in opposite directions, cancelling each other out.
- Use the sum of all the masses.

When analysing a single object within the connected system:

- Consider only the forces acting directly on that object, including the relevant contact force.
- Use only the mass of that object.

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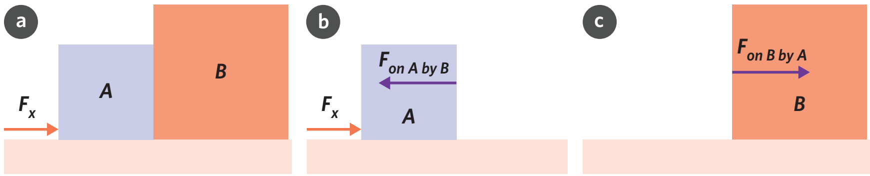
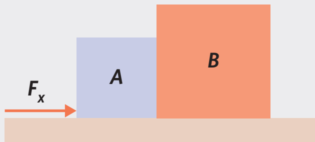
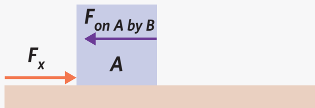
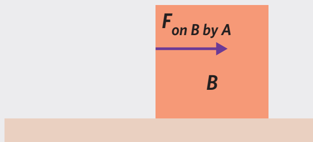


Figure 5 The relevant forces from Figure 4 when we analyse **(a)** the whole system, **(b)** only block *A*, and **(c)** only block *B*.

Taking right as the positive direction, Table 2 shows the application of Newton's second law to the different systems described in Figure 5.

Table 2 The formulas extracted from Figure 5. Note that ***a*** is the same in all the following equations.

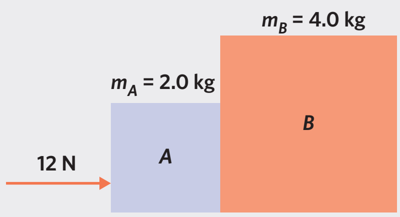
Description	Situation	Formula
The whole system		$F_{net} = F_x = (m_A + m_B) \times a$
Only the car		$F_{net} = F_x - F_{on\ A\ by\ B} = m_A \times a$
Only the trailer		$F_{net} = F_{on\ B\ by\ A} = m_B \times a$

USEFUL TIP

When two bodies are in contact on a frictionless surface, the net force on each block will be directly proportional to its mass. So for a 3 kg and 6 kg block, the 6 kg block will have a net force twice as large as the 3 kg block.

WORKED EXAMPLE 2

Two blocks, *A* and *B*, are in contact being pushed on a frictionless surface by a force of 12 N. Block *A* has a mass of 2.0 kg and block *B* has a mass of 4.0 kg. Take to the right as the positive direction.



a. Show that the magnitude of the acceleration of the blocks is 2.0 m s^{-2}.

Step 1

Identify known and unknown variables and write down the formula that relates these variables.

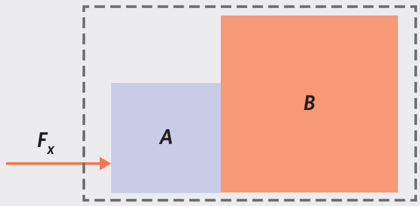
Note: the acceleration of both blocks is equal to the acceleration of the system.

$m_A = 2.0$ kg, $m_B = 4.0$ kg, $F_x = 12$ N, $a = ?$

$F_{net} = F_x = ma = (m_A + m_B) \times a$

Step 2

Substitute values into the formula and solve for the acceleration.



$F_{net} = F_x = (m_A + m_B) \times a$

$12 = (2.0 + 4.0) \times a$

$a = 2.0$ m s^{-2}, as required.

Continues →

b. Show that the magnitude of the force on block A by block B is 8.0 N.

Step 1

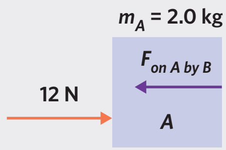
Identify known and unknown variables and write down the formula that relates these variables.

$m_A = 2.0$ kg, $F_x = 12$ N, $a = 2.0$ m s^{-2}, $F_{on\ A\ by\ B} = ?$

$F_{net} = F_x - F_{on\ A\ by\ B} = m_A \times a$

Step 2

Substitute values into the formula and solve for the magnitude of the force on block A by block B.



$F_{net} = F_x - F_{on\ A\ by\ B} = m_A \times a$

$12 - F_{on\ A\ by\ B} = 2.0 \times 2.0$

$F_{on\ A\ by\ B} = 8.0$ N, as required.

---

c. Calculate the magnitude of the force on block B by block A.

Step 1

Identify known and unknown variables and write down the formula that relates these variables.

$F_{on\ A\ by\ B} = 8.0$ N, $F_{on\ B\ by\ A} = ?$

$F_{on\ B\ by\ A} = -F_{on\ A\ by\ B}$

Step 2

Substitute values into the formula and solve for the magnitude of the force on block B by block A.

$F_{on\ B\ by\ A} = -F_{on\ A\ by\ B} = -8.0$ N

The magnitude of $F_{on\ B\ by\ A}$ is 8.0 N.

PROGRESS QUESTIONS

Question 4

Two solid wooden blocks of different masses are in contact and are being pushed by a constant force F_x on a frictionless surface. The larger block has twice the mass of the smaller block. The net force that acts on each block is

A. the same.

B. independent of the body's mass.

C. proportional to the masses of the two blocks.

D. equal to the combined mass of the two blocks.

Question 5

Fatma is pushing a boulder along a flat surface. The boulder has a mass of 1200 kg and Fatma has a mass of 75 kg. Considering the boulder accelerates at 0.50 m s^{-2}, the net force on Fatma is

A. 38 N.

B. 75 N.

C. 6.0×10^2 N.

D. 6.4×10^2 N.

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Theory summary

- Newton's second law of motion can be applied to the whole system or individual components of connected body systems to calculate acceleration, mass, and net force.
- Tension is the pulling force on an object attached to a string, rope, or cable.
  - The tension force will have the same magnitude but opposite direction for both objects it is attached to.
  - These two forces will cancel out when working with the whole connected body tension system.
- Connected bodies in contact experience an equal and opposite contact force which cancel each other out when examining the whole system. However, when analysing forces acting on an individual body, these forces must be included.

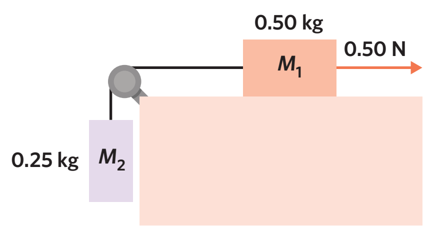
1D Questions

Mild 🌶 Medium 🌶🌶 Spicy 🌶🌶🌶

Deconstructed exam-style

Use the following information to answer questions 6–9.

Jesse connects two masses M_1 (0.50 kg) and M_2 (0.25 kg) with a string. The second mass is hanging off the edge of a table and the string runs through a frictionless pulley. M_1 is on a surface with a constant frictional force of 0.50 N and the mass of the string is negligible.



Question 6 🌶 (1 MARK)

Calculate the magnitude of the force due to gravity acting on M_2.

Question 7 🌶 (1 MARK)

Calculate the magnitude of the acceleration of the system.

Question 8 🌶 (1 MARK)

State the magnitude of the acceleration of M_2.

Question 9 🌶🌶 (4 MARKS)

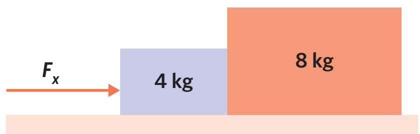
Calculate the magnitude of the tension in the rope connecting the two masses.

Adapted from VCAA 2010 Exam 1 Section A AoS 1 Q13

Exam-style

Question 10 🌶 (1 MARK)

Two blocks of mass 4 kg and 8 kg are placed in contact on a horizontal surface, as shown in the diagram. A constant horizontal force, F_x, is applied to the right on the 4 kg block.



If the speed of the blocks is constant. Which of the following statements is true?

A. F_x is the only external force acting on the blocks.

B. The net force on the 8.0 kg block is equal to $2 \times F_x$.

C. A frictional force is equal in magnitude and opposite in direction to F_x.

D. The 8.0 kg block must exert a force equal in magnitude and opposite in direction to balance the force F_x applied to the 4.0 kg block.

Question 11 (3 MARKS)

Penny is using a tractor with a mass of 800 kg to tow a trailer with a mass of 700 kg. The tractor and trailer accelerate at 1.20 m s^{-2}. Ignore the mass of the rope used to tow the trailer and the effects of friction.

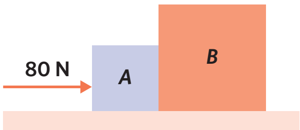
a. What is the driving force of the tractor? 1 MARK

b. Calculate the tension force between the trailer and the tractor. 2 MARKS

Adapted from VCAA 2011 Exam 1 Section A AoS 1 Q1/2

Question 12 (5 MARKS)

Two blocks, *A* and *B*, which have a mass of 2.0 kg and 6.0 kg respectively are in contact and are being pushed on a frictionless surface by a force of 80 N.



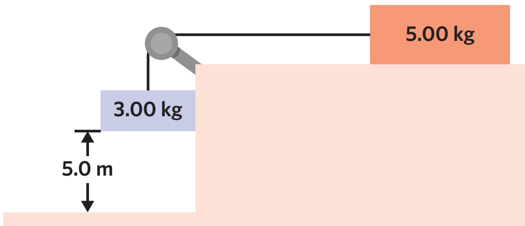
a. Find the magnitude of the force on block *A* by block *B*. 3 MARKS

b. What is the direction and magnitude of the force on block *B* by block *A*? 2 MARKS

Adapted from VCAA 2018 Exam Section B Q8

Use the following information to answer questions 13 and 14.

A 3.00 kg mass attached to a string is hanging 5.00 m above the ground. Assume that the string has no mass. The string is connected to a 5.00 kg mass on a horizontal frictionless table, as shown. The masses are released from rest and an acceleration of 3.68 m s^{-2} is observed.



Question 13 (1 MARK)

The magnitude of the tension in the string is closest to

A. 49.0 N. **B.** 29.4 N. **C.** 18.4 N. **D.** 3.27 N.

Adapted from VCAA 2019 NHT exam Multiple choice Q8

Question 14 (3 MARKS)

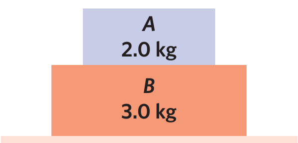
Key science skill

Two students want to measure the distance the 3.00 kg mass falls in one second using a ruler with gradations every 5.0 cm. Comment on how having 5.0 cm gradations affects random error associated with their distance measurements and identify two ways in which the effect of random errors can be reduced.

FROM LESSON 12C

Question 15 (3 MARKS)

Block *B* has a mass of 3.0 kg and sits at rest on top of a table. Block *A* has a mass of 2.0 kg and is resting on top of block *B*.



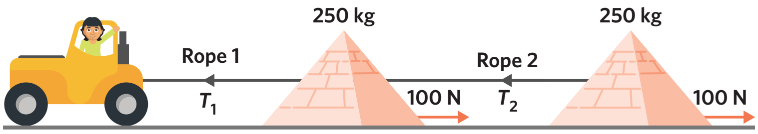
a. Calculate the magnitude and direction of the force exerted on block *A* by block *B*. 2 MARKS

b. The table top is then removed and the blocks accelerate downwards at *g*. What is the magnitude of force that block *B* now exerts on block *A*? 1 MARK

Adapted from VCAA 2019 NHT Exam Section B Q9

Question 16 (10 MARKS)

Amy is driving a tractor that is dragging two miniature pyramids each of mass 250 kg through sand which provides a frictional force of 100 N to each pyramid. T_1 and T_2 represent the tension forces that exist in the rope between Amy and the first pyramid and between the two pyramids respectively. A rope will break if its tension force reaches 1800 N.



a. What is the magnitude of T_1 when Amy is dragging the pyramids at a constant speed? 1 MARK

b. Amy needs to be home for dinner and accelerates in the direction of motion at 0.25 m s^{-2}. Calculate the magnitude of T_2 and T_1. 4 MARKS

c. Amy's dinner has already been served for her and is beginning to cool down. She increases her acceleration to the point where one of the ropes break. Which rope broke first and what was the magnitude of Amy's acceleration? 3 MARKS

d. ***Key science skill***

Amy records that when more pyramids are added to the rope, it gets more difficult to pull. She also records that the pyramids are easier to pull when they are being pulled on ice. Identify what sort of data Amy is recording and give one reason why this sort of data is useful in building experiments. 2 MARKS

Adapted from VCAA 2012 Exam 1 Section A AoS 1 Q5

Previous lessons

Question 17 (1 MARK)

An ultralight aeroplane of mass 600 kg flies in a horizontal straight line at a constant speed of 120 m s^{-1}. The horizontal resistance force acting on the aeroplane is 1800 N.

Which of the following best describes the magnitude of the forward horizontal thrust on the aeroplane?

A. 1800 N

B. slightly less than 1800 N

C. slightly more than 1800 N

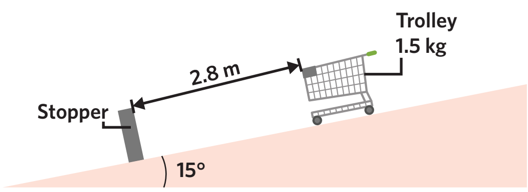
D. 7200 N

Adapted from VCAA 2019 exam Multiple choice Q11

FROM LESSON 1B

Question 18 (5 MARKS)

Students set up an inclined plane surface, as shown. It is angled at 15° to the horizontal. They place a frictionless trolley of mass 1.5 kg at the top of the incline so that the distance from the front of the trolley to the stopper at the bottom is 2.8 m.



a. Calculate the acceleration of the trolley. 2 MARKS

b. The students replace the frictionless trolley with a block of wood of the same mass. They release the block of wood at a distance of 2.8 m from the stopper, the same as they did with the trolley. When the block is sliding down the incline, there is a constant frictional force between it and the surface. They find that it takes 5.0 s to reach the stopper at the bottom.

Calculate the magnitude of the frictional force of the plane surface acting on the block. 3 MARKS

Adapted from VCAA 2013 exam Short answer Q1

FROM LESSON 1A & 1C

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1E Basic circular motion

Image: janez volmajer/Shutterstock.com

Why do planets orbit the Sun?

The Sun exerts a gravitational force on the planets in the solar system. Although the force acts towards the Sun, the planets travel in a circular path around the Sun as the force acts perpendicular to the planet's direction of motion. Whenever a body travels in a circular path it is undergoing circular motion. This lesson examines the basics of uniform circular motion, where objects travel at a constant circular speed. More complex cases of circular motion will be explored in the next few lessons.

STUDY DESIGN DOT POINT

- investigate and analyse theoretically and practically the uniform circular motion of an object moving in a horizontal plane: ($F_{net} = \frac{mv^2}{r}$), including:
  - a vehicle moving around a circular road
  - vehicle moving around a banked track
  - an object on the end of a string

1A 1B 1C 1D 1E 1F 1G 1H 1I

3.1.2.1 Circular speed

3.1.2.2 Centripetal force

3.1.2.3 Centripetal acceleration

ESSENTIAL PRIOR KNOWLEDGE

1A Instantaneous velocity

1B Newton's laws of motion

See questions 10–11.

KEY TERMS AND DEFINITIONS

uniform circular motion the motion of an object travelling around a circle with a constant speed

period the time taken to complete one cycle

centripetal force the net force causing circular motion, which is always directed towards the centre of a body's circular path

centripetal acceleration the rate of change of the instantaneous velocity of an object as it travels in a circular path

FORMULAS

- **circular speed**
  $v = \frac{2\pi r}{T}$
- **centripetal force**
  $F_{net} = \frac{mv^2}{r} = \frac{4\pi^2 rm}{T^2}$
- **centripetal acceleration**
  $a = \frac{v^2}{r} = \frac{4\pi^2 r}{T^2}$

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Circular speed 3.1.2.1

Circular speed is the speed an object travels around a circle. It is given by the circular distance travelled divided by the time for one full revolution.

How can we analyse the velocity of an object travelling in a circle?

The magnitude of the velocity of a body undergoing **uniform circular motion** can be calculated using $speed = \frac{distance}{time}$. For the purposes of VCE Physics, we will assume all circular motion is uniform, where bodies travel at a constant speed along their circular path. The total distance travelled around a full circle is the circumference, $C = 2\pi r$, while the time taken to complete one revolution is the **period**, T. From this, we can derive the formula for circular speed:

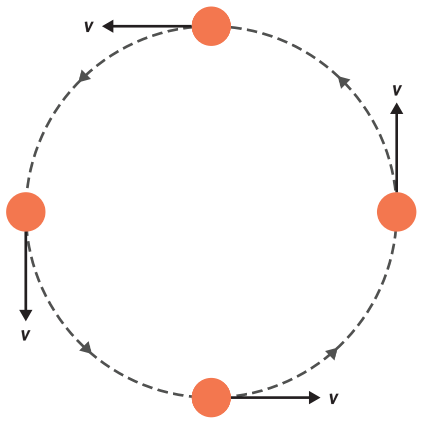


Figure 1 The direction of the instantaneous velocity of an object undergoing circular motion

USEFUL TIP

The period of an object's rotation can be related to its frequency using $T = \frac{1}{f}$.

FORMULA

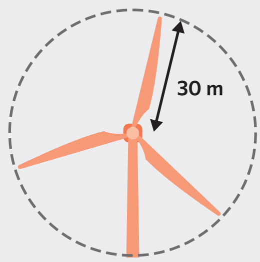
$$v = \frac{2\pi r}{T}$$

v = circular speed (m s^{-1})
r = radius of circle (m)
T = period (s)

Circular speed is a scalar quantity – it has no direction associated with it. The direction of motion (instantaneous velocity) of an object undergoing circular motion is always tangential to the circular path it is travelling in (Figure 1).

WORKED EXAMPLE 1

A wind turbine with a radius of 30 metres takes 15 seconds to complete a full rotation. It rotates in the anticlockwise direction. The circular path of the blades is shown with a dotted line.



a. Calculate the speed of the wind turbine at the end of the blades.

Step 1

Identify known and unknown variables and write down the formula that relates these variables.

$r = 30$ m, $T = 15$, $v = ?$

$v = \frac{2\pi r}{T}$

Step 2

Substitute values into the formula and solve for speed.

$v = \frac{2\pi \times 30}{15} = 12.6 = 13$ m s^{-1}

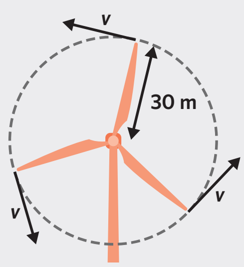
b. Draw an arrow at the end of each blade showing the direction of the instantaneous velocity at the position shown.

Breakdown

Draw three arrows of equal length.

The arrows must be perpendicular to the blades.

Answer



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PROGRESS QUESTIONS

Question 1

Which of the following objects are undergoing circular motion?
(Select all that apply)

A. a football being kicked in the air

B. a stone being thrown off of a cliff

C. a ferris wheel continuously rotating

D. a person running around a circular track

Question 2

Circle the correct terms to complete the paragraph.

An object undergoing uniform circular motion has (constant / changing) circular speed, with an instantaneous velocity that is always (constant / changing) and directed (at a tangent to / towards the centre of) the circle it is travelling in.

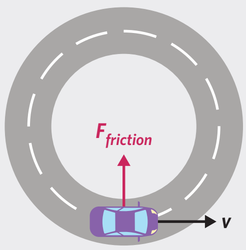
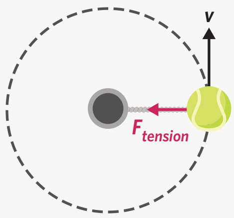
Centripetal force 3.1.2.2

The **centripetal force** is the net force that causes a body to undergo circular motion. It always acts towards the centre of the circular path.

How can we analyse the net force acting on an object undergoing uniform circular motion?

Centripetal force is the name for the net force acting on a body that is undergoing uniform circular motion. For an object to undergo circular motion, it must have a net force pointing towards the centre of the circle. This can be provided by a single force or a combination of forces. Table 1 shows a variety of different forces causing objects to undergo circular motion.

Table 1 Examples of centripetal forces

Scenario	Force causing circular motion	Direction of force	Diagram
A car travelling around a circular roundabout.	Friction on the car's wheels	Towards the centre of the roundabout.	
A ball swinging around on a string attached to a pole	Tension on the ball from the string	Towards the pole.	

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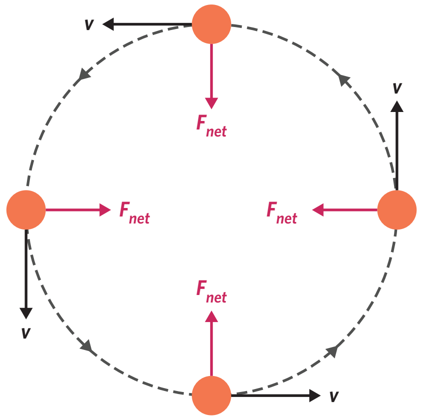
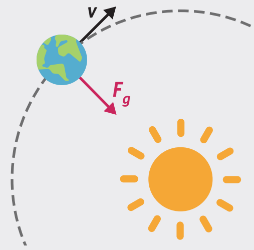


Figure 2 The direction of the centripetal force acting on an object undergoing circular motion

USEFUL TIP

$F_{net} = \frac{4\pi^2 rm}{T^2}$ can be derived by substituting the formula for circular speed $v = \frac{2\pi r}{T}$ into $F_{net} = \frac{mv^2}{r}$.

Table 1 Continued.

Scenario	Force causing circular motion	Direction of force	Diagram
Earth orbiting the Sun	The Sun's gravitational force acting on the Earth.	Towards the Sun.	

In each case in the table above, the centripetal force is provided by a force that is directed towards the centre of the circular path (Figure 2). Although the circular speed of the object undergoing circular motion is constant, the net force causes the direction of the instantaneous velocity to continuously change. The magnitude of the centripetal force is given by:

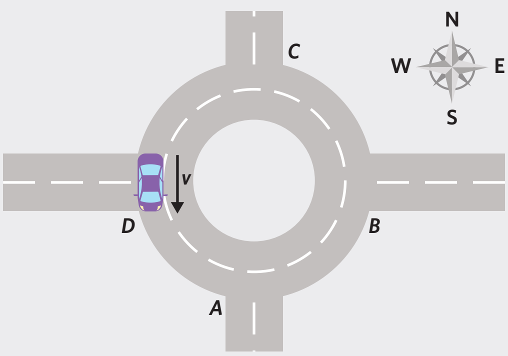
FORMULA

$$F_{net} = \frac{mv^2}{r} = \frac{4\pi^2 rm}{T^2}$$

F_{net} = centripetal force (N)
v = circular speed (m s^{-1})
m = mass of object (kg)
r = radius (m)
T = period (s)

WORKED EXAMPLE 2

A car of mass 700 kg travelling at 60 km h^{-1} around a circular roundabout with radius 15 m. Assume the car's speed does not change throughout the turn.



a. Calculate the magnitude of the frictional force acting on the car.

Step 1

Identify known and unknown variables and write down the formula that relates these variables.

Note that the circular speed is given in km h^{-1} and has to be converted to m s^{-1}.

$m = 700$ kg, $v = \frac{60}{3.6} = 16.7$ m s^{-1}, $r = 15$ m, $F_{net} = ?$

$F_{net} = \frac{mv^2}{r}$

Step 2

Substitute values into the formula and solve for the centripetal force.

$F_{net} = \frac{700 \times 16.7^2}{15} = 1.30 \times 10^4$ N

Step 3

Relate the frictional force to the centripetal force acting on the car.

$F_{friction} = F_{net}$

$F_{friction} = 1.30 \times 10^4 = 1.3 \times 10^4$ N

Continues →

b. Compare the frictional force acting on the car at point D and point A.

Breakdown	Answer
Compare the differences between the frictional force at point D and point A.	As the car moves from point D to point A, the frictional force changes from acting East to acting North.
Compare the similarities between the frictional force at point D and point A.	The magnitude of the frictional force, $F_{friction} = \frac{mv^2}{r}$, is the same at both point D and point A.

PROGRESS QUESTIONS

Question 3

Which of the following best describes the centripetal force?

A. The product of a body's mass and its acceleration.

B. The force that points radially inwards for objects undergoing circular motion.

C. The force that points in the direction of motion for objects undergoing circular motion.

D. The net force acting on objects undergoing circular motion, which points radially inwards.

Question 4

The Moon, of mass 7.35×10^{24} kg, travels around the Earth with an orbital radius of 3.48×10^8 m and an orbital velocity of 1×10^3 m s^{-1}. Which of the following is the gravitational force by the Earth on the Moon? Assume the Moon is undergoing uniform circular motion around the Earth.

A. 1.4×10^{16} N

B. 2.1×10^{22} N

C. 1.4×10^{25} N

D. 2.1×10^{25} N

Centripetal acceleration 3.1.2.3

Centripetal acceleration is a vector quantity that describes the change in velocity with respect to time for an object undergoing circular motion.

How can we analyse the acceleration of an object undergoing uniform circular motion?

According to Newton's second law an object will accelerate in the direction of the net force. Therefore, objects travelling in uniform circular motion have an acceleration towards the centre of the circular path they are travelling (Figure 3).

As $F_{net} = ma = \frac{mv^2}{r}$ for an object undergoing circular motion, we arrive at the formula for centripetal acceleration:

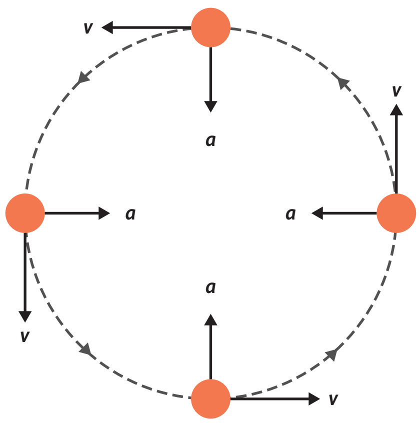


Figure 3 The direction of centripetal acceleration acting on an object undergoing circular motion.

FORMULA

$$a = \frac{v^2}{r} = \frac{4\pi^2 r}{T^2}$$

a = centripetal acceleration (m s^{-2})
v = circular speed (m s^{-1})
r = radius (m)
T = period (s)

USEFUL TIP

$a = \frac{4\pi^2 r}{T^2}$ can be derived by substituting the formula for circular speed $v = \frac{2\pi r}{T}$ into $a = \frac{v^2}{r}$.

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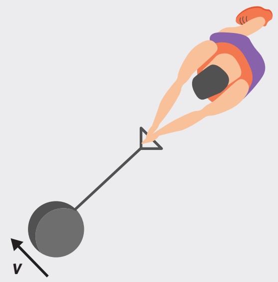
MISCONCEPTION

'An object travelling at a constant speed around a circle isn't accelerating.'

Although the speed (magnitude of the velocity) of the object travelling in uniform circular motion is not changing, the direction of instantaneous velocity is, and so it must be accelerating.

WORKED EXAMPLE 3

A hammer thrower spins in a circle of diameter 2.4 m at 10 m s^{-1}.



a. Calculate the magnitude of the centripetal acceleration of the hammer.

Step 1

Identify known and unknown variables and write down the formula that relates these variables.

Note that the diameter of the hammer's path is given, so the radius should be found using $r = \frac{d}{2}$.

$v = 10\ \text{m s}^{-1}, r = \frac{2.4}{2} = 1.2\ \text{m}, a = ?$

$a = \frac{v^2}{r}$

Step 2

Substitute values into the formula and solve for the centripetal acceleration.

$a = \frac{10^2}{1.2}$

$a = 83.3 = 83\ \text{m s}^{-2}$

b. Describe the horizontal motion of the hammer immediately after it is released, with reference to Newton's first law of motion.

Breakdown	Answer
Apply Newton's first law to the motion of the hammer.	Newton's first law states the hammer in motion will remain in motion until it is acted upon by an unbalanced force.
Describe the motion of the hammer after being released according to Newton's first law.	The hammer will travel tangential to the circle in the direction of the instantaneous velocity vector.

PROGRESS QUESTIONS

Question 5

A tennis ball of mass 60 g and cricket ball of mass 160 g are being rotated in the same circular path with the same circular speed. Which of the following is correct about their respective centripetal acceleration and centripetal force?

A. The tennis ball has a greater centripetal acceleration and centripetal force than the cricket ball.

B. The tennis ball has the same centripetal acceleration but a smaller centripetal force than the cricket ball.

C. The tennis ball has the same centripetal acceleration and a greater centripetal force than the cricket ball.

D. The tennis ball has a lower centripetal acceleration and a smaller centripetal force than the cricket ball.

Continues →

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Question 6

Which of the following rows identifies the correct direction of circular velocity, centripetal acceleration, and centripetal force for an object undergoing circular motion?

	Circular speed	Centripetal acceleration	Centripetal force
A.	tangential to the circle	radially inwards	radially inwards
B.	no direction	radially inwards	radially inwards
C.	tangential to the circle	no direction	radially inwards
D.	radially inwards	tangential to the circle	tangential to the circle

Theory summary

Table 1 Quantities of uniform circular motion

	Formula	Direction	Description
Circular speed	$v = \frac{2\pi r}{T}$	No direction	Is constant for uniform circular motion.
Instantaneous velocity	$v = \frac{2\pi r}{T}$	Tangential	Has the same magnitude as circular speed and a direction tangential to the circle
Centripetal force	$F_{net} = \frac{mv^2}{r} = \frac{4\pi^2 rm}{T^2}$	Radially inwards	Net force that causes circular motion
Centripetal acceleration	$a = \frac{v^2}{r} = \frac{4\pi^2 r}{T^2}$	Radially inwards	Is in the same direction as the centripetal force and has a constant magnitude.

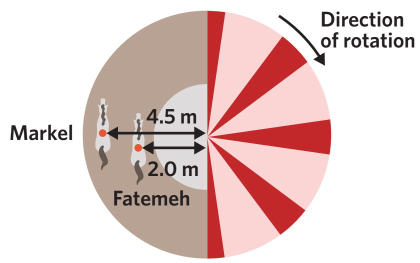
1E Questions

Mild 🌶 Medium 🌶🌶 Spicy 🌶🌶🌶

Deconstructed exam-style

Use the following information to answer questions 7–10.

Markel has a mass of 65 kg and is sitting on a carousel seat 4.5 m from the centre. Fatemeh has a mass of 70 kg and is sitting on a seat 2.0 m from the centre. The carousel rotates clockwise and completes one revolution every 25 seconds.



Question 7 🌶 (1 MARK)

What is the net force acting on Markel?

A. 4.4 N **B.** 8.8 N **C.** 18 N **D.** 36 N

Question 8 (1 MARK)

What is the net force acting on Fatemeh?

A. 4.4 N **B.** 8.8 N **C.** 18 N **D.** 36 N

Question 9 (1 MARK)

State the direction of the net force acting on Markel and Fatemeh at the position shown.

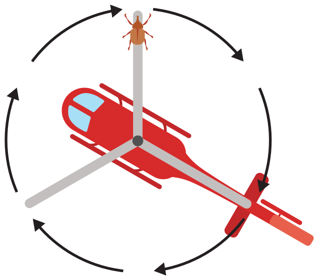
Question 10 (4 MARKS)

Compare the net forces acting on Markel and Fatemeh.

Exam-style

Question 11 (3 MARKS)

A beetle is trying to cling to the end of a helicopter rotor blade rotating at a constant speed. The blades are 12.0 m long and rotate at a frequency of 0.125 Hz.



a. Calculate the circular speed of the beetle. 2 MARKS

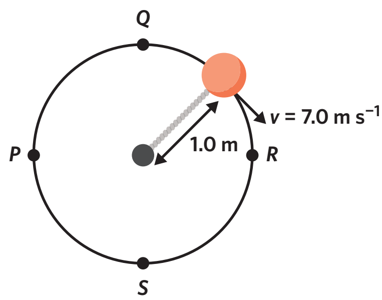
b. Identify the direction of the instantaneous velocity of the beetle at the point shown. 1 MARK

Question 12 (2 MARKS)

A student runs around a circular track with a radius of 50.0 m at a speed of 8.00 m s^{-1}. Calculate the magnitude of the student's centripetal acceleration.

Use the following information to answer questions 13–15.

A mass of 0.30 kg is being rotated by a rope at a constant speed in a horizontal circle as shown. Ignore the effects of the gravitational force acting on the mass.



Question 13 (1 MARK)

At which point is the direction of the net force acting on the mass in the direction R to P?

A. P **B.** Q **C.** R **D.** S

Adapted from VCAA 2013 exam Short answer Q5a

Question 14 (1 MARK)

At which point would the rope need to be broken for the mass to fly off in the direction P to R?

A. P **B.** Q **C.** R **D.** S

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Question 15 (2 MARKS)

The rope is able to withstand a tension of up to 3.0 N. Determine the maximum speed the mass can be travelling in order to not break the rope.

Question 16 (8 MARKS)

Mars has two moons called Deimos and Phobos. Deimos orbits Mars with an orbital radius of 2.60×10^7 m. It takes 30.0 hours for Deimos to complete a circular orbit of Mars.

a. Calculate the orbital speed of Deimos. Give your answer in m s^{-1} 2 MARKS

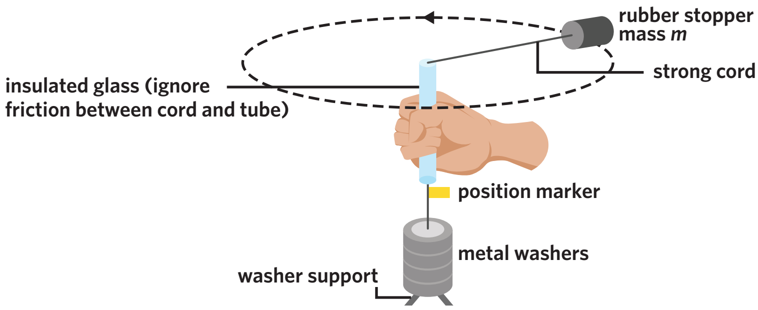
b. Explain how the velocity of Deimos changes in its orbit. 2 MARKS

c. Calculate the magnitude of the orbital acceleration of Deimos. 2 MARKS

d. Phobos takes 8.00 hours to orbit Mars, and orbits at a speed of 2.00×10^3 m s^{-1}. Calculate the radius of orbit of Phobos around Mars. 2 MARKS

Question 17 (7 MARKS)

Two Physics students set out to investigate centripetal force. The diagram shows the experimental set-up and the apparatus that the students use. They attempt to find a relationship between the mass of the metal washers attached and the period of rotation of the rubber stopper. One student uses a stopwatch to measure the time for 5 rotations of the rubber stopper.



a. *Key science skill*

State one variable that must be kept constant to ensure the experiment is valid. 1 MARK

b. *Key science skill*

Discuss why the student takes a measurement for five revolutions of the stopper to swing in a circle as opposed to one revolution, and what effect this is likely to have on the accuracy and precision of the data. 3 MARKS

Adapted from VCAA 2021 exam Short answer Q20b

c. *Key science skill*

The gravitational force acting on the metal washers is given by Mg, where M is the total mass of the washers and g is the gravitational field strength.

Symbol	Symbol represents
π	a constant
m	mass of rubber stopper
r	radius of revolution
T	period of rotation

Develop an equation between Mg and the quantities listed in the table. 3 MARKS

Adapted from VCAA 2021 exam Short answer Q20c

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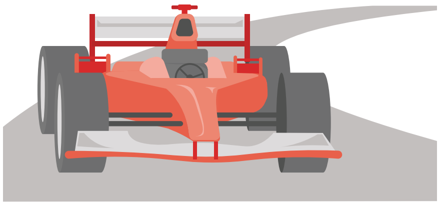
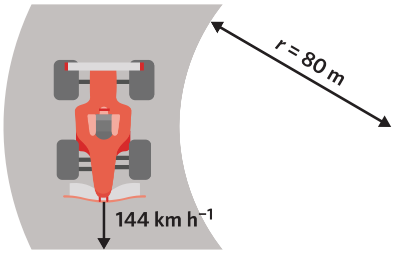
Question 18 (6 MARKS)

A Formula 1 racing car is travelling at a constant speed of 144 km h^{-1} around a horizontal corner of radius 80 m. The combined mass of the driver and the car is 800 kg. A front view and top view of the car is shown.



Front view



Top view

a. Calculate the magnitude of the net force acting on the racing car and driver as they go around the corner. 2 MARKS

Adapted from VCAA 2022 exam Short answer Q8a

b. Draw an arrow, on the top view of the racing car, showing the direction of the net force acting on it. 1 MARK

Adapted from VCAA 2022 exam Short answer Q8b

c. Explain why the racing car needs a net horizontal force to travel around the corner and state what exerts this horizontal force 3 MARKS

Adapted from VCAA 2022 exam Short answer Q8c

Question 19 (4 MARKS)

The magnetic force acting on a charged particle is $F = qvB$, and acts perpendicular to the particle's motion at all times. This causes the particle to undergo circular motion. An electron, with mass $m_e = 9.1 \times 10^{-31}$ kg and charge $q_e = 1.6 \times 10^{-19}$ C, enters a magnetic field of strength $B = 2.0$ T at a speed of $v = 2.4 \times 10^8$ m s^{-1}.

Use the equation $F_{net} = \frac{mv^2}{r}$ to calculate the radius of the path the electron travels in.

Previous lessons

Question 20 (1 MARK)

Two students pull on opposite ends of a rope with a force of 400 N. Which one of the following is closest to the magnitude of the force of the rope on each student?

A. 0 N

B. 400 N

C. 600 N

D. 800 N

FROM LESSON 1B

Question 21 (2 MARKS)

A tractor, including the driver, has a mass of 500 kg and is towing a trailer of mass 2000 kg. The tractor and trailer are accelerating at 0.50 m s^{-2}. Ignore any frictional forces and the mass of the towing rope. What is the tension in the rope connecting the tractor and trailer?

Adapted from VCAA 2011 Exam 1 Area of Study 1 Section A Q2

FROM LESSON 1D

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1F Banked circular motion


Image: Shahjehan/Shutterstock.com

STUDY DESIGN DOT POINT

- investigate and analyse theoretically and practically the uniform circular motion of an object moving in a horizontal plane: ($F_{net} = \frac{mv^2}{r}$), including:
  - a vehicle moving around a circular road
  - a vehicle moving around a banked track
  - an object on the end of a string

1A 1B 1C 1D 1E **1F** 1G 1H 1I

3.1.2.4 Banked tracks

3.1.2.5 Conical pendulums

ESSENTIAL PRIOR KNOWLEDGE

- **1B** Normal force
- **1E** F_{net} in uniform circular motion
- Trigonometry

See questions 12–14.

Why is a velodrome track banked?

An object travelling in a circle has a centripetal force acting on it towards the centre of the circle. For a bike going around a flat track, this centripetal force is provided by the friction between the tyres and track. However, by banking the track we can reduce the need for a sideways frictional force as a component of the normal force acts towards the centre of the circle. A similar analysis can be applied to the motion of a conical pendulum, where a component of the tension force provides the centripetal force.

KEY TERMS AND DEFINITIONS

banked track an inclined circular track

design angle the angle of a banked track for which a vehicle driving at the design speed will have no sideways friction force acting on it

design speed the speed a vehicle needs to travel around a banked track to have no sideways frictional force acting on it

conical pendulum a mass at the end of a string that undergoes horizontal circular motion

FORMULAS

- **circular speed**
  $v = \frac{2\pi r}{T}$
- **design angle**
  $\theta = \tan^{-1}\left(\frac{v^2}{rg}\right)$
- **design speed**
  $v = \sqrt{rg\tan(\theta)}$
- **tension in a conical pendulum**
  $T = \frac{mv^2}{r\sin(\theta)} = \frac{mg}{\cos(\theta)} = \sqrt{(mg)^2 + \left(\frac{mv^2}{r}\right)^2}$

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Banked tracks 3.1.2.4

Banked tracks are curved sections of track that are inclined at an angle from the horizontal. They are commonly used on racetracks and at freeway exits, to reduce or eliminate the need for sideways frictional forces acting on the vehicle.

How can we analyse the forces acting on an object travelling around a banked track?

In most real-world circumstances, a vehicle undergoing circular motion on a banked track experiences three forces:

- the force due to gravity (F_g)
- a normal force (F_N)
- a sideways frictional force.

When a vehicle travels around a non-banked track, the centripetal force is provided by a sideways frictional force.

- By increasing the angle of banking of a track to the **design angle,** the centripetal force is provided by the horizontal component of the normal force.
- Figure 1a shows the forces and net force acting on a cyclist travelling around a banked track at the **design speed** so that there is no sideways frictional force acting.

USEFUL TIP

Design angle is a term that will be used in this book to describe the angle of banking required, for a particular speed and radius, to eliminate the need for a sideways frictional force. This is not a term used by VCAA.

We can analyse the force triangle in Figure 1b to get the mathematical expression:

$$\tan(\theta) = \frac{opp}{adj} = \frac{\left(\frac{mv^2}{r}\right)}{mg} = \frac{v^2}{rg}$$

By rearranging this expression we can calculate either the design angle or design speed:

FORMULA

$$\theta = \tan^{-1}\left(\frac{v^2}{rg}\right)$$

θ = design angle (°)
v = circular speed (m s^{-1})
r = radius (m)
g = acceleration due to gravity (m s^{-2})

FORMULA

$$v = \sqrt{rg\tan(\theta)}$$

v = design speed (m s^{-1})
r = radius (m)
g = acceleration due to gravity (m s^{-2})
θ = angle of banking (°)

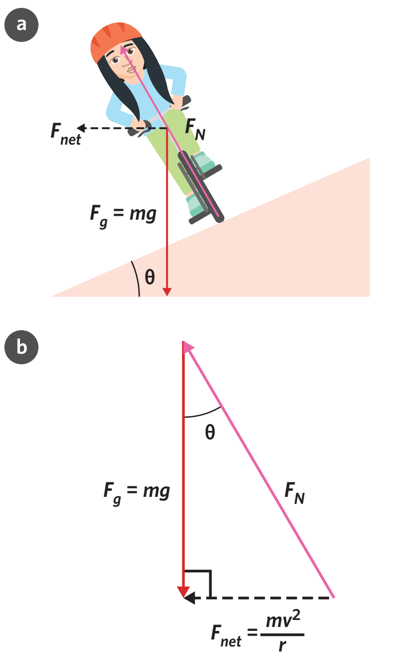

Figure 1 **(a)** The forces and the net force acting on the cyclist with **(b)** the force triangle for the situation

The forces can be related using Pythagoras' theory:

$$F_N^{\,2} = F_g^{\,2} + F_{net}^{\,2}$$

USEFUL TIP

Note these formulas are only applicable to situations in which there is no sideways frictional force acting on the object travelling around a banked track.

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USEFUL TIP

Do not confuse the relationships between forces for banked circular motion with the relationships that apply to objects on inclined planes (Lesson 1C). Although the diagrams look similar, the relationships between the forces for banked circular motion are different.

- The normal force is the hypotenuse of the force triangle for banked circular motion.
- The force due to gravity is the hypotenuse of the force triangle for objects on inclined planes.
- The net force acts horizontally radially inwards for banked circular motion.
- The net force acts up or down the slope for objects on inclined planes.

WORKED EXAMPLE 1

A bus is exiting the freeway at a constant speed of 10 m s^{-1} on a circular banked road with a radius of 45 m. The freeway exit is banked so that there is no sideways friction force applied by the road on the wheels.

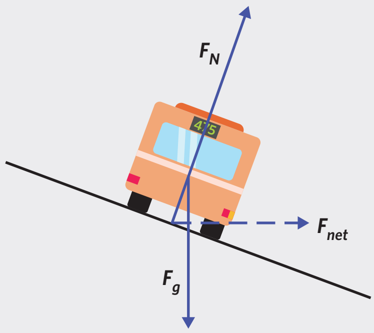
a. On the cross section of the freeway, draw all forces on the bus. Draw the net force as a dotted arrow labelled F_{net}.

Breakdown

I have drawn a normal force acting perpendicular to the road.

I have drawn a gravitational force acting downwards.

I have drawn a dotted arrow horizontally labelled F_{net}.



b. Calculate the correct angle of banking for there to be no sideways friction force applied by the road on the wheels.

Step 1

Identify known and unknown variables and write down the formula that relates these variables.

$v = 10$ m s^{-1}, $r = 45$ m, $\theta = ?$

$\theta = \tan^{-1}\left(\frac{v^2}{rg}\right)$

Step 2

Substitute values into the formula and solve for the angle of banking.

$\theta = \tan^{-1}\left(\frac{10^2}{45 \times 9.8}\right)$

$\theta = 12.8 = 13°$

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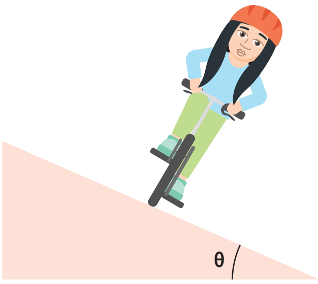
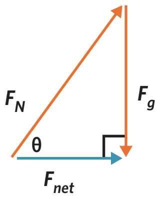
PROGRESS QUESTIONS

Question 1

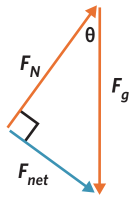
Which of the following force triangles correctly shows the forces and net force acting on the bicycle? Assume that there is no sideways frictional force acting on the bicycle.



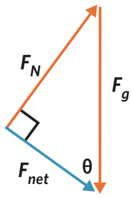
A.



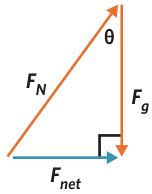
B.



C.



D.



Question 2

Which of the following statements is true about a truck travelling on a banked curve at the design speed? **(Select all that apply)**

A. The truck is accelerating.

B. The truck's velocity is constantly changing.

C. The net force acting on the truck is acting down the slope.

D. A sideways frictional force is providing the centripetal force acting on the truck.

Conical pendulums 3.1.2.5

USEFUL TIP

While VCE Physics exams do not use the term 'conical pendulum' (they usually describe 'a ball on a string moving in a horizontal circle'), it is a term used in this book to assist with understanding.

Conical pendulums are set up like standard pendulums (a mass hanging from a string) which are then made to undergo horizontal circular motion. The shape made by this motion resembles a cone (Figure 2). The forces acting on a conical pendulum can be analysed in a similar way as vehicles undergoing circular motion on banked tracks.

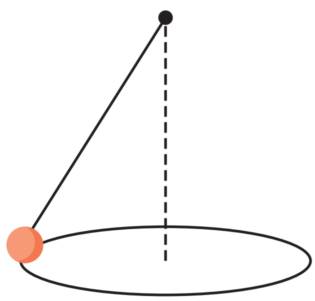


Figure 2 A conical pendulum

How can we analyse the forces acting on a conical pendulum?

Figure 3a shows the forces and the net force acting on an example of a conical pendulum: totem tennis.

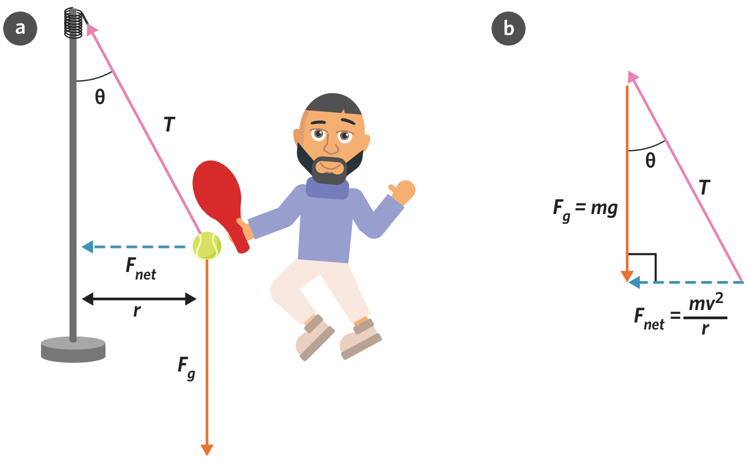


Figure 3 **(a)** The forces and the net force acting on a conical pendulum with **(b)** the force triangle for the situation

The force triangle in Figure 3b is similar to that of an object travelling around a banked track.

- The hypotenuse of the triangle is provided by the tension in the string rather than the normal force.
- The net force is provided by the horizontal component of the tension rather than the horizontal component of the normal force.
- The angle θ represents the angle between the string and the vertical, rather than the angle of banking.

STRATEGY

There are three alternative approaches to find the tension acting on a conical pendulum. Analysing the force triangle in Figure 3b gives:

1. $\sin(\theta) = \frac{O}{H} = \frac{\frac{mv^2}{r}}{T}$

   $T = \frac{mv^2}{r\sin(\theta)}$

2. $\cos(\theta) = \frac{A}{H} = \frac{mg}{T}$

   $T = \frac{mg}{\cos(\theta)}$

3. $T^2 = F_g{}^2 + F_{net}{}^2$

   $T = \sqrt{F_g{}^2 + F_{net}{}^2}$

   $T = \sqrt{(mg)^2 + \left(\frac{mv^2}{r}\right)^2}$

In questions where multiple approaches may be used to find the correct answer, we will use the first method. The other methods are also correct and could be used.

USEFUL TIP

From the force triangle in Figure 3b:

$\tan(\theta) = \frac{O}{A} = \frac{F_{net}}{F_g} \Rightarrow F_{net} = F_g\tan(\theta)$.

This relates the net force, force due to gravity and angle of inclination to conical pendulums or objects travelling on banked tracks at the design speed.

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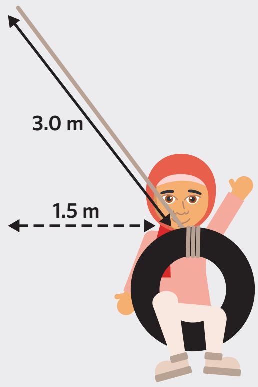
WORKED EXAMPLE 2

Poppy is swinging on a tyre, with a combined mass of 35 kg, attached to a 3.0 m rope. They are travelling in a horizontal circle of radius 1.5 m at a constant speed of 2.9 m s^{-1}, as shown. Consider Poppy and the tyre as one object.



a. Draw and label all the forces on the system. Draw the net force as a dotted arrow labelled F_{net}.

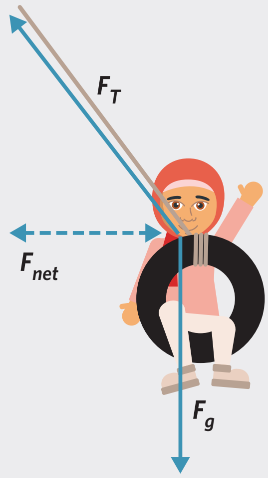
Breakdown

I have drawn a tension force acting up the rope.

I have drawn a gravitational force acting downwards.

I have drawn a dotted arrow towards the centre of the circle and labelled it F_{net}.

Answer



b. Calculate the tension in the rope.

Step 1

Identify known and unknown variables and write down the formula that relates these variables.

Note that any of the trigonometric relationships between the forces can be used to find the tension in the rope.

$m = 35$ kg, $v = 2.9$ m s^{-1}, $r = 1.5$ m,

$\theta = \sin^{-1}\left(\frac{1.5}{3.0}\right) = 30°$, $T = ?$

$T = \frac{mv^2}{r\sin(\theta)}$

Step 2

Substitute values into the formula and solve for the tension in the rope.

$T = \frac{35 \times 2.9^2}{1.5 \times \sin(30)}$

$T = 392 = 4.0 \times 10^2$ N

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PROGRESS QUESTIONS

Question 3

Which of the following forces is not expected to be involved in a conical pendulum problem?

A. Tension

B. Normal force

C. Centripetal force

D. Force due to gravity

Question 4

The centripetal force in a conical pendulum is provided by

A. the gravitational force.

B. the vertical component of the tension.

C. the horizontal component of the tension.

D. the horizontal component of the normal force.

Theory summary

Table 1 Comparison between motion around banked tracks and conical pendulums

	Banked track	Conical pendulum
Description	A vehicle undergoing horizontal circular motion that experiences a gravitational force, normal force, and sometimes a sideways frictional force (if not at the design speed).	A pendulum undergoing horizontal circular motion that experiences a gravitational force and a tension force.
Speed	Design speed is calculated by $v = \sqrt{rg\tan(\theta)}$. Other speeds are possible at the same radius but would require a sideways frictional force to be present.	Speed of mass is calculated by $v = \sqrt{rg\tan(\theta)}$ This is the only speed possible for an object in circular motion at that radius.
Angle	The angle of banking for there to be no sideways frictional forces present is calculated by $\theta = \tan^{-1}\left(\frac{v^2}{rg}\right)$.	The angle between the string and the vertical line can be found using $\theta = \tan^{-1}\left(\frac{v^2}{rg}\right)$.
Hypotenuse of force triangle	The normal force is always the hypotenuse of the force triangle. $F_N = \frac{mv^2}{r\sin(\theta)}$ $F_N = \frac{mg}{\cos(\theta)}$ $F_N = \sqrt{{F_{net}}^2 + F_g^2}$	The tension is always the hypotenuse of the force triangle. $T = \frac{mv^2}{r\sin(\theta)}$ $T = \frac{mg}{\cos(\theta)}$ $T = \sqrt{{F_{net}}^2 + F_g^2}$

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1F QUESTIONS

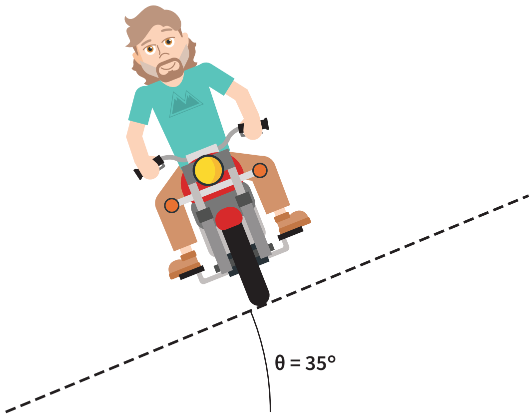
1F Questions

Mild Medium Spicy

Deconstructed exam-style

Use the following information to answer questions 5-7.

A demonstration at a show involves a motorbike being ridden around a circular banked track. The distance horizontally from the rider's position on one side of the circular track to the other is 60 m, and the track is banked at an angle of 35° to the horizontal. The motorbike and rider have a total mass of 300 kg, and travel at the design speed so that there are no sideways frictional forces present.



Question 5

Which of the following can be used to calculate the radius of the path?

A. $r = \frac{60}{2} = 30$ **B.** $r = 60 \times \sin(35°) = 34$ **C.** $r = 60 \times \cos(35°) = 49$ **D.** $r = 60$

Question 6

Which of the following correctly finds the design speed?

A. $v = \sqrt{rg\tan(\theta)}$ **B.** $v = rg\tan(\theta)$ **C.** $v = \frac{2\pi}{r}$ **D.** $v = \frac{F_{net}m}{r}$

Question 7 (3 MARKS)

Calculate the speed of the motorbike.

Adapted from VCAA 2011 Exam 1 Area of Study 1 Section A Q6

Exam-style

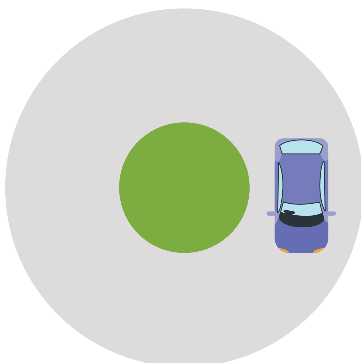
Question 8 (1 MARK)

A pair of dice hanging from a rear view mirror can be modelled as a conical pendulum. Which of the following best describes the net force acting on the dice as they rotate?

A. constant in magnitude and direction
B. changing in magnitude and direction
C. changing in magnitude but constant in direction
D. constant in magnitude but changing in direction

Question 9 (2 MARKS)

The following diagram shows an aerial view of a car travelling around a banked track. Draw an arrow showing the direction of the velocity and acceleration of a car travelling on the banked track.



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Question 10 (2 MARKS)

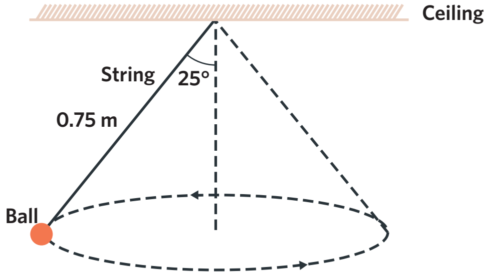
Identify which force or component of a force is providing the centripetal force in the following examples.

a. A cyclist is travelling around a velodrome at the design speed of the track. 1 MARK

b. A tyre hanging from a rope is swung so that it is undergoing horizontal circular motion. 1 MARK

Question 11 (3 MARKS)

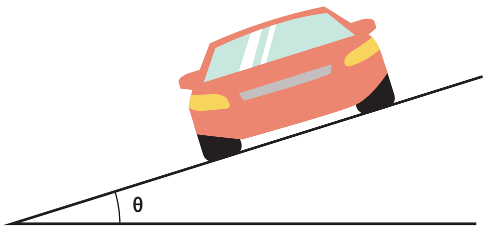
A small ball of mass 1.8 kg is travelling in a horizontal circular path at a constant speed while suspended from the ceiling by a 0.75 m long string. Calculate the speed of the ball.



Adapted from VCAA 2020 exam Short answer Q8b

Question 12 (5 MARKS)

Danielle Ricardina is driving their 2000 kg formula one car around a banked section of a racing track.



a. Draw the forces acting on the car as it is driven around the track. In addition, use a dashed arrow to show the net force acting on the car. 3 MARKS

b. Calculate the design angle of the banked track for Danielle, if they are travelling at the design speed of 40 m s^{-1} in a circular path with radius of 380 m. 2 MARKS

Adapted from VCAA 2017 exam Short answer Q7

Question 13 (2 MARKS)

A totem tennis ball is moving towards someone at a speed of 12 m s^{-1}. If they hit the ball back at a quicker speed, explain how the tension in the string changes.

Question 14 (9 MARKS)

Georgina is analysing the design speed of a small car around several banked tracks with different radii. She measures the following data. The uncertainty in radius measurements is ±1 m.

Radius r (m)	Velocity v (m s^{-1})	v^2 (m^{2}s^{-2})
5.0	5.32	
10	7.52	
15	9.21	
20	10.6	
25	11.9	
30	13.0	

a. *Key science skill*

Calculate the values of v^2 (the last column of the table) to three significant figures. 1 MARK

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b. *Key science skill*

Plot a graph of v^2 vs. r 5 MARKS

- include scales and units on each axis
- insert appropriate uncertainty bars for the graph
- draw a line of best fit for the data.

Adapted from VCAA 2019 NHT exam Short answer Q8cii

c. *Key science skill*

Calculate the gradient of the line of best fit from part **b.** Using this gradient, calculate the angle of the track.

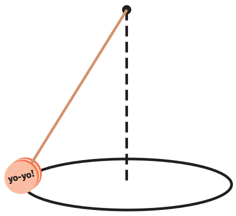
The relationship between radius and velocity is $\frac{v^2}{r} = g\tan(\theta)$. 3 MARKS

Adapted from VCAA 2019 NHT exam Short answer Q8d

FROM LESSONS 12C, 12D & 12E

Question 15 (4 MARKS)

A 300 g yo-yo is swung in a horizontal circle from above. The length of the yo-yo string is 0.70 m, and the radius of the circle is 0.40 m.



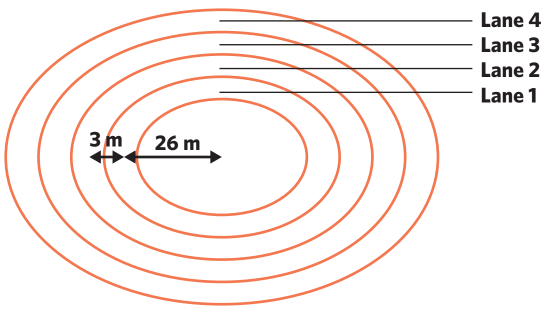
a. Calculate the magnitude of the net force acting on the yo-yo. 2 MARKS

b. Calculate the tension in the string. 2 MARKS

Adapted from VCAA 2016 exam Short answer Q2b

Question 16 (1 MARK)

A cyclist is travelling on the velodrome with multiple lanes, inclined at 32° to the horizontal. As the cyclist travels around the left hand side of the track, its path can be modelled as a circular path. Travelling in the middle of lane 1, their circular path would have a radius of 26 m, with each outer lane corresponding to an additional 3 m in radius of circular path. Determine which lane the cyclist should ride in, if they are to maintain a speed of 14 m s^{-1} without the need for a sideways frictional force.



A. Lane 1
B. Lane 2
C. Lane 3
D. Lane 4

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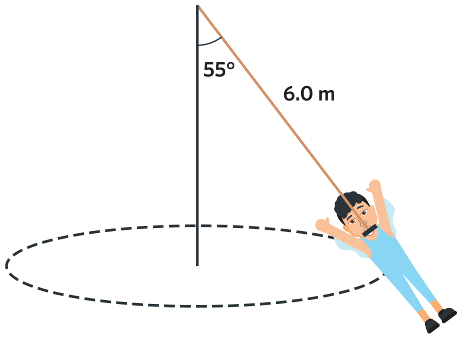
Question 17 (4 MARKS)

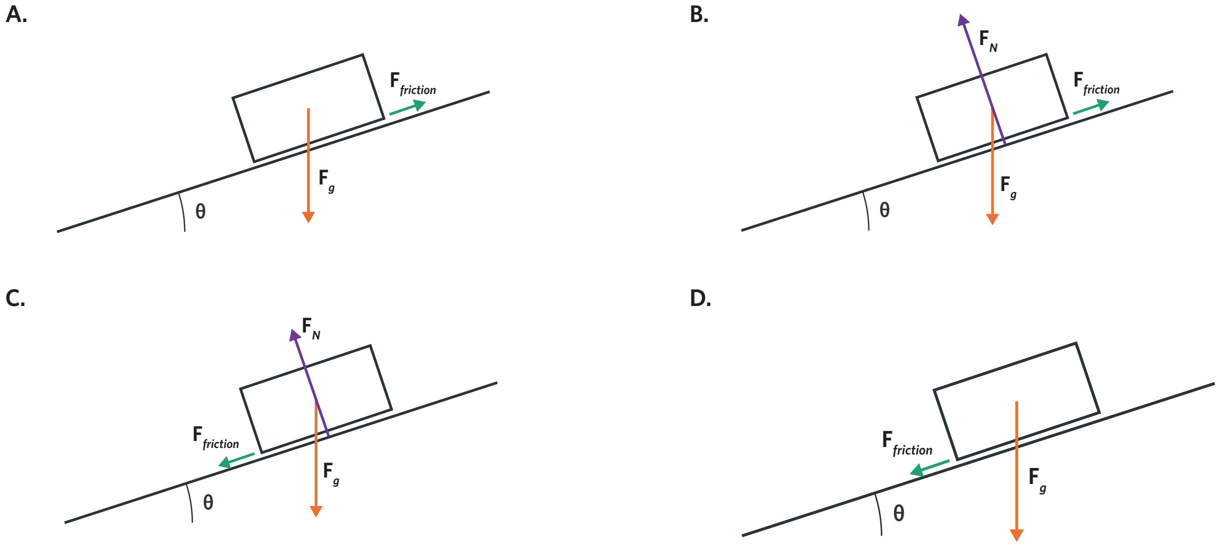
A performer of mass 60 kg grips a 6.0 m rope with their mouth at an angle of 55° to the vertical. Determine how long it takes the performer to complete one full revolution of their circular path.



Previous lessons

Question 18 (1 MARK)

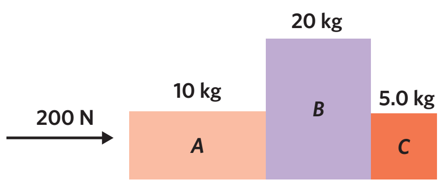
Which of the following correctly shows the forces acting on a mass moving up an inclined plane?



FROM LESSON 1C

Question 19 (3 MARKS)

Blocks A, B and C have masses of 10, 20 and 5.0 kg respectively. They are pushed along a frictionless surface and stay in contact while moving. Calculate the magnitude of the force $F_{on\ C\ by\ B}$.



FROM LESSON 1D

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1G Vertical circular motion

STUDY DESIGN DOT POINT

- investigate and apply theoretically Newton's second law to circular motion in a vertical plane (forces at the highest and lowest positions only)

1A 1B 1C 1D 1E 1F 1G 1H

3.1.4.1 Forces in vertical circular motion

3.1.4.2 Zero normal force in vertical circular motion

ESSENTIAL PRIOR KNOWLEDGE

1B Newton's second law of motion

1E Circular motion

See questions 15–16.

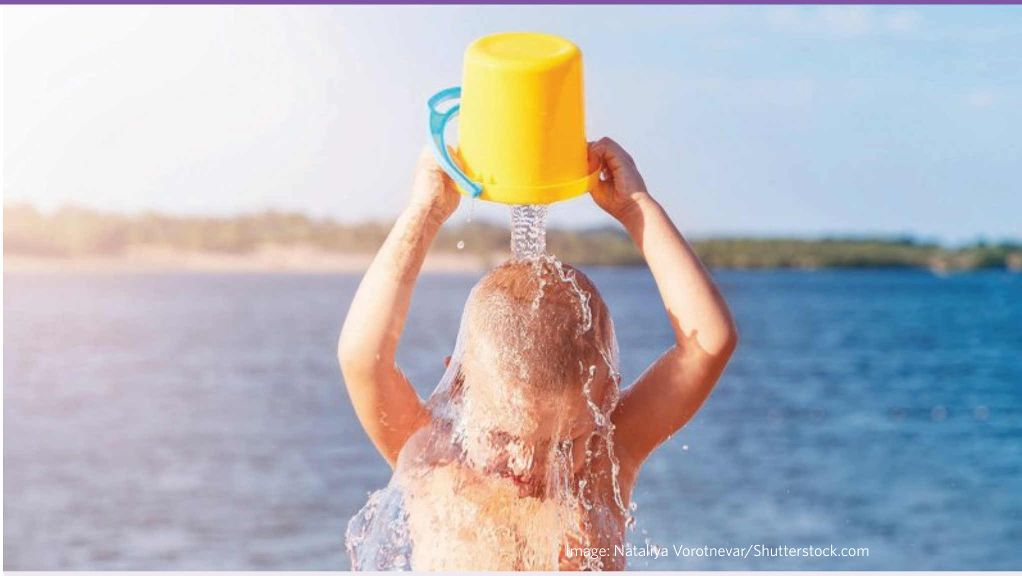

Image: Natalya Vorotnevar/Shutterstock.com

Can you tip a bucket upside down without the water pouring out?

Yes! If you swing a bucket of water in a vertical circle fast enough, the bucket can be upside down without the water coming out. In this lesson, we will explore the forces involved in vertical circular motion. This combines what we have learned about circular motion with our understanding of gravitational, normal, and tension forces.

FORMULAS

- force due to gravity
  $F_g = mg$
- centripetal force
  $F_{net} = \frac{mv^2}{r} = \frac{4\pi^2 rm}{T^2}$
- centripetal acceleration
  $a = \frac{v^2}{r} = \frac{4\pi^2 r}{T^2}$
- velocity when normal force is zero
  $v = \sqrt{gr}$ when $F_N = 0$

Forces in vertical circular motion 3.1.4.1

Investigating vertical circular motion requires the addition and subtraction of forces in different scenarios and positions around the circle.

How do we apply Newton's laws of motion to objects undergoing vertical circular motion?

In VCE Physics, we have to consider the following scenarios:

- objects on the top and outside of vertical circles
- objects on the top and inside of vertical circles
- objects on the bottom of vertical circles.

All three scenarios are governed by the same forces acting: the centripetal force, $F_{net} = \frac{mv^2}{r}$, is the sum of the force due to gravity, F_g, and the normal force/tension force, F_N or F_T.

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In order for an object to travel in a circle, the net force must act radially inwards. Therefore, it doesn't matter if the object is at the top or bottom of a vertical circle, the normal or tension force and the force due to gravity, must add to produce a centripetal force acting towards the centre of the circle. The normal force will always act perpendicular to the circular path. The force due to gravity always acts downwards.

Forces at the top and outside of vertical circles

This situation is often associated with carts, cars, and roller coasters.

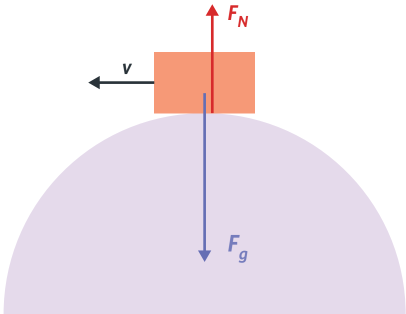


Figure 1 An object moving on the top and outside of a vertical circle.

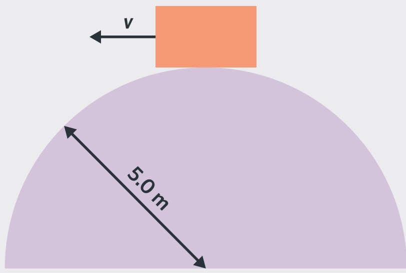
Figure 1 shows the forces acting on an object at the top and outside of a vertical circular track; from this we can conclude that:

- the normal force acts upwards
- F_g must be larger than F_N for vertical circular motion
- the net force, $F_{net} = \frac{mv^2}{r}$, is downwards (towards the centre of the circle)

$$\frac{mv^2}{r} = F_g - F_N$$

WORKED EXAMPLE 1

A cart of mass 10 kg is moving over a circular track with a radius of 5.0 m at a speed of 6.0 m s^{-1}. Take the acceleration due to gravity to be 9.8 m s^{-2}.



Calculate the magnitude of the normal force when the cart is at the top of the track.

Step 1

Identify known and unknown variables and write down the formula that relates these variables.

Note that the direction of the normal force is upwards as the cart is on the top and outside of a circular track.

$m = 10$ kg, $r = 5.0$ m, $v = 6.0$ m s^{-1}, $g = 9.8$ m s^{-2}, $F_N = ?$

$F_{net} = \frac{mv^2}{r} = F_g - F_N$

$\frac{mv^2}{r} = F_g - F_N$

Step 2

Substitute values into the formula and solve for the normal force.

$\frac{mv^2}{r} = F_g - F_N = mg - F_N$

$\frac{10 \times 6.0^2}{5.0} = 10 \times 9.8 - F_N$

$F_N = 26$ N

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Forces at the top and inside of vertical circles

This situation is often associated with roller coasters completing loop the loops or objects swinging on a string.

In situations involving strings, the tension force is used instead of the normal force. Although they are distinct forces, in these situations, they are mathematically equivalent.

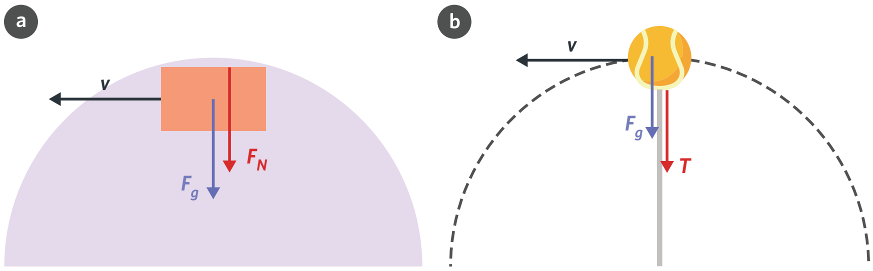


Figure 2 **(a)** An object moving on the top and inside of a vertical circle **(b)** compared to a ball on a string at the top of its vertical circular motion.

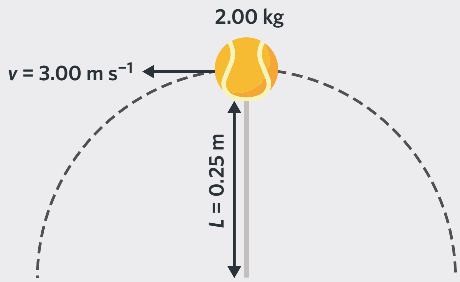
Figure 2a shows the forces acting on an object at the top and inside of a vertical circular track, while Figure 2b shows the forces acting on an object attached with a string at the top of a vertical circle. From these diagrams, we can conclude that:

- the normal/tension force acts downwards
- the net force, $F_{net} = \frac{mv^2}{r}$, is downwards (towards the centre of the circle)

$$\frac{mv^2}{r} = F_g + F_N \text{ OR } \frac{mv^2}{r} = F_g + T.$$

WORKED EXAMPLE 2

A 2.00 kg ball is being swung in a circle at a velocity of 3.00 m s^{-1} on the end of a rope that is 0.25 m long. Take the acceleration due to gravity to be 9.8 m s^{-2}.



Calculate the magnitude of the tension force on the ball by the rope when the ball is at its maximum height.

Step 1

Identify known and unknown variables and write down the formula that relates these variables.

Note that the direction of the tension force is downwards in situations modelled at the top and inside of a vertical circle. Also, the radius of the circular path is the length of the string.

$m = 2.00$ kg, $r = 0.25$ m, $v = 3.00$ m s^{-1}, $g = 9.8$ m s^{-2}, $T = ?$

$$F_{net} = \frac{mv^2}{r} = F_g + T$$

$$\frac{mv^2}{r} = F_g + T$$

Step 2

Substitute values into the formula and solve for the tension force.

$$\frac{mv^2}{r} = F_g + T = mg + T$$

$$\frac{2.00 \times 3.00^2}{0.25} = 2.00 \times 9.8 + T$$

$$T = 52.4 = 52 \text{ N}$$

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Forces at the bottom and inside of vertical circles

This situation is often associated with carts, cars, roller coasters, or objects swinging on a string.

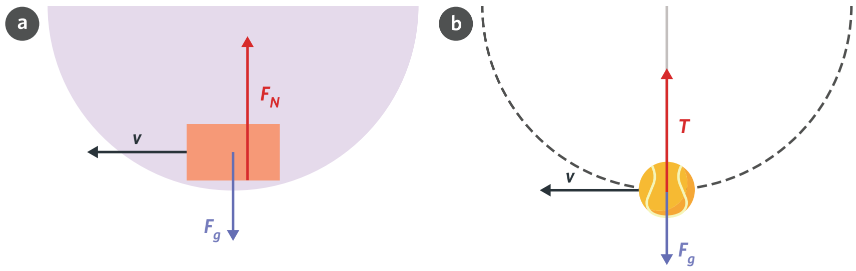


Figure 3 **(a)** An object at the bottom and inside of a vertical circle **(b)** compared to a ball on a string at the bottom of its vertical circular motion.

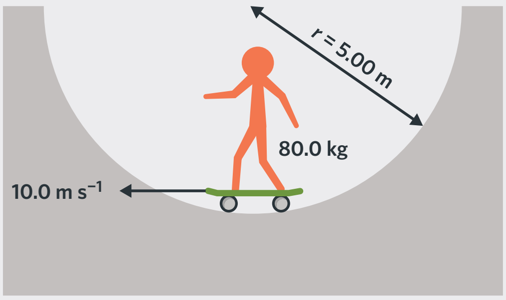
For an object at the bottom and inside of a vertical circular track (Figure 3a), or at the bottom of vertical circular motion while attached to a string (Figure 3b):

- the normal/tension force acts upwards
- the net force, $F_{net} = \frac{mv^2}{r}$, is upwards (towards the centre of the circle)

$$\frac{mv^2}{r} = F_N - F_g \text{ OR } \frac{mv^2}{r} = T - F_g.$$

WORKED EXAMPLE 3

A skateboarder of 80.0 kg slides down a circular half-pipe of radius 5.00 m with no friction and reaches a speed of 10.0 m s^{-1} at the bottom of the dip. Take the acceleration due to gravity to be 9.8 m s^{-2}.



Calculate the normal force on the skater when they are at the bottom of the dip.

Step 1

Identify known and unknown variables and write down the formula that relates these variables.

$m = 80.0$ kg, $r = 5.00$ m, $v = 10.0$ m s^{-1}, $g = 9.8$ m s^{-2}, $F_N = ?$

Note that the direction of the normal force is upwards in situations modelled at the bottom and inside of a vertical circle.

$$F_{net} = \frac{mv^2}{r} = F_N - F_g$$

$$\frac{mv^2}{r} = F_N - F_g$$

Step 2

Substitute values into the formula and solve for the tension force.

$$\frac{mv^2}{r} = F_N - F_g = F_N - mg$$

$$\frac{80.0 \times 10.0^2}{5.00} = F_N - 80.0 \times 9.8$$

$$F_N = 2.38 \times 10^3 = 2.4 \times 10^3 \text{ N}$$

PROGRESS QUESTIONS

Question 1

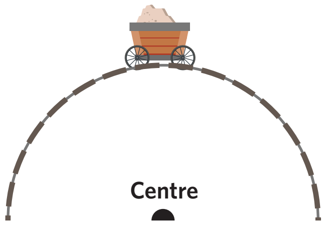
Identify the direction of the net force in this scenario, assuming the cart is moving along the track and does not leave the track.

A. up

B. left

C. right

D. down



Question 2

A 1000 kg car is travelling at 20 m s^{-1} over a hill that can be modelled as a circle with a radius of 500 m. What is the value of the normal force acting on the car?

A. 4.5×10^3 N

B. 9.0×10^3 N

C. 1.2×10^4 N

D. 1.8×10^4 N

Question 3

A 2.00 kg ball is rotating vertically on a rope of 1.00 m at a velocity of 12.0 m s^{-1}. Calculate the magnitude of the tension in the rope when the ball is at the bottom.

A. 2.0×10^1 N

B. 2.7×10^2 N

C. 3.1×10^2 N

D. 6.2×10^2 N

Zero normal force in vertical circular motion 3.1.4.2

In vertical circular motion, when the centripetal force at the top of the circle is equal to the force due to gravity, the magnitude of the normal (or tension) force acting on the object is zero. On a roller coaster, this produces the feeling of flying at the top of the loop.

How do we analyse zero normal force for objects undergoing vertical circular motion?

If an object travels at the right speed at the top of a vertical circle, the normal force can equal zero.

This speed has a different importance in each scenario.

- For an object at the top and outside of a vertical circle, it is the maximum speed at which the object will remain in contact with the track.
- For an object at the top and inside of a vertical circle, it is the minimum speed at which the object will remain in contact with the track (or the minimum speed at which the string will retain tension and not collapse).

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From the net force equations, we can derive an equation for this speed. When an object is at the top of the circle (either on the outside or inside) $\frac{mv^2}{r} = mg \pm F_N$

OR $\frac{mv^2}{r} = mg + T$.

When the track does not exert a normal force $(F_N = 0)$ or when there is no tension force $(T = 0)$, we have:

$$\frac{mv^2}{r} = mg.$$

This leads to the following equation for the speed at which there will be zero normal (or tension) force:

FORMULA

$$v = \sqrt{gr}$$

v = speed (m s^{-1})

r = radius (m)

g = acceleration due to gravity (m s^{-2})

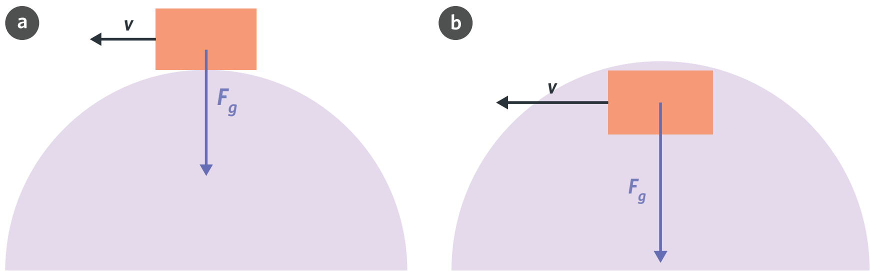


Figure 4 The normal force is zero such that $v = \sqrt{gr}$ when the object is at the top and **(a)** outside or **(b)** inside a vertical circle.

A person undergoing this motion will feel as if they are not experiencing a force due to gravity – just like a person in freefall. This is because we associate the feeling of weight with the normal force, which has the same magnitude as the gravitational force when we are at rest on flat ground. It is important to understand that:

- the force due to gravity is not zero
- this feeling is a result of the normal force being zero (Figure 4).

MISCONCEPTION

'We experience "zero gravity" or feel "weightless" at the top of a loop the loop.'

The force due to gravity is never zero, even when very far away from Earth, so we never truly experience 'zero gravity'. This term is discouraged by the VCE Physics study design for this reason. Instead, as explained in the lesson, we experience zero normal force.

WORKED EXAMPLE 4

A car drives over a circular hill that has a radius of 40 m. Calculate the maximum speed the car can travel without leaving the road. Take the acceleration due to gravity to be 9.8 m s^{-2}.

Step 1

Identify known and unknown variables and write down the formula that relates these variables.

Note that by asking for the maximum speed without leaving the road, we know to use the zero normal force equation for velocity.

$r = 40$ m, $g = 9.8$ m s^{-2}, $v = ?$

$v = \sqrt{gr}$

Step 2

Substitute values into the formula and solve for the velocity.

$v = \sqrt{9.8 \times 40}$

$v = 19.79 = 20$ m s^{-1}

20 m s^{-1} is the maximum speed the car can travel without leaving the road.

PROGRESS QUESTIONS

Question 4

A roller coaster is travelling at 14 m s^{-1} at the top of a loop. If the normal force acting on the passengers equals zero, which of the following gives the radius of the loop?

A. 10 m **B.** 12 m **C.** 17 m **D.** 20 m

Question 5

In which of the following situations will the tension/normal force not equal zero?

A. A fast travelling roller coaster at the bottom of its loop.

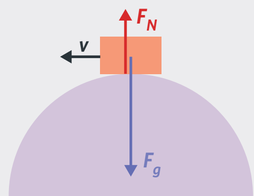
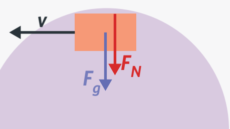
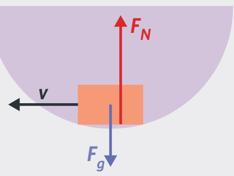
B. A car goes over a hill, which can be approximated to a circle, and is on the verge of leaving the road.

C. A cart is travelling at a speed inside the top of a loop where the centripetal force and the force on the cart due to gravity are equal.

D. A stone is connected to a rope and is spun vertically. At the top of the spin, it is travelling at a speed where the rope is slack but the stone still makes it around.

Theory summary

Table 1 A summary of objects at the top and bottom of vertical circular motion and their formulae

	Situation	Formula
Objects on the top and outside vertical circles		$\frac{mv^2}{r} = F_g - F_N$
Objects on the top and inside vertical circles		$\frac{mv^2}{r} = F_g + F_N$
Objects on the bottom and inside vertical circles		$\frac{mv^2}{r} = F_N - F_g$

- The speed corresponding to a zero normal force at the top of vertical circular motion can be found using $v = \sqrt{gr}$.
- On the surface of Earth, gravity is never equal to zero. However, our feeling of weight comes from the normal force acting on us. When the normal force is equal to zero, it feels like gravity is not acting on us. When this happens at the top of vertical circular motion, the centripetal force is equal to the force due to gravity.

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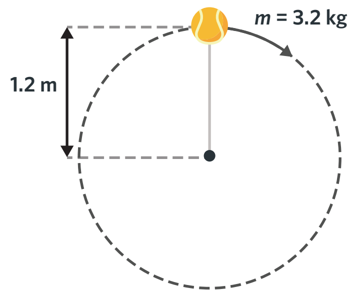
1G Questions

Mild 🌶 Medium 🌶🌶 Spicy 🌶🌶🌶

Deconstructed exam-style

Use the following information to answer questions 6–8.

A ball of mass 3.2 kg is being spun in a perfect vertical circle at the end of a string. The string has a length of 1.2 m.



Question 6 🌶 (2 MARKS)

Identify all the forces acting on the ball and their direction when the ball is at the bottom of the circle.

Question 7 🌶 (1 MARK)

What effect does increasing the ball's speed have on the tension force?

Question 8 🌶🌶 (3 MARKS)

The string will break at a tension of 150 N. If the ball is travelling at 7.3 m s^{-1} at the bottom of the arc, will the string break?

Exam-style

Question 9 (5 MARKS)

A car drives over a hill in the road which can be modelled as a circle with a radius of 5.2 m at the top.

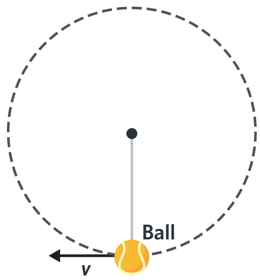
a. Draw a diagram and include arrows to show the forces on the car when it is at the top of the hill. The magnitude of the forces is not required. 🌶 3 MARKS

b. Calculate the speed that the car must be travelling at the peak of the hill in order to experience zero normal force. 🌶 2 MARKS

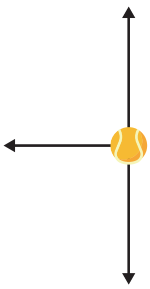
Question 10 🌶 (1 MARK)

A ball is rotated in a circle at the end of a string. It is moving at a constant speed and rotating in the vertical plane.

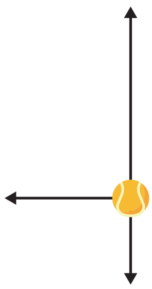
The arrows in options *A* to *D* indicate the direction and size of the forces acting on the ball. Ignoring air resistance, which of the following best represents the forces acting on the ball when it is at the bottom of the circular path?



A.



B.



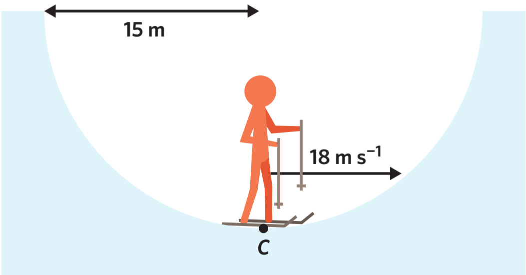
C.

D.

Adapted from VCAA 2020 exam Multiple choice Q8

Question 11 (3 MARKS)

A 60 kg skier skis down a bowl-shaped ramp which has a radius of 15 m. At the ramp's lowest point, *C*, she is travelling at 18 m s^{-1}.



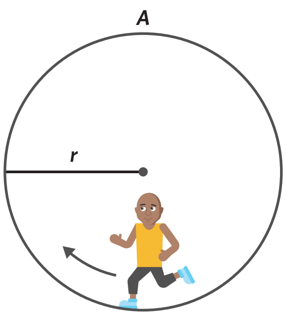
a. Copy the diagram and draw an arrow to show the direction of the net force on the skier at point *C*. The magnitude of the force is not required. 1 MARK

b. Calculate the magnitude of the force exerted by the bowl on the skier at point *C*. 2 MARKS

Adapted from VCAA 2015 exam Short answer Q3

Question 12 (1 MARK)

Usain Bolt's fastest speed was 44.72 km h^{-1} during his fastest world record 100 m. If Usain was running around a vertical circle, which of the following gives the maximum radius at which he would not fall off at the top?



A. 6.35×10^{-2} m

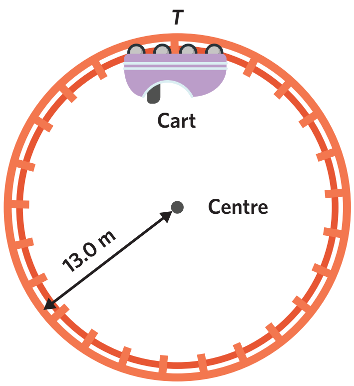
B. 15.7 m

C. 20.9 m

D. 204 m

Question 13 (8 MARKS)

A roller coaster designer wants to know whether a cart travelling at 9.0 m s^{-1} at point *T* is safe to ride. The cart has a mass of 320 kg and the loop has a radius of 13.0 m.



a. Will the cart stay on the track if it is not supported by an additional upwards force? Use calculations to justify your answer. 3 MARKS

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b. *Key science skill*
The designer conducts an experiment where they gradually increase the radius, r, of the loop and record the minimum speed, v, required for a cart to complete the loop.
They choose to graph the variables v^2 and r. Identify which axis (vertical or horizontal) should be used for each variable. Justify your answer. 2 MARKS

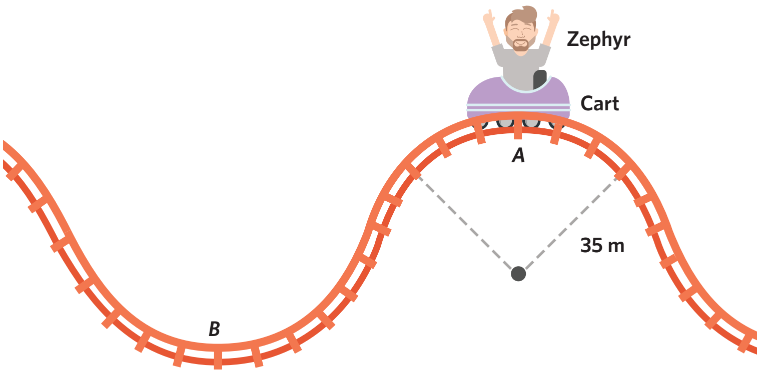
FROM LESSONS 12A & 12D

c. *Key science skill*
If the data is accurate and recorded in SI units, show that the value of the gradient would be 9.8 m s^{-2}. 3 MARKS

FROM LESSON 12E

Question 14 (5 MARKS)

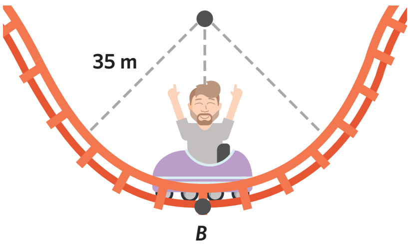
Zephyr is riding a roller-coaster. It is designed such that riders will experience zero normal force at the top of the track, point *A*. Assume that the track is circular and ignore forces due to friction and air resistance. The track's radius at both points *A* and *B* is 35 m.



a. The combined mass of Zephyr and the cart is 350 kg. Calculate the maximum speed that the cart can travel and not leave the track. 2 MARKS

b. Zephyr travels through point *A* at this maximum speed. Explain why Zephyr experiences zero normal force at point *A*. 1 MARK

c. Treating Zephyr and the cart as a single object, draw all the forcing acting on them at point *B*. 2 MARKS



Adapted from VCAA 2014 exam Short answer Q4

Question 15 (8 MARKS)

Safa is travelling on a motorbike around a loop. She is trying to work out if she will have enough speed to make it around while remaining in contact with the road. The radius of the loop is *r*.

a. Using the forces acting on the motorbike, show that the condition for the motorbike to just stay in contact with the track and make it around the loop is given by $\frac{v^2}{r} = g$. 2 MARKS

b. If the speed of the motorbike is 20 m s^{-1}, calculate the maximum height of the loop (in metres) that will ensure the motorbike stays in contact with the track at its highest point. Show your working. 3 MARKS.

c. If Safa takes into account air resistance as she moves through the loop, will she need to increase or decrease her predicted value for the height of the loop? Explain your answer. 3 MARKS

Adapted from VCAA 2021 exam Short answer Q9

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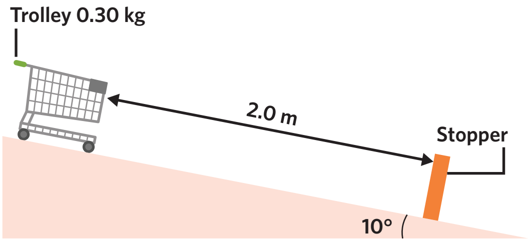
Previous lessons

Question 16 (3 MARKS)

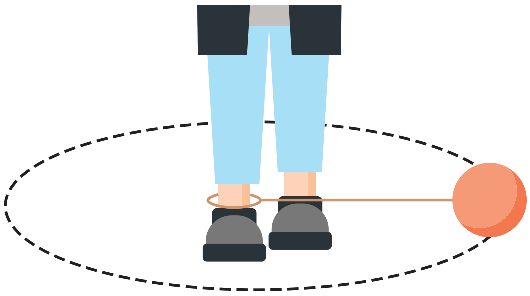
A 0.30 kg trolley rolls down a 2.0 m frictionless ramp angled at 10° to the horizontal until it hits a stopper at the bottom of the ramp. The trolley is released from rest. Calculate the speed of the trolley as it hits the stopper.



FROM LESSON 1C

Question 17 (3 MARKS)

A child is playing with a swing ball (a toy where someone jumps with one foot over a rod connected to a mass that is spun in a circle by the other foot). The rod has a length of 60 cm and the ball at the end has a mass of 0.20 kg. The ball takes 1.4 seconds to complete one horizontal revolution.



a. Calculate the magnitude of the centripetal acceleration of the ball. 2 MARKS

b. Calculate the magnitude of the centripetal force experienced by the ball. 1 MARK

FROM LESSON 1E

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1H Projectile motion

Image: LeStudio/Shutterstock.com

STUDY DESIGN DOT POINT

- investigate and analyse theoretically and practically the motion of projectiles near Earth's surface, including a qualitative description of the effects of air resistance

1A 1B 1C 1D 1E 1F 1G 1H 1I

3.1.5.1 Vertical motion of projectiles

3.1.5.2 Horizontal motion of projectiles

3.1.5.3 Linking the vertical and horizontal motion of projectiles and the effects of air resistance

ESSENTIAL PRIOR KNOWLEDGE

1A Constant acceleration equations

- Trigonometry

See questions 17–18.

How can cannons use the movement of a ship to fire further?

Firing a cannon at an enemy ship might seem straightforward, but finding the right angle to maximise the range involves a shipload of physics! Skilled gunners would fire near the top of the ship's roll to make the cannon balls fly further. Studying projectile motion allows physicists to predict the motion of objects that are thrown, launched, or dropped. So, let's sail the high seas and explore how the initial velocity, launch angle, and air resistance affect a projectile's motion, flight time, and maximum range.

KEY TERMS AND DEFINITIONS

projectile an object that has been launched or dropped without any form of self propulsion

air resistance the force of air particles resisting the motion of objects through the air

range the horizontal distance a projectile travels

FORMULAS

- **the constant acceleration equations**

$v = u + at$

$v^2 = u^2 + 2as$

$s = \frac{1}{2}(u + v)t$

$s = ut + \frac{1}{2}at^2$

$s = vt - \frac{1}{2}at^2$

- **average velocity**

$v = \frac{\Delta s}{\Delta t}$

Vertical motion of projectiles 3.1.5.1

Projectiles take a curved path in the air. By resolving the velocity vector into its vertical and horizontal components we can analyse the motion of a projectile. Problems involving the vertical motion of projectiles can be solved using the equations of constant acceleration.

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USEFUL TIP

The path of a projectile, ignoring air resistance, can be modelled as a parabola (Figure 1).

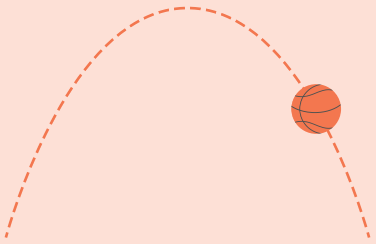

Figure 1 The parabolic path of projectile

How can we model the vertical motion of a projectile?

In VCE Physics, **air resistance** is ignored for calculations involving projectile motion, therefore the only force acting on a projectile is the force due to gravity.

- Close to the surface of Earth, a projectile has a constant acceleration of 9.8 m s^{-2} downwards due to the force of gravity acting upon it.
- This means the vertical component of a projectile's motion can be analysed using the constant acceleration equations.

It's important to remember that displacement, *s*, is a measure of the change in position. In vertical motion, displacement represents the change in height of the object (Figure 2).

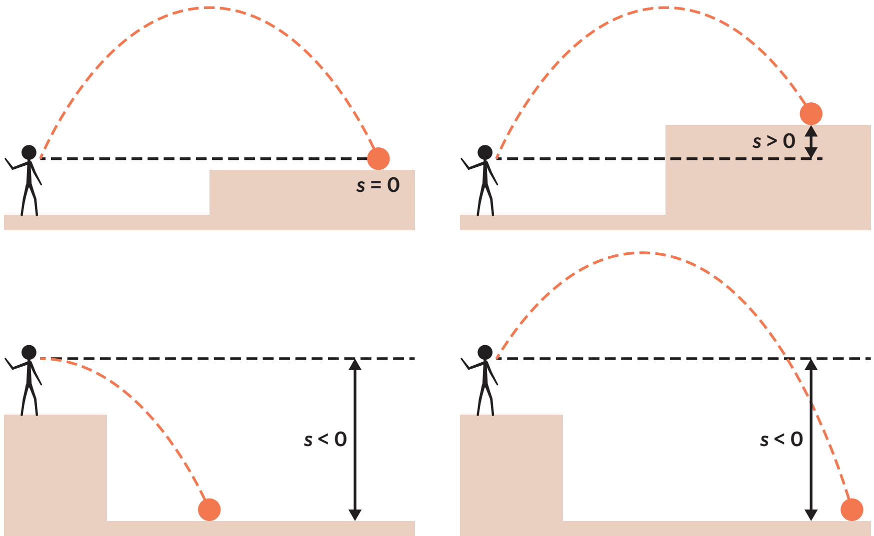

Figure 2 Examples of the vertical displacement of a ball being thrown

Projectiles launched upwards

Figure 3 shows how the vertical component of a projectile's velocity changes as it travels. It's important to note that:

- The vertical component of the initial velocity is represented by u_y.
- The vertical component of the final velocity is represented by v_y.
- Upwards can be taken as the positive direction. This means the acceleration due to gravity acts in the negative direction.
- At the top of a projectile's motion, the vertical component of its velocity is zero. This is because as the object travels up, the acceleration due to gravity slows it down. Momentarily at the maximum height, the object stops (vertically) before gravity accelerates it back towards the ground.

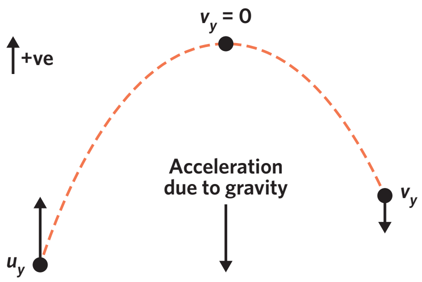

Figure 3 How the vertical component of the velocity vector changes for a projectile

In the absence of air resistance, two projectiles with the same initial vertical velocity will reach the same height at the same time, regardless of their mass and horizontal velocity (Figure 4).[1]

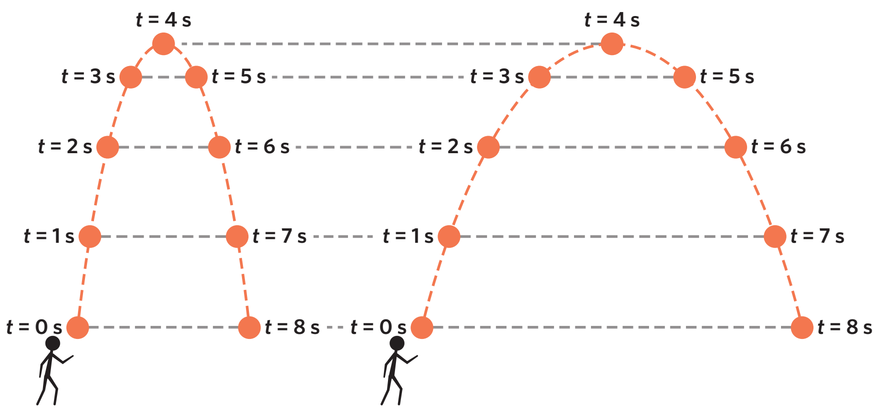

Figure 4 Two balls thrown with the same initial vertical velocity will have the same vertical motion.

KEEN TO INVESTIGATE?

1 **How does horizontal velocity impact vertical motion?**
Search YouTube: Shoot-n-drop

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Figure 5 shows the symmetry of a projectile that lands at the same height from which it was launched:

- The path of the projectile is symmetrical about a vertical axis that passes through the maximum height.
- The time taken to reach its maximum height is the same as the time taken for the projectile to go from its maximum height back to its initial vertical displacement ($t_{total} = 2 \times t_{max\ height}$).
- The magnitude of the vertical velocity of the projectile at a certain height will be the same going up or down. The only thing that changes is the direction. This means, if a ball is thrown upwards at 10 m s^{-1}, it will return to the hand that threw it at 10 m s^{-1} downwards.

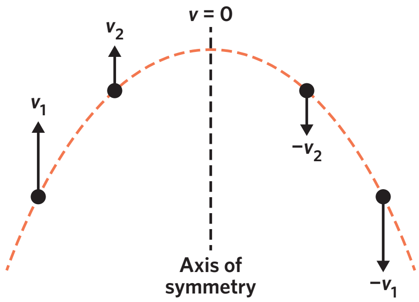


Figure 5 Symmetry of vertical motion

MISCONCEPTION

'Heavier objects always fall quicker than lighter objects.'

The equations of constant acceleration are used to model the vertical motion of projectiles as they are accelerating at a constant rate due to gravity. These equations do not rely on mass to calculate the speeds at which objects fall.[2]

KEEN TO INVESTIGATE?

[2] **Do heavier objects fall faster?**
Search YouTube: World's biggest vacuum

WORKED EXAMPLE 1

A ball is launched with an initial vertical velocity of 19 m s^{-1} upwards. Ignore the effects of air resistance. Take upwards to be the positive direction.

---

a. How long does the ball take to reach the maximum height?

Step 1

Identify known and unknown variables and write down the formula that relates these variables.

Note that the final velocity at the maximum height equals zero.

$u_y = 19$ m s^{-1}, $a_y = -9.8$ m s^{-2}, $v_y = 0$ m s^{-1}, $t = ?$

$v_y = u_y + a_y t$

Step 2

Substitute values into the formula and solve for the time to reach the maximum height.

$0 = 19 + (-9.8) \times t$

$t = \dfrac{0 - 19}{(-9.8)} = 1.94 = 1.9$ s

---

b. Find the maximum height the ball reaches.

Step 1

Identify known and unknown variables and write down the formula that relates these variables.

$u_y = 19$ m s^{-1}, $a = -9.8$ m s^{-2}, $v_y = 0$ m s^{-1}, $s_y = ?$

$v_y{}^2 = u_y{}^2 + 2a_y s_y$

Step 2

Substitute values into the formula and solve for the maximum height.

$0^2 = 19^2 + 2 \times (-9.8) \times s_y$

$s_y = \dfrac{0^2 - 19^2}{2 \times (-9.8)} = 18.4 = 18$ m

Projectiles launched horizontally

If a projectile is launched horizontally, its initial vertical velocity is zero. However, we can still use the equations of constant acceleration, but we cannot apply the symmetry of vertical motion because the projectile begins at its maximum height.

- In Figure 6, the magnitude of the projectile's vertical velocity starts from zero and increases with time.

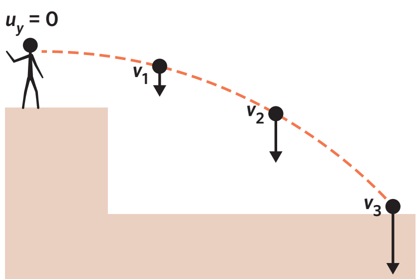
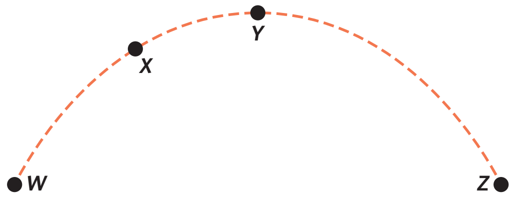


Figure 6 A projectile thrown horizontally has an initial vertical velocity of zero

PROGRESS QUESTIONS

Question 1

At which point is the vertical component of the projectile's velocity zero?



A. point W

B. point X

C. point Y

D. point Z

Question 2

A ball is thrown vertically upwards and lands on a shelf that is higher than the height it was thrown from. Which of the following must be correct?

A. The ball's velocity is zero at the top of the flight.

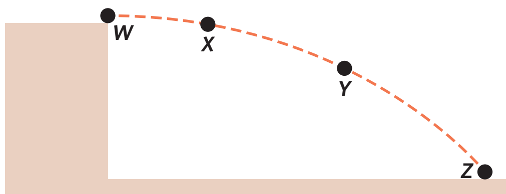
B. The equations of constant acceleration cannot be used to solve this problem.

C. The total time the ball was in the air is twice the time it takes to reach the maximum height.

D. The magnitude of the initial vertical velocity is equal to the magnitude of the final vertical velocity.

Question 3

At which point in the diagram is the vertical component of the projectile's velocity equal to zero?



A. point W

B. point X

C. point Y

D. point Z

Horizontal motion of projectiles 3.1.5.2

The horizontal motion of a projectile is independent of its vertical motion. When air resistance is ignored, there is no force acting upon a projectile in the horizontal direction, so we model projectiles as moving with a constant horizontal component of velocity.

How can we model the horizontal motion of a projectile?

We exclude the vertical components of a projectile's motion when analysing horizontal motion. There are no forces acting on a projectile in the horizontal direction. This means that horizontal velocity is constant throughout the projectile's motion (Figure 7). It's important to note that:

- The horizontal component of the initial velocity is represented by u_x.
- The horizontal component of the final velocity is represented by v_x.
- The projectile has no acceleration in the horizontal direction.
- At any point in the object's flight, $u_x = v_x$.
- This means we can use $v_x = \frac{s_x}{t}$ to solve problems of horizontal projectile motion.
- The horizontal distance the projectile travels, s_x, is referred to as the **range**.

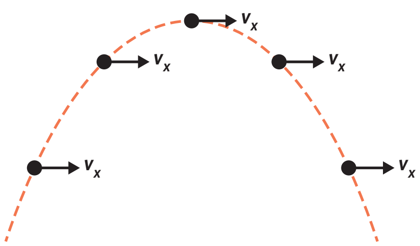


Figure 7 The horizontal velocity of a projectile is the same at all points during its flight.

USEFUL TIP

In the horizontal direction, the instantaneous velocity of the projectile is the same as its average velocity in the horizontal direction. As a result the equation for average velocity, $v_x = \frac{\Delta s_x}{\Delta t}$, can be simplified to $v_x = \frac{s_x}{t}$.

WORKED EXAMPLE 2

A ball is thrown with an initial horizontal velocity of 13 m s^{-1}. If the ball takes 5.0 s to hit the ground, how far in the horizontal direction does it travel? Ignore the effects of air resistance.

Step 1

Identify known and unknown variables and write down the formula that relates these variables.

$u_x = v_x = 13 \text{ m s}^{-1}, t = 5.0 \text{ s}, s_x = ?$

$v_x = \frac{s_x}{t}$

Step 2

Substitute values into the formula and solve for the range of the ball.

$13 = \frac{s_x}{5.0}$

$s_x = 13 \times 5.0 = 65.0 = 65 \text{ m}$

PROGRESS QUESTIONS

Question 4

Wes throws a shot put with an initial horizontal speed of 8 m s^{-1}.
What is the shot put's horizontal speed just before it hits the ground?

A. 0 m s^{-1}

B. 4 m s^{-1}

C. 8 m s^{-1}

D. There is not enough information provided.

Question 5

A javelin travels 10 m horizontally in 5.0 s. What is the horizontal speed of the javelin?

A. 2.0 m s^{-1} **B.** 5.0 m s^{-1} **C.** 10 m s^{-1} **D.** 50 m s^{-1}

Linking the vertical and horizontal motion of projectiles and the effects of air resistance 3.1.5.3

The parabolic arc of a projectile's motion is a result of its vertical acceleration due to gravity and its constant horizontal velocity. Time can be used to link both components of a projectile's motion, while air resistance alters its trajectory.

How can we combine the vertical and horizontal motion of a projectile?

Launching projectiles at different angles has an impact on how far and high they travel.[3] When solving a problem for projectile motion, we resolve (separate) the velocity vector into its horizontal and vertical components. This can be done using trigonometry (Figure 8).

KEEN TO INVESTIGATE?

3 **How does the launch angle impact the flight path of a projectile?**
Search: Projectile motion simulator

USEFUL TIP

We can use subscripts to indicate which component of a variable acts in which direction. Variables related to the horizontal direction are subscripted with an x (s_x, u_x, v_x) and variables related to the vertical direction are subscripted with a y (s_y, u_y, v_y, a_y).

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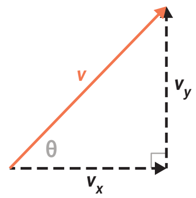

Figure 8 Resolving the velocity of a projectile into the horizontal and vertical components

For a projectile launched at an angle, θ:

- The velocity vector, v, can be resolved into:
  - a horizontal component, v_x

    $$v_x = v\cos(\theta)$$

  - a vertical component, v_y

    $$v_y = v\sin(\theta)$$

- The magnitude of v can be determined from its components using Pythagoras' theorem

  $$v^2 = {v_x}^2 + {v_y}^2$$

- The launch angle, θ, can be related to the horizontal and vertical components using

  $$\tan(\theta) = \frac{v_y}{v_x}$$

Regardless of which component of the motion we are looking at, the time taken for the projectile to complete its flight will be the same.

- This means we can use time to link horizontal and vertical motion as it is the only common variable.
- We can calculate the time it takes for the projectile to travel in the horizontal direction and use this to calculate values in the vertical direction, and vice versa.

STRATEGY

The one variable that the vertical and horizontal motion have in common is the time in the air, *t*. As such, a useful method for projectile analysis is to calculate the time in flight in one direction (either horizontally or vertically), and then to use this value in the remaining direction to solve for any other unknowns.

1. Determine whether the horizontal or vertical direction determines the end of the projectile motion.
2. Use appropriate kinematic equations to calculate the time for the projectile motion.
3. Use the flight time to calculate the required unknowns in the other direction.

WORKED EXAMPLE 3

A rugby player kicks a ball towards a goal that is 30 m away. The ball has an initial velocity of 19 m s^{-1} at an angle 50° from the horizontal.

---

a. Resolve the initial velocity vector into its two components, u_x and u_y.

Step 1

Identify the known and unknown variables and write down the formula that relates these variables.

$u = 19$ m s^{-1}, $\theta = 50°$, $u_x = ?$, $u_y = ?$

$u_x = u\cos(\theta)$

$u_y = u\sin(\theta)$

Step 2

Substitute values into the formula and solve for the horizontal and vertical components of the velocity vector.

$u_x = 19 \times \cos(50°) = 12.2 = 12$ m s^{-1}

$u_y = 19 \times \sin(50°) = 14.6 = 15$ m s^{-1}

Continues →

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b. Show that the ball takes 2.5 s to reach the goal.

Step 1

Identify the known and unknown variables in the horizontal direction and write down the formula that relates these.

$s_x = 30$ m, $u_x = v_x = 12.2$ m s^{-1}, $t = ?$

$v_x = \frac{s_x}{t}$

Step 2

Substitute values into the formula and solve for the time it takes for the ball to reach the goal.

$12.2 = \frac{30}{t}$

$t = \frac{30}{12.2} = 2.46 = 2.5$ s

---

c. In order to score a goal, the ball has to pass over a bar that is 3.0 m high. Does the player score?

Step 1

Identify the known and unknown variables in the vertical direction and write down the formula that relates these.

$u_y = 14.6$ m s^{-1}, $a_y = -9.8$ m s^{-2}, $t = 2.46$, $s_y = ?$

$s = u_y t + \frac{1}{2}at^2$

Step 2

Substitute values into the formula and solve for the height of the ball after 2.6 s.

$s_y = 14.6 \times 2.46 + \frac{1}{2} \times (-9.8) \times (2.46)^2$

$s_y = 6.26$

As $6.26 > 3$, the player scores a goal.

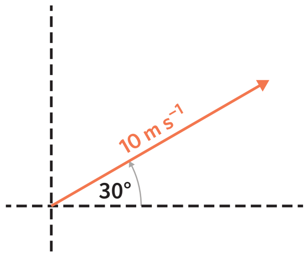
PROGRESS QUESTIONS

Question 6

A ball is thrown into the air at 30° to the horizontal with an initial velocity of 10 m s^{-1} as per the diagram.

Which of the following correctly represents the horizontal and vertical components of the ball's initial velocity vector?

	Horizontal velocity (m s^{-1})	Vertical velocity (m s^{-1})
A.	$10 \times \sin(30°)$	$10 \times \cos(30°)$
B.	$10 \times \tan(30°)$	$10 \times \sin(30°)$
C.	$10 \times \cos(30°)$	$10 \times \tan(30°)$
D.	$10 \times \cos(30°)$	$10 \times \sin(30°)$



Question 7

Which variable can be used to relate the horizontal and vertical motion of a projectile?

A. time
B. final speed
C. displacement
D. acceleration due to gravity

Question 8

Ball *A* and ball *B* are thrown with initial velocities of magnitudes of 6 m s^{-1} and 8 m s^{-1} respectively, but have the same initial vertical speed. Ignoring air resistance, which ball will hit the ground first?

A. ball *A*
B. ball *B*
C. There is not enough information provided.
D. Both balls will hit the ground at the same time.

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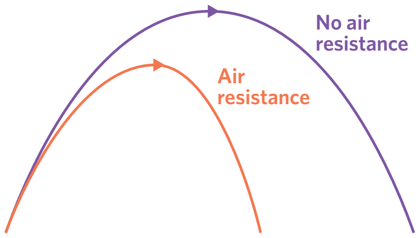


Figure 9 Comparison of projectile trajectories with and without the effects of air resistance

How does air resistance affect projectile motion?

Air resistance is a force applied by the air on a projectile, opposing its motion through the air.

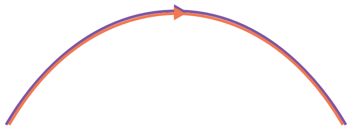
Air resistance acts to slow the object in both the vertical and horizontal directions, leading to a reduced maximum height and range of the projectile (Figure 9).

PROGRESS QUESTIONS

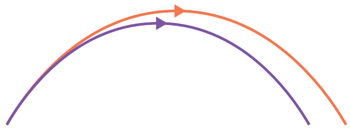
Question 9

In the following diagrams, the purple line represents the flight path of a projectile without air resistance, while the orange line shows the flight path with air resistance. Which option is correct?

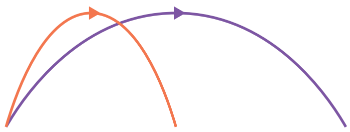
A.



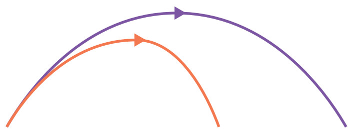
B.



C.



D.



Theory summary

- A projectile is a launched object with no form of self propulsion.
- We can separate the vertical and horizontal parts of a projectile's motion to analyse each component of its motion individually.
- Vertical motion:
  - There is a constant acceleration downwards, due to gravity.
  - We can use the constant acceleration equations to describe and analyse its motion.
  - At maximum height, the vertical velocity is zero.
- Horizontal motion:
  - The horizontal velocity of a projectile is constant.
  - We can use $v_x = \frac{s_x}{t}$ to describe the motion.
- We use time to relate the horizontal motion to the vertical motion.
  - Air resistance resists motion of a projectile in both the vertical and horizontal directions.
  - This causes a reduced range, slower speeds, and an asymmetrical trajectory.

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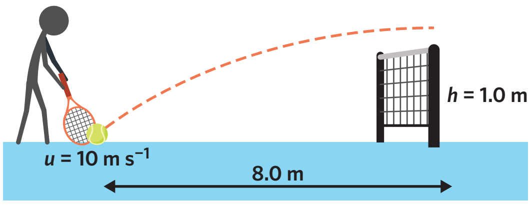
1H Questions

Mild 🌶 Medium 🌶🌶 Spicy 🌶🌶🌶

Deconstructed exam-style

Use the following information to answer questions 10–14.

A tennis player flicks a ball off the ground with their racket towards the net. The ball leaves the ground at a speed of 10 m s^{-1} and an angle of 40° to the horizontal. The net is 8.0 m away from the player, and the height of the net above the court is 1.0 m. Take $g = 9.8$ m s^{-2} and ignore the effects of air resistance.



Question 10 🌶 (1 MARK)

What is the magnitude of the initial horizontal velocity of the ball?

Question 11 🌶 (1 MARK)

What is the magnitude of the initial vertical velocity of the ball?

Question 12 🌶 (1 MARK)

Calculate the time it takes the ball to travel to the net.

Question 13 🌶 (1 MARK)

Which of the following formulae can be used to find the height of the ball when it reaches the net?

A. $v_y = \frac{s_y}{t}$

B. $s_y = u_y t + \frac{1}{2}at^2$

C. $v_y{}^2 = u_y{}^2 + 2as_y$

D. $s_y = \frac{1}{2}(u_y + v_y)t$

Question 14 🌶🌶 (3 MARKS)

Does the ball make it over the net? Show your calculations.

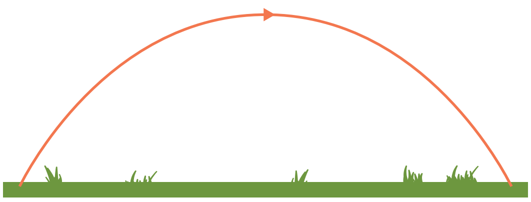
Adapted from VCAA 2019 NHT exam Short answer Q6b

Exam-style

Question 15 🌶 (1 MARK)

Nell kicks a football. Ignoring the effects of air resistance, she expects it to travel as shown.

On a copy of the diagram, draw a dotted line showing the path of the football when the effects of air resistance are included.



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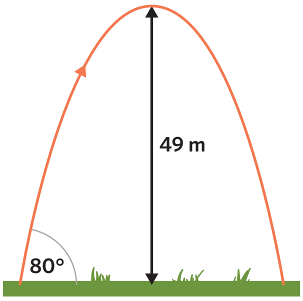
Question 16 (5 MARKS)

Jeremy is playing with a bottle rocket. He launches the rocket at an angle of 80° and records a maximum height of 49 m. Ignore the effects of air resistance.

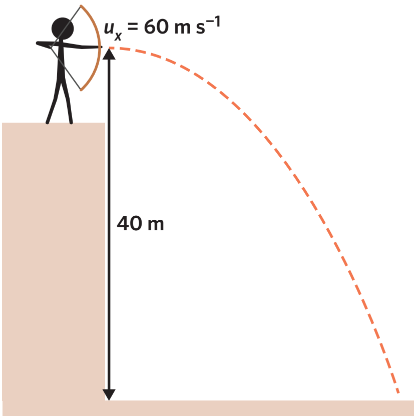


a. Calculate the magnitude and direction of the initial vertical velocity of the rocket. 2 MARKS

b. Calculate the rocket's range, if the horizontal velocity of the rocket is 5.47 m s^{-1} to the right. 3 MARKS

Question 17 (5 MARKS)

Katie shoots an arrow horizontally from the top of a cliff that is 40 m above the ground. Initially the arrow has a horizontal velocity of 60 m s^{-1}. Ignore the effects of air resistance.



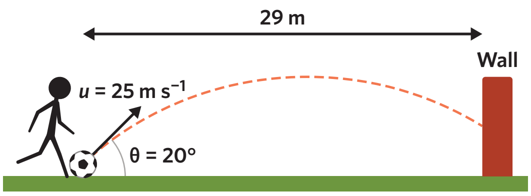
a. Calculate the time it takes for the arrow to reach the ground. 3 MARKS

b. How far away from the base of the cliff does the arrow land? 2 MARKS

Adapted from VCAA 2018 NHT exam Short answer Q6

Question 18 (3 MARKS)

Susie kicks a soccer ball towards a wall with an initial speed of 25 m s^{-1} at an angle 20° to the horizontal. If the wall is 29 m away, calculate the height above the ground the ball hits the wall. Ignore air resistance.



Adapted from VCAA 2017 exam Short answer Q9a

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Question 19 (5 MARKS)

Some students are studying the effect of launch angle on the range of a projectile, by changing the angle a projectile is launched at and measuring how far away it lands.

One of their projectiles is launched from the ground at an angle of 53° from the horizontal and at a speed of 31 m s^{-1}. Ignore air resistance.

a. *Key science skill*
Write a hypothesis for their experiment. 2 MARKS

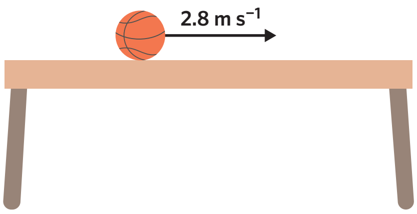
FROM LESSON 12A

b. Show that the projectile's time of flight from launch to the highest point is 2.5 s. 1 MARK
Adapted from VCAA 2019 exam Short answer Q10a

c. Calculate the range of the projectile. Show your calculations. 2 MARKS
Adapted from VCAA 2019 exam Short answer Q10b

Question 20 (7 MARKS)

Mark rolls a ball horizontally off a table at 2.8 m s^{-1}. It hits the ground after 0.45 s. Ignore the effects of air resistance.



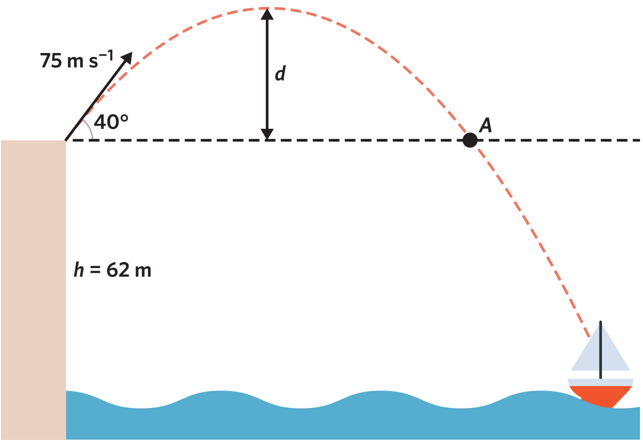
a. Calculate the height of the table. 2 MARKS
Adapted from VCAA 2018 exam Short answer Q7b

b. What is the magnitude of the velocity of the ball when it hits the floor? Justify your answer 3 MARKS
Adapted from VCAA 2018 exam Short answer Q7c

c. Calculate the angle to the horizontal the ball hits the floor at. 2 MARKS

Question 21 (8 MARKS)

Isaac is testing his catapult's effectiveness against enemy ships by launching a 20.0 kg stone, with a speed of 75 m s^{-1} at an angle of 40° to the horizontal. The stone is launched from the top of a cliff that is 62 m above the water. Ignore the effects of air resistance.



a. Calculate the maximum height, d, above the cliff that the stone reaches. 2 MARKS

b. Calculate the horizontal distance to point A, which is at the same height as the cliff. 3 MARKS

c. The enemy's boat can withstand stones with speeds of up to 70.0 m s^{-1} without sinking. Find the speed of Isaac's stone as it hits the water and determine whether a boat in this position would sink. 3 MARKS

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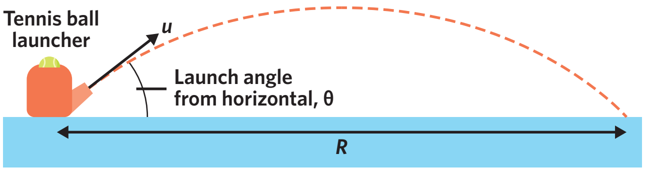
Question 22 (4 MARKS)

A physics class uses a tennis ball launcher outside on a level field to investigate projectile motion. Assume the tennis balls are launched from ground level.



The tennis ball launcher can be set to launch tennis balls at speeds, u, between 10 m s^{-1} and 35 m s^{-1} and at angles, θ, between 20° and 70°.

Students measure the range, R, of the tennis balls with an uncertainty of ± 0.1 m at varying speeds for a fixed angle.

The students think that air resistance on the tennis ball may affect the maximum range. They decide to compare their data to the theoretical range achieved when air resistance is ignored.

a. Using the formula $R = \frac{u^2 \sin(2\theta)}{g}$, calculate the theoretical range of a projectile launched at an initial speed of 15 m s^{-1} and at an angle of 40°. 2 MARKS

b. *Key science skill*
If the students measure a maximum range of 22.2 m. Evaluate whether the effect of air resistance can be ignored by the students when analysing their data. Justify your answer. 2 MARKS

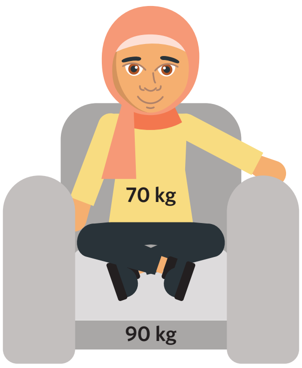
FROM LESSON 12C

Adapted from VCAA 2022 exam Short answer Q10d

Previous lessons

Question 23 (2 MARKS)

Marie has a mass of 70 kg and sits a couch that has a mass of 90 kg.



Calculate the magnitude and direction of the force on Marie by the couch.

Adapted from VCAA 2019 NHT exam Short answer Q9

FROM LESSON 1D

Question 24 (2 MARKS)

A cyclist is travelling around a banked track with a constant speed of 7.0 m s^{-1}. If the radius of the track is 10 m and there is no sideways friction force applied by the track on the wheels, calculate the angle of banking.

FROM LESSON 1F

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1I Momentum and impulse

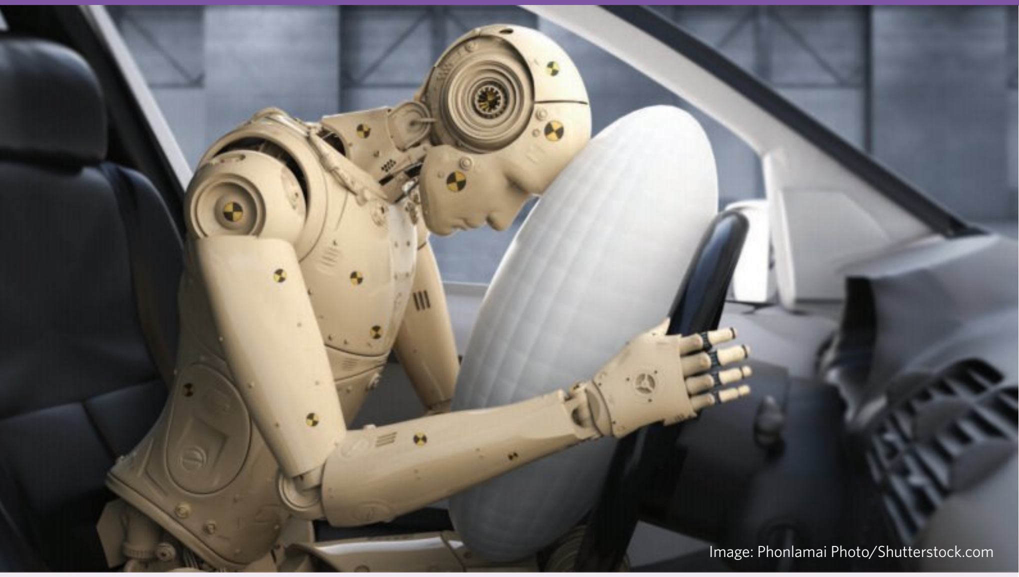
Image: Phonlamai Photo/Shutterstock.com

How do airbags keep us safe in the event of a crash?

When a collision between two cars occurs, equal and opposite forces act to change the velocities of the cars involved. These forces are reduced through the use of safety equipment such as airbags and crumple zones. This lesson will explore the concepts of momentum and impulse in collisions.

STUDY DESIGN DOT POINTS

- investigate and apply theoretically and practically the laws of energy and momentum conservation in isolated systems in one dimension
- investigate and analyse theoretically and practically impulse in an isolated system for collisions between objects moving in a straight line: $F\Delta t = m\Delta v$

1A 1B 1C 1D 1E 1F 1G 1H 1I

3.1.6.1 Momentum

3.1.7.1 Impulse

ESSENTIAL PRIOR KNOWLEDGE

1A Velocity as a vector quantity

1B Newton's laws of motion

See questions 19–20.

KEY TERMS AND DEFINITIONS

momentum a property of an object in motion, which is dependent on the mass and the velocity of the object (vector)

isolated system a collection of interacting objects for which there is no change in the total mass and energy

collision the coming together of two or more objects, where each object exerts a force on the other

impulse the change in momentum of a body, as the result of a force acting over a time (vector)

FORMULAS

- **momentum**
  $p = mv$
- **conservation of momentum**
  $\sum p_i = \sum p_f$
- **impulse**
  $I = \Delta p = m\Delta v = F\Delta t$

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Momentum 3.1.6.1

Momentum is a vector quantity which is conserved in an **isolated system**.

How does an object's mass and velocity affect its momentum?

An object in motion has momentum, p. Momentum, measured in kg m s^{-1} or N s, is equal to the product of the mass of an object and its velocity. The direction of the momentum is the same as the direction of velocity, as both values are vector quantities.

FORMULA

$$p = mv$$

p = momentum (kg m s^{-1})
m = mass (kg)
v = velocity (m s^{-1})

Momentum varies with both mass and velocity, but larger objects do not necessarily have more momentum.

- If two objects are travelling at the same speed but one has more mass, the heavier object will have more momentum (Figure 1a).
- If two objects have the same mass but one is travelling faster, the faster one will have more momentum (Figure 1b).
- Objects with greater momentum will require more force and/or more time to stop – this is the concept of **impulse** and will be looked at later in the lesson.

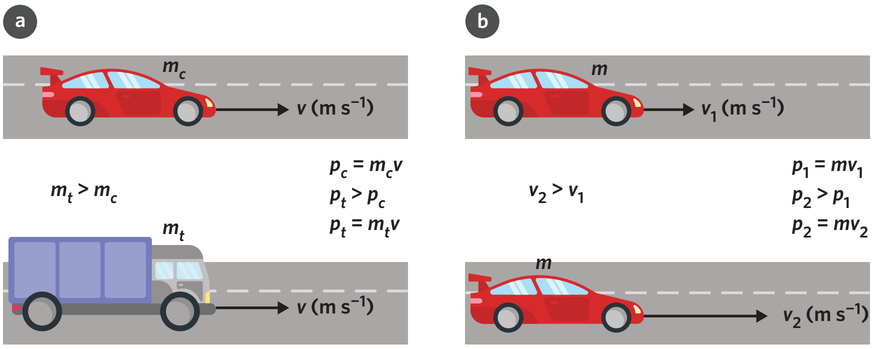

Figure 1 (a) Momentum of different objects travelling at the same speed versus (b) momentum of identical objects travelling at different speeds

PROGRESS QUESTIONS

Question 1

A ball with a mass of 5.0 kg is travelling at 3.0 m s^{-1}. What is the magnitude of the ball's momentum?

A. 1.7 kg m s^{-1}
B. 3.0 kg m s^{-1}
C. 15 kg m s^{-1}
D. The ball does not have any momentum.

Question 2

Katie is skating with a velocity of 6 m s^{-1} north in an ice rink. In which direction is her momentum?

A. north
B. south
C. Katie does not have any momentum.
D. Momentum is a scalar quantity and does not require a direction.

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How can we apply the law of conservation of momentum?

The law of conservation of momentum states that any interaction or **collision** between two or more bodies in an isolated system does not change the total momentum of the system. In other words, the total initial momentum, $\sum p_i$, will be equal to the total final momentum, $\sum p_f$.

$$\sum p_i = \sum p_f$$

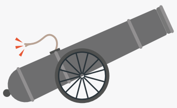
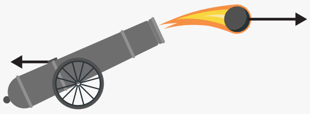
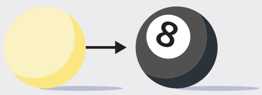
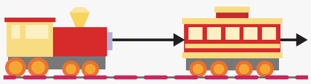
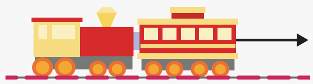
- An isolated system is a group of interacting objects where there is no change in the total mass and energy.
- In VCE Physics, all calculation questions involving momentum will assume an isolated system where momentum is conserved.

USEFUL TIP

The symbol $\sum$ (sigma) is used to denote the sum of multiple terms. For example, $\sum p_f$ is the sum of all the final momentums in the system.

Table 1 shows examples of conservation of momentum in three collisions or interactions.

Table 1 Three situations of momentum conservation in collisions or interactions

Scenario		Before interaction	After interaction
Before	**After**		
		Stationary cannon and cannon ball. Total momentum is zero. $\sum p_i = 0$	Cannon and cannon balls have equal magnitude of momentum but in opposite directions. Total momentum is zero. $\sum p_f = p_{cannon,f} + p_{ball,f} = 0$
		Yellow ball moving to the right. Black ball is stationary. Momentum of the whole system is the same as the yellow ball. $\sum p_i = p_{yellow\ ball,\ i}$	Yellow ball is stationary. Black ball is moving with the momentum the yellow ball initially had. $\sum p_f = p_{black\ ball,\ f}$
		Train and carriage are both moving to the right. $\sum p_i = p_{train,\ i} + p_{carriage,\ i}$	Train and carriage are stuck together. They are moving to the right with the exact same velocity $\sum p_i = (m_{train} + m_{carriage}) \times v_f$

WORKED EXAMPLE 1

A toy truck of mass 200 g rolls along the ground at a constant velocity of 2.0 m s^{-1} to the right when a person places a coin onto the truck. The truck and coin now have a combined mass of 250 g. Ignore the effects of friction.

---

a. Calculate magnitude and direction of the total momentum of the system before the coin is placed on the toy truck.

Step 1

Identify the known and unknown variables and the formula that relates these variables.

Note that before the coin is placed, only the truck has a non-zero momentum.

$m_i = \frac{200}{1000} = 0.200$ kg, $v_i = 2.0$ m s^{-1}, $p_i = ?$

$p_i = m_i v_i$

Step 2

Substitute values into the formula and solve or the total initial momentum of the system.

The direction of the momentum is in the same direction as the velocity.

$p_i = 0.200 \times 2.0 = 0.40$ kg m s^{-1} to the right.

Continues →

b. What is magnitude and direction of the total momentum after the coin is placed on the toy truck?

Step 1

Identify the known and unknown variables, and the formula that relates these variables.

$\sum p_i = 0.40$ kg m s^{-1} to the right, $\sum p_f = ?$

$\sum p_i = \sum p_f$

Step 2

Substitute values into the formula and solve for the total final momentum.

$\sum p_f = 0.40$ kg m s^{-1} to the right

---

c. Calculate the speed of the truck and the coin after the event.

Step 1

Identify the known and unknown variables and the formula that relates these variables.

$p_f = 0.40$ kg m s^{-1}, $m_f = 0.250$ kg, $v_f = ?$

$p_f = m_f v_f$

Step 2

Substitute values into the formula and solve for the final velocity of the truck and coin.

$0.40 = 0.250 \times v_f$

$v_f = \frac{0.40}{0.250} = 1.6 \text{ m s}^{-1}$

PROGRESS QUESTIONS

Question 3

During a collision momentum is

A. never conserved.

B. always conserved in an isolated system.

C. conserved only if the objects are travelling at the same speed after the collision.

D. conserved only if the objects are travelling in the same direction after the collision.

Question 4

A hockey puck with mass of 0.060 kg is slid across the ground with a speed of 12 m s^{-1} horizontally at a wall. The puck bounces back with the same speed as it was thrown. What is the magnitude of the puck's final momentum?

A. 0 kg m s^{-1}

B. 0.72 kg m s^{-1}

C. 1.4 kg m s^{-1}

D. There is not enough information to answer the question.

Impulse 3.1.7.1

Impulse is a vector quantity that is equal to the change in momentum of an object. It occurs due to a force that acts over a period of time.

How does impulse describe changes in momentum?

When a collision occurs, the objects involved exert equal and opposite forces on each other.

- These forces acting between the bodies cause a change in momentum.
- This change in momentum is defined as impulse, *I*.
- Just like momentum, impulse is also a vector quantity measured in kg m s^{-1} or N s.
- The direction of the impulse will be in the same direction as the change in momentum.

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FORMULA

$I = \Delta p = m\Delta v$

I = impulse (kg m s^{-1} or N s)
Δp = change in momentum (kg m s^{-1} or N s)
m = mass (kg)
Δv = change in velocity (m s^{-1})

A force must be involved in a collision between objects. This force is responsible for the impulse.

Using Newton's second law of motion, $F = ma$, and $a = \frac{\Delta v}{\Delta t}$, we can obtain an alternative formula for calculating impulse.

FORMULA

$I = F\Delta t$

I = impulse (kg m s^{-1} or N s)
F = force (N)
Δt = change in time (s)

In this equation, the force is constant. If the force were to vary, then the force used in calculations would be the average force.

The direction of the impulse is always in the same direction as the force being applied. We can apply Newton's third law of motion to the force that causes an impulse.

- In Figure 2, the ball and bat collide.
- This means there is a force on the ball by the bat, acting to the right.
- This force causes an impulse to the right, $I_{on\ ball\ by\ bat}$.
- There must also be a force of equal magnitude on the bad by the ball acting to the right. So $F_{on\ ball\ by\ bat} = -F_{on\ bat\ by\ ball}$.
- This force causes an impulse to the left, $I_{on\ bat\ by\ ball}$.
- Since both objects experience the same collision times and magnitudes of force, $I_{on\ ball\ by\ bat} = -I_{on\ bat\ by\ ball}$

As we know that $I = m\Delta v$ and $I = F\Delta t$, we can join these formulas to create:

$$F\Delta t = m\Delta v$$

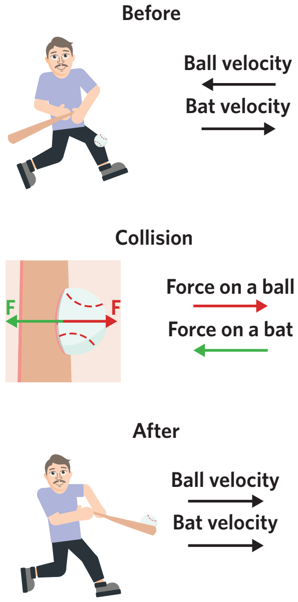


Figure 2 A ball undergoes an impulse as the bat hits it

USEFUL TIP

When unsure about how to approach a physics question relating to force, momentum and impulse, just use $F\Delta t = m\Delta v$.

WORKED EXAMPLE 2

A stationary golf ball of mass 45 g is struck by a golf club. The time that the ball is in contact with the club is 5.0×10^{-3} s, and the ball has a final velocity of 95 m s^{-1} to the east.

a. Calculate the magnitude and direction of the change in the golf ball's momentum.

Step 1

Identify the known and unknown variables and the formula that relates these variables.

$m = 0.045$ kg, $\Delta v = v - u = 95 - 0$ m s^{-1}, $\Delta p = ?$

$\Delta p = m\Delta v$

Step 2

Substitute values into the formula and solve for the change in momentum of the golf ball.

$\Delta p = 0.045 \times (95 - 0)$

$\Delta p = 4.28 = 4.3$ kg m s^{-1} to the east

Continues →

b. Calculate the magnitude and direction of the impulse experienced by the golf ball.

Step 1

Identify the known and unknown variables and the formula that relates these variables.

$\Delta p = 4.3 \text{ kg m s}^{-1}$ to the east, $I = ?$

$I = \Delta p$

Step 2

Substitute values into the formula and solve for the impulse experienced by the golf ball.

$I_{ball} = 4.3 \text{ kg m s}^{-1}$ to the east

---

c. Calculate the magnitude and direction of the impulse experienced by the golf club.

Step 1

The impulse experienced by the golf club will be equal in magnitude but opposite in direction to the impulse experienced by the golf ball.

$I_{club} = -I_{ball} = 4.3 \text{ kg m s}^{-1}$ to the west.

---

d. Calculate the magnitude and direction of the average force experienced by the golf ball during its contact with the golf club.

Step 1

Identify the known and unknown variables and the formula that relates these variables.

$I_{ball} = 4.3 \text{ kg m s}^{-1}$, $\Delta t = 5.0 \times 10^{-3}$ s, $F_{avg} = ?$

$I = F\Delta t$

Step 2

Substitute values into the formula and solve for the average force experienced by the golf ball.

$4.3 = F_{avg} \times 5.0 \times 10^{-3}$

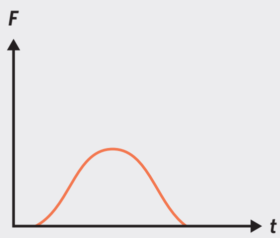
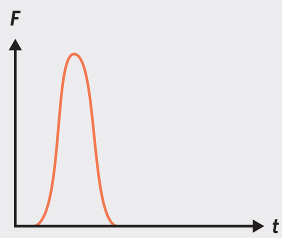
$$F_{avg} = \frac{4.3}{5.0 \times 10^{-3}} = 860 = 8.6 \times 10^2 \text{ N to the east.}$$

Image: Tricky_Shark/Shutterstock.com

Figure 3 The crumple zone of a car increases the change in time, and therefore decreases the force, during a collision.

Safety features in cars are designed to decrease the force experienced in a crash by increasing the time of the collision (Figure 3). Table 2 and Figure 4 compare what happens to a car in a collision with a large versus small crumple zone.

Table 2 Comparison of crumple zones in collisions

	Car 1 with large crumple zone	Car 2 with small crumple zone
Final momentum	Same (0 kg m s^{-1})	
Impulse	Same	
Time to reach final momentum	Longer time	Shorter time
Average force	Smaller	Larger
Force vs. time graph **The area under the curve represents impulse and is the same for both graphs.**	 **Figure 4 (a)** Force-time graphs for a collision with a crumple zone	 **Figure 4 (b)** Force-time graphs for a collision without a crumple zone

Continues →

The same principles can be applied to seatbelts, helmets, airbags, and many other types of safety equipment.

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WORKED EXAMPLE 3

Two cars of equal mass are travelling down the road at equal speeds. Car A has a longer bonnet (crumple zone) than Car B. Both cars crash into a truck that has parked perpendicular to the street. With reference to collisions, discuss which driver is more likely to be injured as a result of the collision.

Breakdown	Answer
Identify which driver is more likely to be injured.	The driver in Car B is more likely to be injured.
Explain what impact the bonnet size has on the collision.	The longer bonnet of Car A, increases the time of which the collision occurs.
Explain the importance of decreasing time in a collision.	Since both cars experience the same impulse, this decreases the average force experienced by Car A.

PROGRESS QUESTIONS

Question 5

Impulse is best described as

A. the change in the velocity of an object.

B. the change in the momentum of an object.

C. the average force experienced by an object.

D. the change in the velocity of an object over a given time.

Question 6

Two cars with equal mass are travelling down a road at 80 km h^{-1} when the traffic lights in front of them turn red and both cars stop. Car A decelerates very rapidly from 80 km h^{-1} to 0 km h^{-1}, whereas Car B slowly decelerates. Relative to Car B, Car A experiences

A. no impulse.

B. a lesser magnitude of impulse.

C. a greater magnitude of impulse.

D. the same magnitude of impulse.

Theory summary

- Objects in motion have momentum.
  - Momentum, p, is a vector quantity measured in kg m s^{-1} or N s.
  - $p = mv$
- The law of conservation of momentum states that the total momentum before a collision will be the same as the total momentum after the collision within an isolated system.
  - $\sum p_i = \sum p_f$
- Impulse is equal to the change in momentum of an object due to a force which acts over a given time.
  - $I = \Delta p = m\Delta v = F\Delta t$
- Momentum and impulse are both vector quantities measured in kg m s^{-1} or N s.
- By increasing the time over which a collision occurs, the average force is decreased, making collisions safer.

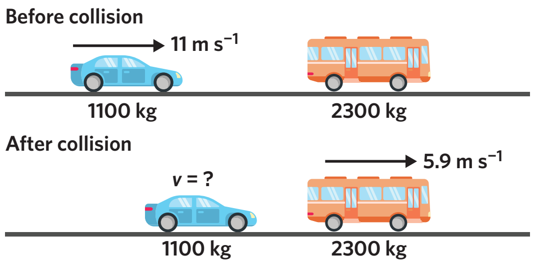
1I Questions

Mild 🌶 Medium 🌶🌶 Spicy 🌶🌶🌶

Deconstructed exam-style

Use the following information to answer questions 7–10

A car of mass 1100 kg is moving to the right at 11 m s^{-1}. It collides into a stationary bus of mass 2300 kg. After the collision, the bus moves to the right at 5.9 m s^{-1}.



Question 7 🌶 (1 MARK)

What is the magnitude and direction of the momentum of the car before the collision?

A. 1.7×10^2 kg m s^{-1} to the left

B. 1.7×10^2 kg m s^{-1} to the right

C. 1.2×10^4 kg m s^{-1} to the left

D. 1.2×10^4 kg m s^{-1} to the right

Question 8 🌶 (1 MARK)

What is the magnitude and direction of the momentum of the system after the collision?

Question 9 🌶 (1 MARK)

What is the magnitude and direction of the momentum of the bus after the collision?

A. 3.9×10^2 kg m s^{-1} to the left

B. 3.9×10^2 kg m s^{-1} to the right

C. 1.4×10^4 kg m s^{-1} to the left

D. 1.4×10^4 kg m s^{-1} to the right

Question 10 🌶🌶 (4 MARKS)

Calculate the magnitude and direction of the velocity of the car after the collision.

Adapted from VCAA 2020 exam Short answer Q10a

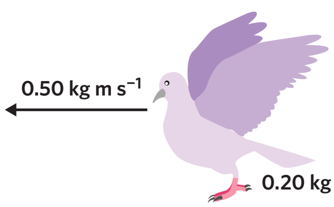
Exam-style

Question 11 🌶 (2 MARKS)

A basketball of mass 0.25 kg is thrown to the right at a speed of 4.0 m s^{-1}. What is the magnitude and direction of the momentum of the ball?

Question 12 🌶 (2 MARKS)

A pigeon with a mass of 0.20 kg is in flight with a momentum of magnitude of 0.50 kg m s^{-1}. Calculate the speed of the pigeon.



Question 13 (4 MARKS)

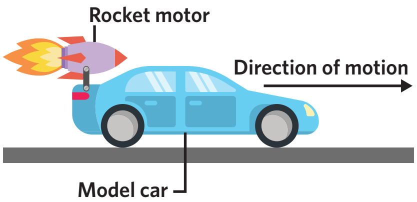
A young adult driving a car approaches an intersection at a speed of 50 m s^{-1}. A truck pulls out in front of the car which is forced to stop in 8.5 s. The driver and car have a combined mass of 1500 kg.

a. Calculate the magnitude of the impulse experienced by the car and the driver. 2 MARKS

b. Calculate the magnitude of the average force acting to decelerate the car. 2 MARKS

Question 14 (1 MARK)

A model car of mass 3.0 kg is propelled from rest by a rocket motor that applies a constant horizontal force of 5.0 N, as shown. Assume that friction is negligible.



Which of the following best gives the magnitude of the impulse given to the car by the rocket motor in the first 6.0 s?

A. 5.0 N s

B. 15 N s

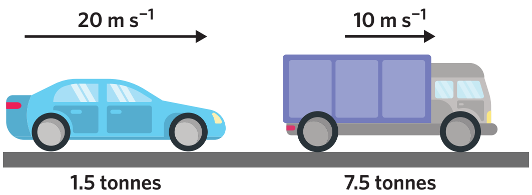
C. 18 N s

D. 30 N s

Adapted from VCAA 2017 exam Multiple choice Q8

Question 15 (9 MARKS)

The figure shows a car of mass 1.5 tonnes moving to the right at a speed of 20 m s^{-1}, and a truck of mass 7.5 tonnes moving to the right at a speed of 10 m s^{-1}. The two vehicles collide and stick together.



a. Calculate the magnitude and direction of the total momentum of the car and truck when they stick together after the collision. 2 MARKS

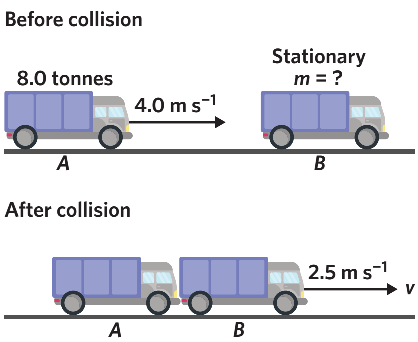
b. Calculate the speed of the truck and car once stuck together after the collision 2 MARKS

c. State the magnitude, direction and units of the impulse given to the car by the truck during the collision. 3 MARKS

d. What is the magnitude and direction of the impulse given to the truck by the car during the collision? 2 MARKS

Question 16 (1 MARK)

A railway truck (A) of mass 8.0 tonnes, moving at 4.0 m s^{-1}, collides with a stationary railway truck (B), as shown. After the collision, they are joined together and move off at a speed of 2.5 m s^{-1}.



What is the mass of railway truck B?

A. 3.0 tonnes

B. 4.8 tonnes

C. 8.0 tonnes

D. 13 tonnes

Adapted from VCAA 2022 exam Multiple choice Q6

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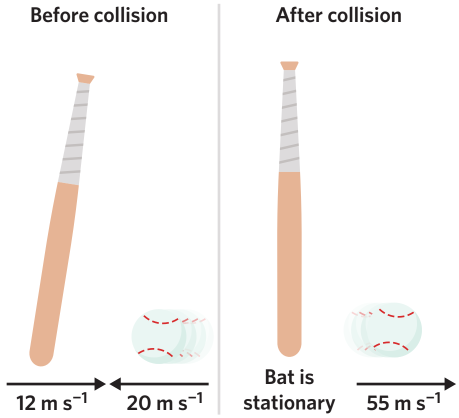
11 QUESTIONS

Question 17

(7 MARKS)

Students in a physical education class are exploring the breaking point of rubber balls by striking them with a bat whilst they are thrown. The physical education students also possess a good knowledge of momentum and impulse, and decide to do some calculations with their data. They record the included measurements.

Mass of ball	0.40 kg
Mass of bat	2.5 kg
Speed of bat immediately before striking ball	12 m s^{-1} (bat is stationary after collision)
Speed of ball immediately before being struck	20 m s^{-1} (towards bat)
Speed of ball immediately after being struck	55 m s^{-1} (away from bat)
Average force between the ball and bat	1.2×10^3 N



a. Calculate the magnitude of the impulse given to the ball by the bat. Include an appropriate unit in your answer. 3 MARKS

b. Calculate the time that the ball is in contact with the bat. 2 MARKS

c. *Key science skill*
In their data, they notice that all the values are consistently off by the same amount. Identify the type of error and how it can be improved. 2 MARKS

Adapted from VCAA 2019 NHT exam Short answer Q7

FROM LESSON 12C

Question 18

(9 MARKS)

Students conduct a physics experiment in which they use a toy car moving at a known constant velocity with variable mass, and collide it with another stationary car of known mass. The students use a tape measure and a stopwatch to measure the velocity of the second car. Due to the inaccuracy of this method, the students estimate the uncertainty of the final momentum to be ± 3.0 kg m s^{-1}. They record the following data.

Initial momentum (kg m s^{-1})	**Final momentum ($\pm$3.0 kg m s^{-1})**
9	10
15	13
22	21
26	28
31	29

a. *Key science skill*
On a set of axes: 6 MARKS

- plot a graph of final momentum versus initial momentum using the data in the table provided
- include appropriate uncertainty bars for the final momentum values
- label each axis correctly
- include an appropriate scale

FROM LESSON 12D

b. *Key science skill*
Use the graph from part **a** to determine whether the students' data supports the law of conservation of momentum. Explain your answer. 3 MARKS

FROM LESSON 12D

Question 19 (3 MARKS)

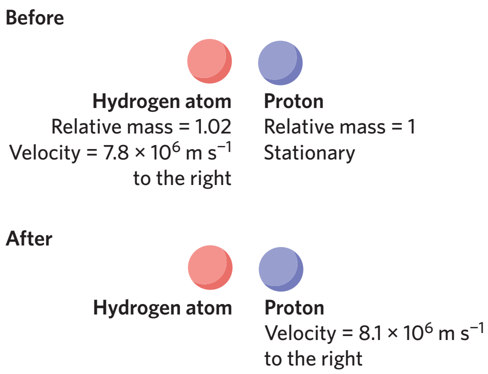
Identical twin race car drivers compete against each other using identical cars. They were distracting each other and missed a turn, crashing into a wall. Zara's airbags inflate while Lara's do not.

In terms of force and impulse, evaluate which driver is safer in their collision? Justify your answer.

Question 20 (3 MARKS)

A hydrogen atom travelling at 7.8×10^6 m s^{-1} to the right strikes a stationary proton. After the impact, the proton travels off to the right at 8.1×10^6 m s^{-1}.

The mass of the hydrogen atom is 1.02 times the mass of the proton.



Calculate the magnitude and direction of the velocity of the hydrogen atom after the collision.

Previous lessons

Question 21 (2 MARKS)

Tim has a mass of 80 kg and he is pulling his trolley full of groceries which has a mass of 15 kg. If their combined acceleration is 4.0 m s^{-2}, what is the magnitude of the net force acting on Tim and the trolley?

FROM LESSON 1D

Question 22 (2 MARKS)

Jeanie is riding her bike over a hill that has a radius of 4.0 m. Calculate the maximum speed that she can travel and not leave the ground.

FROM LESSON 1G

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Chapter 1 review

Mild 🌶 Medium 🌶🌶 Spicy 🌶🌶🌶

These questions are typical of one hour's worth of questions on the VCE Physics Exam.

Total marks: 50

Section A

All questions in this section are worth one mark.

Unless otherwise indicated, the diagrams in this book are not drawn to scale.

Question 1 🌶

A toy car of mass 1.5 kg is propelled forward by a net force of 3.0 N. What is the magnitude of the acceleration of the toy?

A. 0.50 m s^{-2}

B. 1.5 m s^{-2}

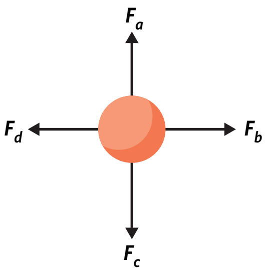
C. 2.0 m s^{-2}

D. 4.5 m s^{-2}

Adapted from VCAA 2017 exam Multiple choice Q7

Question 2 🌶

Four different forces act on a body simultaneously. $F_a = 18$ N, $F_b = 34$ N, $F_c = 14$ N and $F_d = 26$ N.



What is the magnitude of the resultant force on the body? Force vectors in the diagram are not drawn to scale.

A. 6 N

B. 8 N

C. 9 N

D. 2×10^2 N

Adapted from VCAA 2018 exam Multiple choice Q5

Question 3 🌶🌶

A race track is designed so that when cars go around a corner they do not exert any sideways friction force in order to turn. The radius of the corner is 55 m and cars move around it at 60 km h^{-1}. What is the angle of the corner to the horizontal?

A. 6.4°

B. 10°

C. 27°

D. 62°

Question 4 🌶🌶

A roller coaster loop the loop has been designed so that the passengers will experience a zero normal reaction force at the top of the loop. The loop has a radius of 7.0 m and the combined mass of the cart and passengers is 450 kg. What speed must the cart be going at the top of the loop to achieve this?

A. 3.9 m s^{-1}

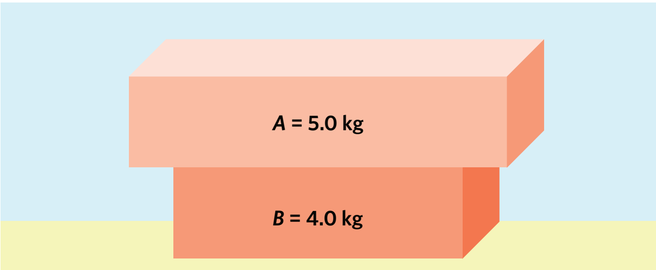
B. 6.5 m s^{-1}

C. 8.3 m s^{-1}

D. 13.9 m s^{-1}

Question 5 🌶🌶🌶

Whilst making a geometric sculpture, a person places brick *A* of mass 5.0 kg on top of brick *B* of mass 4.0 kg, as shown in the diagram.



What is the magnitude and direction of $F_{on\ A\ by\ B}$?

A. 39 N upwards

B. 49 N upwards

C. 39 N downwards

D. 49 N downwards

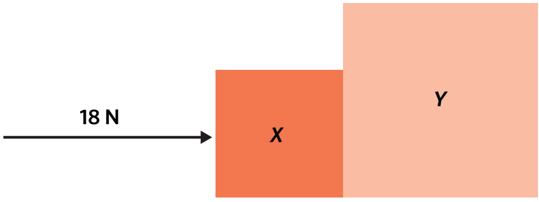
Section B

In questions where more than one mark is available, appropriate working must be shown.

Unless otherwise indicated, the diagrams in this book are not drawn to scale

Question 6 🌶🌶 (2 MARKS)

An 18 N force is applied to block *X*, of mass 2.0 kg, which is in contact with block *Y*, of mass 4.0 kg, sitting on a smooth, frictionless surface.



Calculate the magnitude and direction of the force on block *Y* by block *X*.

Adapted from VCAA 2018 exam Short answer Q8a

Question 7 (4 MARKS)

A 1600 kg car is pulling a trailer that has a mass of 600 kg. The trailer is connected to the car through a metal coupling. The car accelerates from rest at a rate of 0.50 m s^{-2}.

a. Calculate the time it takes for the car to have a speed of 10 m s^{-1}. 🌶🌶 2 MARKS

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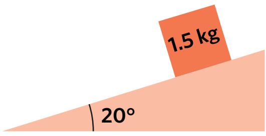
b. The trailer provides a constant resistance force of 1000 N. Calculate the magnitude of the tension force in the metal coupling between the car and the trailer. 2 MARKS

Adapted from VCAA 2016 exam Short answer Q1

Question 8 (6 MARKS)

A 1.5 kg block is placed on a ramp at an angle of 20° to the horizontal. A constant friction force acts on the block as it starts from rest and slides down the ramp. The block travels 1.5 m and takes 5.0 s to slide to the bottom of the ramp.



a. Show that the magnitude of the acceleration of the block is 0.12 m s^{-2}. 1 MARK

b. Hence calculate the magnitude of the frictional force acting on the block. 2 MARKS

c. ***Key science skill***

Students are investigating the effect of increasing the angle of inclination on the acceleration of the block. They produce a graph of the sin(θ) vs. *a*. Discuss how the students could use the graph to determine the magnitude of the frictional force acting on the block. 3 MARKS

FROM LESSON 12E

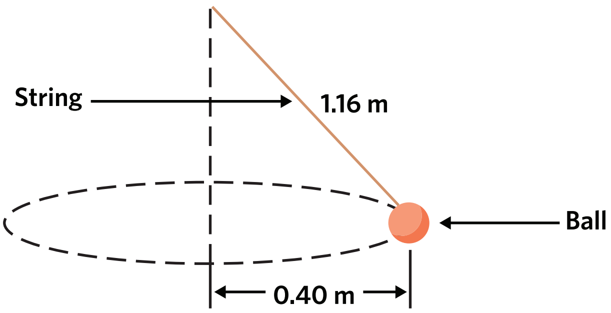
Adapted from VCAA 2013 exam Short answer Q1

Question 9 (3 MARKS)

In a crash test, a car of mass 1200 kg is crashed into a solid stone wall. It was travelling at a speed of 90 km h^{-1} to the right before decelerating and stopping in 0.10 s as it crashes into the wall. Calculate the magnitude and direction of the average force acting on the car during the collision.

Question 10 (5 MARKS)

A child is swinging a ball attached to a string in a horizontal circle during break time in school. Being an aspiring physicist, the child decides to take some measurements. The length of the string is 1.16 m and the ball, which has a mass of 0.50 kg, is moving in a circle of radius 0.40 m at 1.2 m s^{-1}.



a. Draw a diagram showing all the forces acting on the ball. Draw the net force as a dashed line labelled F_{net}. 2 MARKS

b. Calculate the tension in the string. 3 MARKS

Adapted from VCAA 2016 exam Short answer Q2

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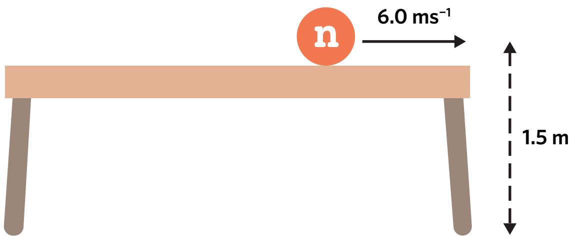
Question 11 (6 MARKS)

A giant N&N is rolled off a bench that is 1.5 m above the ground. It has a speed of 6.0 m s^{-1} when it leaves the bench. If the N&N hits the ground at a speed greater than 7.0 m s^{-1} it will shatter.



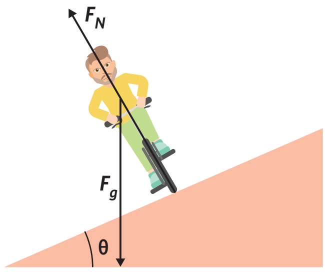
Ignore all friction and resistance forces.

a. Calculate the horizontal distance that the N&N travels before it hits the ground. 3 MARKS

b. Does the N&N tragically break when it hits the ground? 3 MARKS

Question 12 (4 MARKS)

Lance is riding his bike around a circular banked track of radius 45 m to legally and ethically win La Tour de Straya. Lance and his bike have a combined mass of 85 kg and travel at 14 m s^{-1}. The forces acting on Lance and his bike are shown in the diagram below.

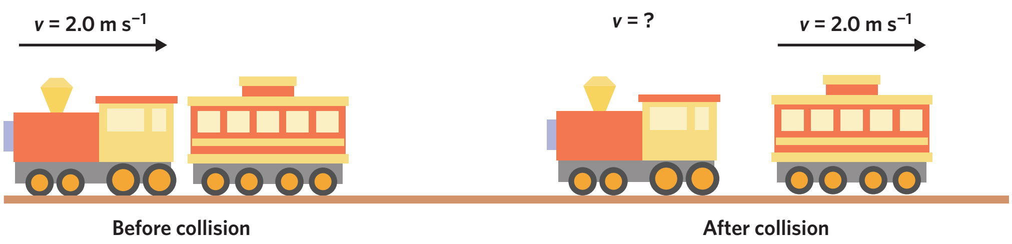


a. What is the magnitude and direction of the net force acting on Lance? 2 MARKS

b. Calculate the correct angle of bank for there to be no sideways frictional force applied by the track on the wheels. 2 MARKS

Adapted from VCAA 2017 exam Short answer Q7

Question 13 (6 MARKS)



An engine of mass 20 tonnes, moving to the right at 2.0 m s^{-1}, collides with but does not couple with the stationary wagon of mass 10 tonnes. After the collision, the wagon moves off to the right at 2.0 m s^{-1}.

a. Calculate the magnitude and direction of the velocity of the engine after the collision. Show your working. 3 MARKS

Adapted from VCAA 2016 exam Short answer Q1e

b. Compare the average force exerted by the engine on the wagon to the force exerted by the wagon on the engine. Justify your answer. 3 MARKS

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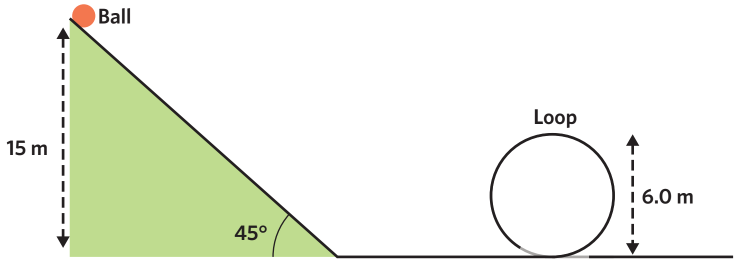
Question 14 (9 MARKS)

A ball of mass 1.50 kg is placed at the top of a hill with a 6.0 m tall loop at the bottom. The hill is 15 m tall and is inclined at an angle of 45°. All surfaces are frictionless.



a. Calculate the magnitude of the acceleration of the ball down the hill. 2 MARKS

b. Calculate the speed of the ball at the bottom of the hill. 3 MARKS

c. Calculate the minimum speed the ball must have at the top of the loop in order to stay in contact with the loop. 2 MARKS

d. Suppose the speed of the ball at the top of the loop is 13 m s^{-1}. Calculate the value of the normal force, F_N, acting on the ball by the track at this point. 2 MARKS

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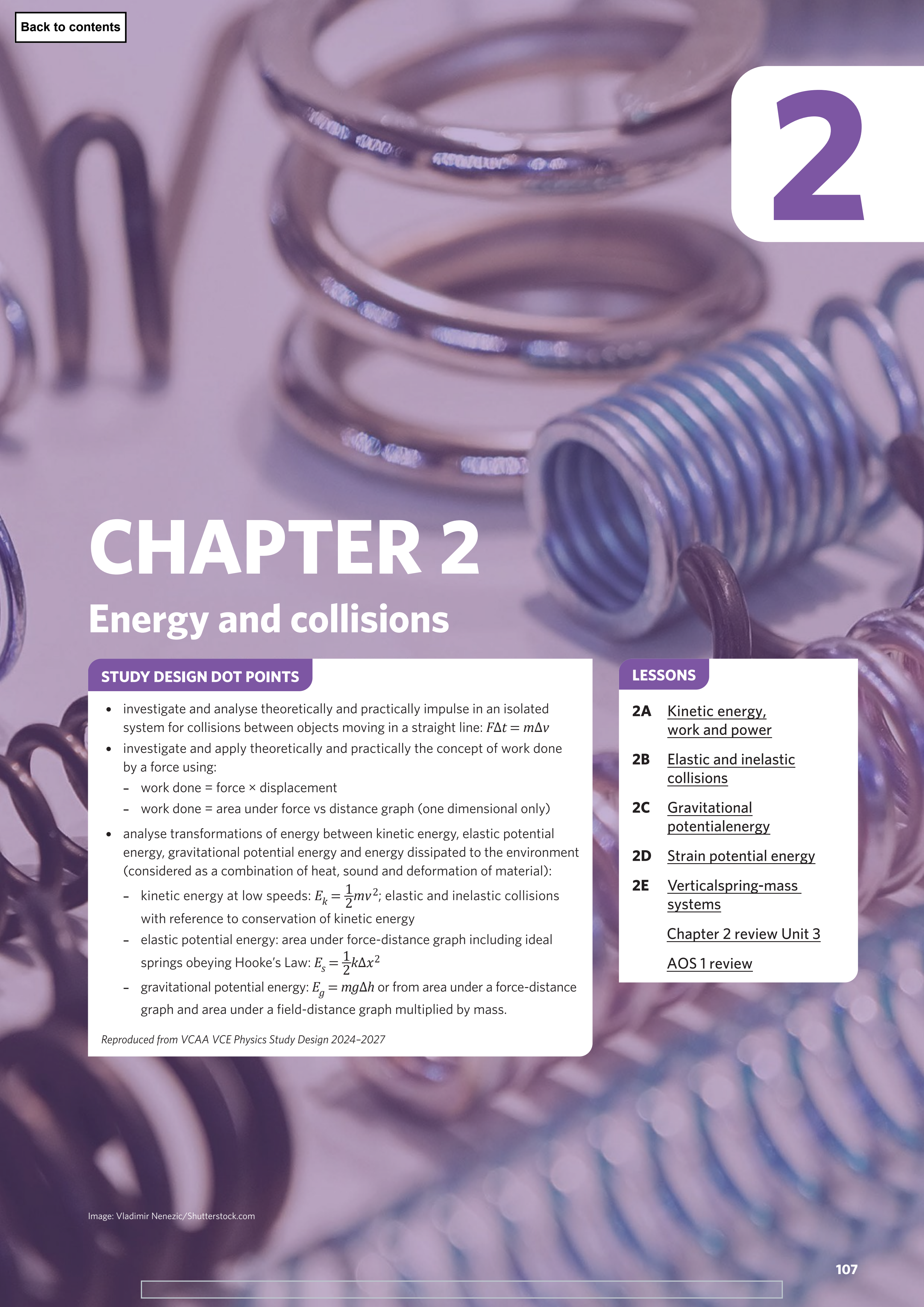

2

CHAPTER 2

Energy and collisions

STUDY DESIGN DOT POINTS

- investigate and analyse theoretically and practically impulse in an isolated system for collisions between objects moving in a straight line: $F\Delta t = m\Delta v$
- investigate and apply theoretically and practically the concept of work done by a force using:
  - work done = force × displacement
  - work done = area under force vs distance graph (one dimensional only)
- analyse transformations of energy between kinetic energy, elastic potential energy, gravitational potential energy and energy dissipated to the environment (considered as a combination of heat, sound and deformation of material):
  - kinetic energy at low speeds: $E_k = \frac{1}{2}mv^2$; elastic and inelastic collisions with reference to conservation of kinetic energy
  - elastic potential energy: area under force-distance graph including ideal springs obeying Hooke's Law: $E_s = \frac{1}{2}k\Delta x^2$
  - gravitational potential energy: $E_g = mg\Delta h$ or from area under a force-distance graph and area under a field-distance graph multiplied by mass.

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LESSONS

Image: Vladimir Nenezic/Shutterstock.com

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2A Kinetic energy, work and power

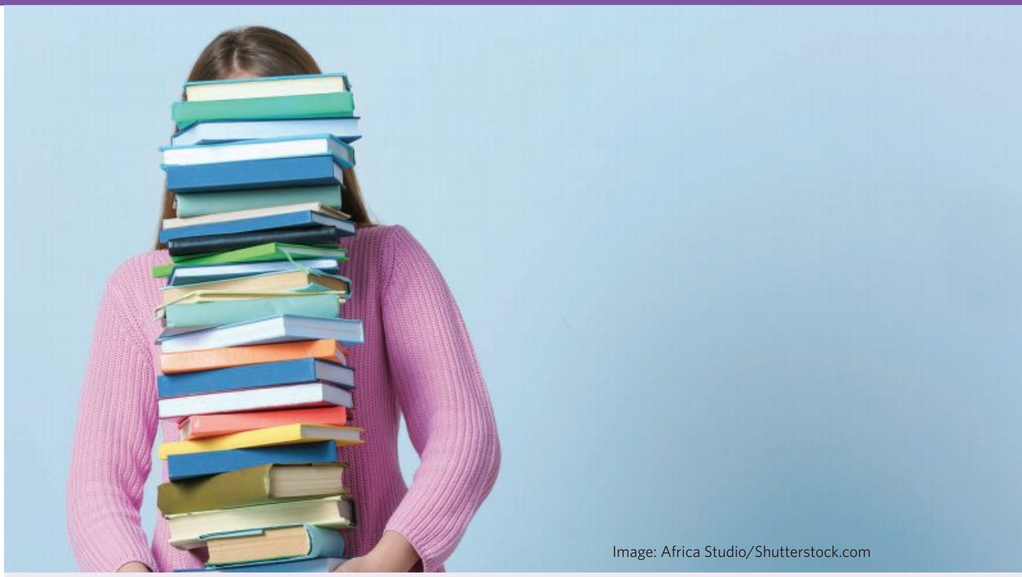
Image: Africa Studio/Shutterstock.com

STUDY DESIGN DOT POINTS

- investigate and apply theoretically and practically the concept of work done by a force using:
  - work done = force × displacement
  - work done = area under force vs distance graph (one dimensional only)
- analyse transformations of energy between kinetic energy, strain potential energy, gravitational potential energy and energy dissipated to the environment (considered as a combination of heat, sound and deformation of material):
  - kinetic energy at low speeds: $E_k = \frac{1}{2}mv^2$; elastic and inelastic collisions with reference to conservation of kinetic energy
  - strain potential energy: area under force-distance graph including ideal springs obeying Hooke's Law: $E_s = \frac{1}{2}k\Delta x^2$
  - gravitational potential energy: $E_g = mg\Delta h$ or from area under a force-distance graph and area under a field-distance graph multiplied by mass

2A 2B 2C 2D 2E

3.1.9.1 Kinetic energy

3.1.8.1 Work done

3.1.8.2 Power as the rate of change in energy

ESSENTIAL PRIOR KNOWLEDGE

1A Velocity vs. speed

1A Displacement vs. distance

1B Force

See questions 21–23.

Is the student doing any work on the books?

Studying physics may feel like a lot of work, but despite the tiredness in your arms, holding your physics books stationary is not doing any work on them. If you want to actually do some work on your physics books, you'd have to apply a force that causes them to move a distance – like the force required to open the front page and read it. This lesson explores how understanding work, kinetic energy, and power, will give you the potential to understand conservation of energy.

KEY TERMS AND DEFINITIONS

kinetic energy (KE) the energy associated with an object's motion

energy a scalar quantity describing the ability to cause a physical change

conservation of energy the total energy of an isolated system remains constant

work the change in energy caused by a force acting on an object in a direction parallel to its motion

power the rate of change of energy with respect to time

FORMULAS

- kinetic energy
  $KE = \frac{1}{2}mv^2$
- work
  $W = \Delta E = Fs$
- power
  $P = \frac{\Delta E}{\Delta t} = \frac{W}{\Delta t}$

Kinetic energy 3.1.9.1

Kinetic energy (KE) is the **energy** associated with an object because of its motion. The SI unit for all types of energy is the joule (J). All forms of energy are scalar quantities, meaning they do not have an associated direction.

How can we calculate kinetic energy?

In classical physics, the kinetic energy of an object is related to its mass and speed by the following formula:

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FORMULA

$$KE = \frac{1}{2}mv^2$$

KE = kinetic energy (J)
m = mass (kg)
v = speed (m s^{-1})

USEFUL TIP

Note that the VCE Physics Study Design uses the abbreviation E_k for kinetic energy but this textbook will use *KE*.

The benefit of quantifying kinetic energy will become clear in the next section, which explores the concept of work. In later lessons, we introduce other types of energy and use the **conservation of energy** to analyse real-world problems.

WORKED EXAMPLE 1

A toy car with a mass of 500 g is travelling at 3.00 m s^{-1}. Calculate the kinetic energy of the toy car.

Step 1

Identify the known and unknown variables and the formula that relates these variables.

$m = \frac{500}{1000} = 0.500$ kg, $v = 3.00$ m s^{-1}, $KE = ?$

$KE = \frac{1}{2}mv^2$

Step 2

Substitute values into the formula and solve for the kinetic energy of the toy car.

$KE = \frac{1}{2} \times 0.500 \times 3.00^2$

$KE = 2.25$ J

PROGRESS QUESTIONS

Question 1

Which of the following is the kinetic energy of an object, with a mass of 5.0 kg, travelling at a speed of 8.0 m s^{-1}?

A. 2.0×10^1 J **B.** 4.0×10^1 J **C.** 1.6×10^2 J **D.** 3.2×10^2 J

Question 2

A 200 kg sailboat has the capacity to travel at speeds up to 7.0 m s^{-1}.
What is the kinetic energy of the boat when it is stationary at the harbour?

A. 0 J **B.** 1.2×10^3 J **C.** 1.4×10^3 J **D.** 4.9×10^3 J

Work done 3.1.8.1

Work is the change in the energy of an object due to the application of a force. The SI unit for work is the joule (J), meaning work is a scalar quantity.

How can we calculate work?

As we know from Newton's first law of motion, a change in the speed of an object (and therefore its kinetic energy) must be caused by a force. Work is a measure of the change in energy caused by the application of this force.

- If a force is applied to an object and the object gains energy, then we say that work was done on the object.
- If a force is applied by an object and the object loses energy, then we say that work was done by the object.

For example, if a person applies a force to a stationary trolley causing it to gain kinetic energy, we would say that work was done by the person on the trolley.

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If given the initial and final energy of an object, the work done can be calculated by subtracting the object's initial energy from the object's final energy:

$$W = \Delta E = E_f - E_i$$

WORKED EXAMPLE 2

A 1500 kg car is initially travelling at 10 m s^{-1} and then speeds up to 30 m s^{-1}. Calculate the work done by the engine to speed up the car.

Step 1

Identify the known and unknown variables and the formula that relates these variables.

$m = 1500$ kg, $u = 10$ m s^{-1}, $v = 30$ m s^{-1}, $KE_i = ?$, $KE_f = ?$

$KE = \frac{1}{2}mv^2$

Step 2

Substitute values into the formula and solve for the initial and final kinetic energy of the car.

$KE_i = \frac{1}{2} \times 1500 \times 10^2 = 7.50 \times 10^4$ J

$KE_f = \frac{1}{2} \times 1500 \times 30^2 = 6.75 \times 10^5$ J

Step 3

Identify the known and unknown variables and the formula that relates these variables.

$KE_i = 7.50 \times 10^4$ J, $KE_f = 6.75 \times 10^5$ J, $W = ?$

$W = \Delta KE = KE_f - KE_i$

Step 4

Substitute values into the formula and solve for the work done by the engine.

$W = 6.75 \times 10^5 - 7.50 \times 10^4$

$W = 6.0 \times 10^5$ J

MISCONCEPTION

'Work isn't scalar because it can have a positive or negative value'

The sign indicates whether energy has been lost or gained. A positive value for work means energy has been gained. A negative value for work means energy has been lost.

For an object to gain energy a force must be applied to it, however, not all forces result in the object gaining energy. For example, holding your physics book stationary requires you to apply a force that's equal and opposite to gravity. But does the physics book gain energy? No, it doesn't. Therefore we haven't done any work on it (just like many of the students reading this now). To do work on the physics book we need to apply a force that causes it to move a distance, and therefore gain energy.

Using this we can develop another equation for calculating work:

$$W = Fs$$

Combining our two equation for work gives:

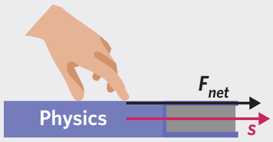
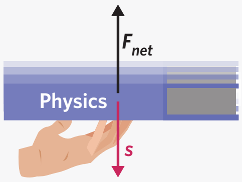
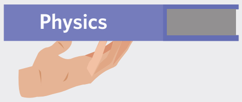
FORMULA

$$W = \Delta E = Fs$$

W = work (J)
ΔE = change in energy (J)
F = force (N)
s = displacement of object in the direction of force (m)

In VCE Physics, we need to consider three situations where work is done. Table 1 provides a summary of these.

Table 1 Work done in different scenarios

Figure	Explanation	Displacement direction	Net Force direction	Change in energy of physics book	Work done on physics book
	Pushing a book in the same direction as a force	To the right	To the right	$E_f > E_i$	Positive
	Catching a falling physics textbook requires a force to be provided up to resist the direction of motion	Downwards	Upwards	$E_f < E_i$	Negative
	Holding a physics book stationary	No displacement	There is 0 net force acting on the book	$E_f = E_i$	Zero

WORKED EXAMPLE 3

A person pushes a box across a horizontal surface by applying a force of 10 N in the direction of motion, while a frictional force of 4.0 N acts on the box in the opposite direction. The box moves a distance of 5.0 m.

a. Calculate the work done on the box by the person.

Step 1

Identify known and unknown variables and write down the formula that relates these variables.

$F_p = 10$ N, $s = 5.0$ m, $W_p = ?$

$W = Fs$

Step 2

Substitute values into the formula and solve for the work done on the box by the person.

$W_p = 10 \times 5.0$

$W_p = 50$ J

b. Calculate the work done on the box by friction.

Step 1

Identify known and unknown variables and write down the formula that relates these variables.

Note that the force is negative since it is applied opposite to the direction of motion.

$F_f = -4.0$ N, $s = 5.0$ m, $W_f = ?$

$W = Fs$

Step 2

Substitute values into the formula and solve for the work done on the box by friction.

$W_f = -4.0 \times 5.0$

$W_f = -20$ J

Continues →

c. Calculate the work done on the box.

Step 1

Identify known and unknown variables and write down the formula that relates these variables.

$W_p = 50$ J, $W_f = -20$ J, $W_{tot} = ?$

$W_{tot} = W_p + W_f$

OR

$F_{net} = (10 - 4.0) = 6.0$ N, $s = 5.0$ m,

$W_{tot} = ?$

$W_{tot} = F_{net}s$

Step 2

Substitute values into the formula and solve for the total work done on the box.

$W_{tot} = 50 + (-20)$

$W_{tot} = 30$ J

OR

$W_{tot} = 6.0 \times 5.0$

$W_{tot} = 30$ J

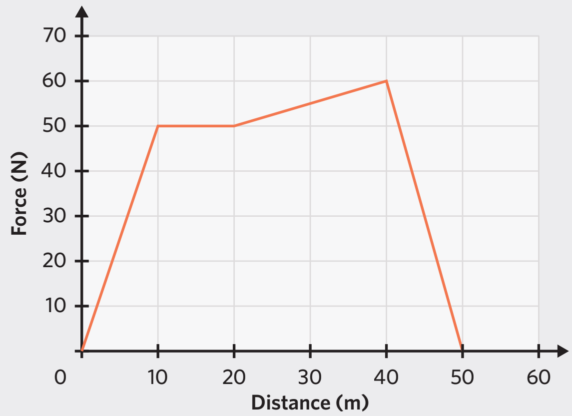
We can also use the area under a force-distance graph to find the work done on an object. This is especially helpful when the force applied to an object is changing.

USEFUL TIP

Ensure that you check the units of the axes when calculating the area under a graph. You will need to convert units that are not in their SI form.

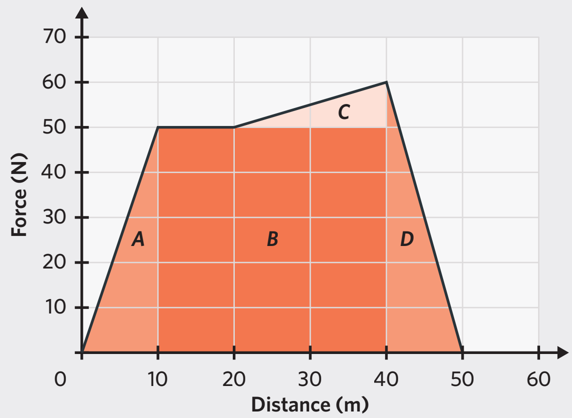
WORKED EXAMPLE 4

Calculate the work done on an object that moves 50 m in a constant direction, with an applied force that acts in the direction of motion and varies according to the force-distance graph shown.



Step 1

Divide the graph into areas.



Continues →

Step 2

Calculate the area of each shape.

$A_A = \frac{1}{2} \times 10 \times 50 = 250 \text{ J}$

$A_B = 30 \times 50 = 1500 \text{ J}$

$A_C = \frac{1}{2} \times 20 \times 10 = 100 \text{ J}$

$A_D = \frac{1}{2} \times 10 \times 60 = 300 \text{ J}$

Step 3

Calculate the total area under the graph to find the total work

$W = 250 + 1500 + 100 + 300$

$W = 2150 \text{ J}$

USEFUL TIP

For some graphs, we can calculate the area under them using the area of a trapezium. $A = \frac{a+b}{2} \times h$

PROGRESS QUESTIONS

Question 3

In which of the following scenarios is the individual not doing work on an object?

A. Cassie pushing a pram

B. Ted opening a sliding door

C. Sam picking up clothes from the floor

D. Jess holding a barbell above her head

Question 4

An object initially has 4.0 J of kinetic energy. A while later, it has 12 J of kinetic energy. What is the total work done on the object?

A. 3 J

B. 4 J

C. 8 J

D. 12 J

Question 5

Which of the following best shows the work done by a person who applies a force of 35 N to push a wheelbarrow a distance of 2.0 m?

A. 1.8×10^1 J

B. 3.7×10^1 J

C. 7.0×10^1 J

D. 1.4×10^2 J

Power as the rate of change in energy 3.1.8.2

Power is the rate of change of energy. The SI unit for power is the watt (W), where one watt is equivalent to one joule per second (J s^{-1}).
Power is a scalar quantity.

What does power measure?

Power is the change in energy over time. As the change in energy is equivalent to the work done ($W = \Delta E$) on an object, the rate of doing work can also be described using power. Power can be calculated using the following formulae.

USEFUL TIP

This knowledge unit is not explicitly included in Units 3 or 4 of VCE Physics but it is a fundamental concept which could reasonably be integrated into assessments in Units 3 or 4.

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FORMULA

$$P = \frac{\Delta E}{\Delta t} = \frac{W}{\Delta t}$$

P = power (W)
ΔE = change in energy (J)
Δt = change in time (s)
W = work (J)

WORKED EXAMPLE 5

An object gains 30 J of energy in 1 min. Calculate the power exerted during this energy transfer.

Step 1

Identify known and unknown variables and write down the formula that relates these variables.

$\Delta E = 30$ J, $\Delta t = 1 \times 60 = 60$ s, $P = ?$

$P = \frac{\Delta E}{\Delta t}$

Step 2

Substitute values into the formula and solve for the power exerted.

$P = \frac{30}{60}$

$P = 0.5$ W

PROGRESS QUESTIONS

Question 6

An object gains 50 J of energy in 80 s. What is the power exerted on the object?

A. 0.63 W **B.** 1.6 W **C.** 40 W **D.** 63 W

Question 7

Power is best described as

A. the change in energy.
B. the change in kinetic energy.
C. the change in energy over time.
D. the change in time over energy.

Theory summary

- Kinetic energy (KE) is the energy associated with the motion of an object
  - $KE = \frac{1}{2}mv^2$
- Work is a change in energy caused by a force parallel to the object's direction of motion
  - $W = \Delta E = Fs$
  - When the force is in the same direction as motion, the work done is positive.
  - When the force is opposite to the direction of motion, the work done is negative.
- If the kinetic energy of an object changes, work has been done on or by the object.
- When the applied force is changing, work can be determined from the area under a force-distance graph.
- Power is the rate of change of energy or of work being done with respect to time.
  - $P = \frac{\Delta E}{\Delta t} = \frac{W}{\Delta t}$

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2A Questions

Mild 🌶 Medium 🌶🌶 Spicy 🌶🌶🌶

Deconstructed exam-style

Use the following information to answer questions 8-10.

A scooter and rider have a combined mass of 90 kg. Initially they are travelling at 2.5 m s^{-1}.
After realising they're running late, they speed up to 5.0 m s^{-1}.

Question 8 🌶 (1 MARK)

What is the initial kinetic energy of the rider and the scooter?

A. 1.1×10^2 J

B. 2.2×10^2 J

C. 2.8×10^2 J

D. 1.1×10^3 J

Question 9 🌶 (1 MARK)

What is the final kinetic energy of the rider and the scooter?

A. 1.1×10^2 J

B. 2.2×10^2 J

C. 2.8×10^2 J

D. 1.1×10^3 J

Question 10 🌶🌶 (3 MARKS)

Calculate the work done by the rider and the scooter to speed up.

Exam-style

Question 11 🌶 (1 MARK)

Key science skill

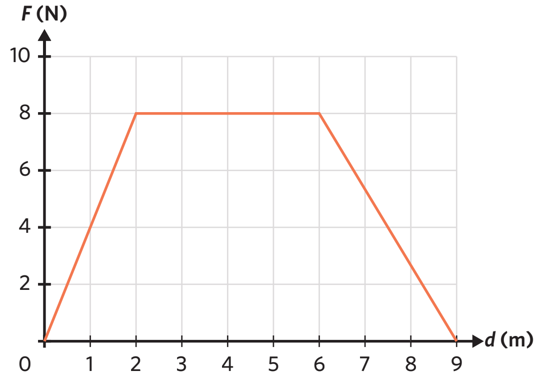
Using the force-distance graph, calculate the amount of work done.

A. 25 J

B. 26 J

C. 52 J

D. 72 J



Question 12 (4 MARKS)

A 900 kg car starts stationary and accelerates to 10 m s^{-1}.

a. Calculate the work that has been done to accelerate it to 10 m s^{-1}. 🌶 2 MARKS

b. Calculate the additional work that must be done to increase the speed of the car from 10 m s^{-1} to 20 m s^{-1}. 🌶 2 MARKS

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Question 13 (1 MARK)

The combined mass of a cyclist and her bike is 80 kg. What is the final speed of the cyclist if she is travelling at 12 m s^{-1} and then does 10 240 J of work to increase her speed? Ignore the effects of frictional forces.

A. 1.1×10^1 m s^{-1}

B. 2.0×10^1 m s^{-1}

C. 1.1×10^3 m s^{-1}

D. 4.0×10^3 m s^{-1}

Question 14 (4 MARKS)

A removalist pushes a heavy box on a surface, such that the net force on the box is 50.0 N. There is a constant friction force acting against the motion of the box, causing energy to be lost as heat.

The power exerted by the removalist is 300 W. They push the box for 30.0 s, causing it to move 15.0 m in the direction of the force.

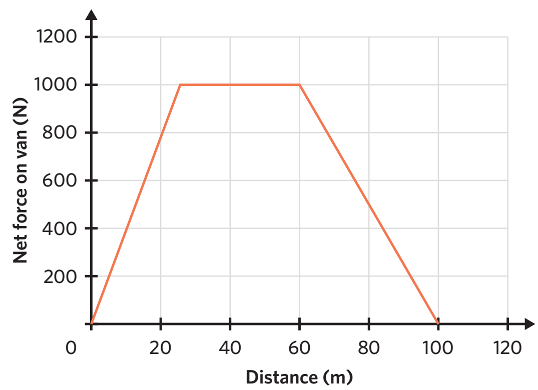
a. Show that the magnitude of the force applied by the removalist is 600 N. — 2 MARKS

b. Calculate the amount of energy lost as heat. — 2 MARKS

Question 15 (3 MARKS)

Key science skill

The graph shows the net force applied to a van with a mass of 1600 kg, which is initially moving at a speed of 8.0 m s^{-1}. The net force is in the direction of motion. Calculate the final speed of the van after it has travelled 100 m.



Question 16 (4 MARKS)

Two cyclists are riding down the road.

a. Carla and her bike have a combined initial kinetic energy of 6000 J. She pedals such that the wheel pushes against the road with a constant force of 130 N. This increases her kinetic energy to 13 540 J. Calculate the distance the cyclist travelled to achieve this increase in kinetic energy. Ignore the effects of frictional forces. — 2 MARKS

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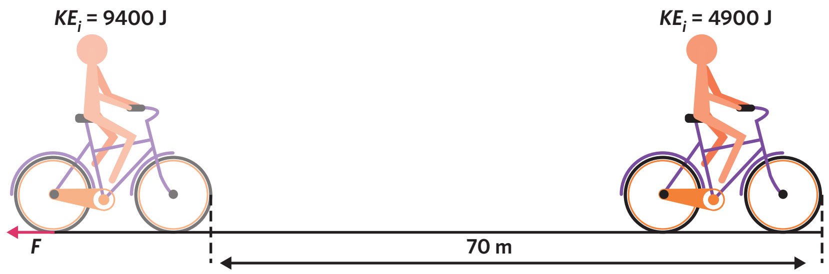
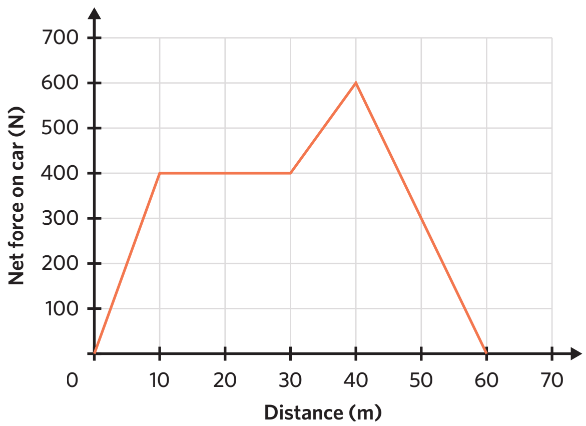
b. Kai starts riding with an initial kinetic energy of 9400 J. He applies a constant braking force to decrease his kinetic energy to 4900 J over a distance of 70 m. What is the magnitude of the braking force? Ignore the effects of other frictional forces. 2 MARKS



Question 17 (3 MARKS)

Key science skill

A 1300 kg car passes through an intersection at a speed of 36.0 km h^{-1}. The driver varies the application of the accelerator so that the net force in the direction of the car's motion varies as shown in the graph. The distance is measured from the intersection.

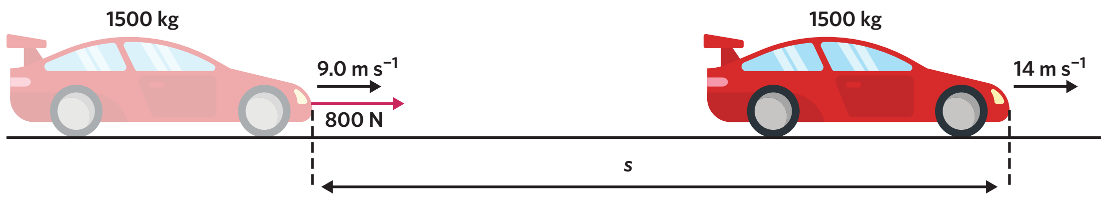


Calculate the speed of the car after it has travelled 60.0 m.

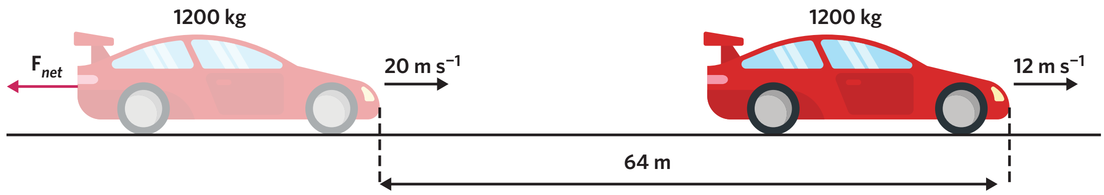
Question 18 (4 MARKS)

Two cars drive down a road.

a. One car, with a mass of 1500 kg, accelerates from a speed of 9.0 m s^{-1} to 14 m s^{-1} due to the application of a net force of magnitude 800 N. Calculate the distance over which the car accelerates. Use the concept of work and energy. 2 MARKS



b. The other car, with a mass of 1200 kg, slows from 20 m s^{-1} to 12 m s^{-1} due to the application of a constant braking force over a distance of 64 m. Calculate the magnitude of the net force applied to the car as it slows down. Use the concepts of work and energy. 2 MARKS



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Question 19 (4 MARKS)

Mikaela, Sergio and Liam are investigating work and kinetic energy. They measure the acceleration of a cart after a force has been applied using a ruler and a stopwatch. Mikaela suggests that it is important to repeat the measurement to reduce the effects of random error. Sergio agrees that they should repeat the measurement, but he suggests this will reduce the effects of systematic error. Liam suggests that repeating the measurement will reduce the absolute uncertainty of each measured value.

Key science skill

Evaluate each of these three claims.

FROM LESSON 12C

Question 20 (3 MARKS)

Genevieve (60.0 kg) is riding a bike (20.0 kg), and she increases her speed from 10.0 km h^{-1} to 15.0 km h^{-1} over 3.00 mins on a flat road. Calculate the power exerted by Genevieve. Ignore the effects of any frictional forces.

Question 21 (4 MARKS)

Brake tests for a new car are conducted where the same brake force is applied in each trial (controlled variable) for a car travelling at two different speeds. The distance to stop is measured.

	Initial speed (independent variable)	Distance to stop (dependent variable)
Trial A	5 m s^{-1}	2 m
Trial B	15 m s^{-1}	18 m

Explain why a car that is moving 3 times faster takes 9 times the distance to stop, given that the same braking force is applied. Use the concepts of work and energy in your explanation

Previous lessons

Question 22 (2 MARKS)

A 1200 kg car drives around a corner on a flat road, with a radius of 20 m, and maintains a speed of 4 m s^{-1}. Calculate the magnitude and direction of the net force on the car.

FROM LESSON 1E

Question 23 (2 MARKS)

An athlete throws a javelin 50 m, with an initial velocity of 28 m s^{-1} at 30° to the horizontal. Calculate the time it takes for the javelin to land.

FROM LESSON 1H

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2B Elastic and inelastic collisions


Image: Jacek Chabraszewski/Shutterstock.com

How many slaps does it take to cook a chicken?

Lesson 1I left us hungry for more after introducing momentum in collisions. Now, using our knowledge of kinetic energy, we can classify different types of collisions and gain an understanding of energy dissipation. Using the physics of collisions and conservation of energy, we can prepare a meal that is im-peck-able.

STUDY DESIGN DOT POINTS

- investigate and apply theoretically and practically the laws of energy and momentum conservation in isolated systems in one dimension
- analyse transformations of energy between kinetic energy, strain potential energy, gravitational potential energy and energy dissipated to the environment (considered as a combination of heat, sound and deformation of material):
  - kinetic energy at low speeds: $E_k = \frac{1}{2}mv^2$; elastic and inelastic collisions with reference to conservation of kinetic energy
  - strain potential energy: area under force-distance graph including ideal springs obeying Hooke's Law: $E_s = \frac{1}{2}k\Delta x^2$
  - gravitational potential energy: $E_g = mg\Delta h$ or from area under a force-distance graph and area under a field-distance graph multiplied by mass

2A 2B 2C 2D 2E

3.1.6.2 Elastic and inelastic collisions

3.1.9.2 Energy dissipation

ESSENTIAL PRIOR KNOWLEDGE

1I Momentum

2A Kinetic energy

See questions 24–25.

KEY TERMS AND DEFINITIONS

elastic collision a collision in which kinetic energy is conserved

inelastic collision a collision in which kinetic energy is not conserved

energy dissipation the transformation of useful energy into other forms of energy

FORMULAS

- **momentum**
  $p = mv$
- **kinetic energy**
  $KE = \frac{1}{2}mv^2$

Elastic and inelastic collisions 3.1.6.2

Collisions can be classified as elastic or inelastic. The difference between these collisions is whether kinetic energy is conserved or not.

How do we distinguish between elastic and inelastic collisions?

Momentum is always conserved in collisions. This means that the sum of the initial momentum of the objects involved in a collision is equal to the sum of the final momentum of the same objects after a collision (Figure 1).

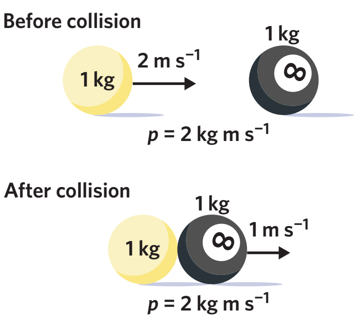

Figure 1 An example of the conservation of momentum

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MISCONCEPTION

'All collisions are elastic.'

In all collisions, momentum is conserved. Just because momentum is conserved, that does not mean that energy is. Both energy and momentum are only conserved in elastic collisions.

Elastic collisions

In **elastic collisions**, kinetic energy is conserved.

- This means that the total kinetic energy of the colliding objects before the collision is equal to the total kinetic energy of the objects after the collision.
- As in all collisions, momentum is also conserved.

Not many everyday collisions are elastic: true elastic collisions only occur at a subatomic level. However, collisions between very rigid objects like billiard balls are often close to elastic collisions.

Inelastic collisions

During **inelastic collisions**, kinetic energy is not conserved.

- This means that the total kinetic energy of the colliding objects before the collision is not equal to the total kinetic energy of the objects after the collision, despite momentum still being conserved.
- Since kinetic energy cannot be gained in a collision, the total kinetic energy after an inelastic collision will be less than before the collision. This is because the kinetic energy lost in the collision is transformed into other types of energy.

Most collisions in the real world are inelastic collisions, such as a car crash or football players tackling each other.

USEFUL TIP

Note that kinetic energy is not a vector quantity. No matter the direction objects are travelling before or after a collision, the kinetic energies of the individual objects can be added to find the total kinetic energy of the system.

STRATEGY

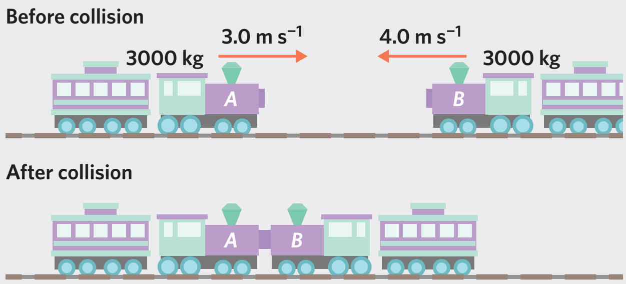
To solve common VCAA collision questions:

1. Calculate the total momentum of the system before collision.
2. Using the conservation of momentum and information provided, calculate the final velocity of the colliding objects.
3. Calculate the total kinetic energy before and after the collision.
4. By comparing the total kinetic energy before and after collision, determine if the collision conserved kinetic energy (elastic) or did not (inelastic).

WORKED EXAMPLE 1

Two 3000 kg trains, train A and train B, are moving toward each other head on. Before they collide, train A is travelling to the right at 3.0 m s^{-1} and train B is travelling to the left at 4.0 m s^{-1}.

After the collisions, the trains join together and move off as one. Take to the right as positive.



a. Calculate magnitude and direction of the final velocity of the joined cars

Step 1

Identify the known and unknown variables and the formula that relates these variables.

$m_A = 3000$ kg, $u_A = 3.0$ m s^{-1}, $m_B = 3000$ kg, $u_B = -4.0$ m s^{-1}, $p_i = ?$

$p = mv$

Continues →

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Step 2

Substitute values into the formula and solve for the total initial momentum.

Note that a negative value indicates the momentum is to the left.

$p_i = p_A + p_B$

$p_i = 3000 \times 3.0 + 3000 \times (-4.0)$

$p_i = -3000 \text{ kg m s}^{-1}$

Step 3

Identify the known and unknown variables and the formula that relates these variables.

Note that the final momentum is equal to the initial momentum by the conservation of momentum.

$p_f = p_i = -3000 \text{ kg m s}^{-1}$, $m_A = 3000$ kg, $m_B = 3000$ kg, $v_f = ?$

$p = mv$

Step 4

Substitute values into the formula and solve for the final velocity of the trains.

Note that a negative value indicates the velocity is to the left.

$p_f = (m_A + m_B) \times v_f$

$-3000 = (3000 + 3000) \times v_f$

$v_f = -0.50 \text{ m s}^{-1}$

---

b. Is the collision elastic or inelastic? Justify your answer with calculations.

Step 1

Identify the known and unknown variables and the formula that relates these variables.

$m_A = 3000$ kg, $u_A = 3.0 \text{ m s}^{-1}$, $m_B = 3000$ kg, $u_B = 4.0 \text{ m s}^{-1}$, $KE_i = ?$

$KE = \frac{1}{2}mv^2$

Step 2

Substitute values into the formula and solve for the total initial kinetic energy of the trains.

$KE_i = \frac{1}{2}m_A u_A{}^2 + \frac{1}{2}m_B u_B{}^2$

$KE_i = \frac{1}{2} \times 3000 \times 3.0^2 + \frac{1}{2} \times 3000 \times 4.0^2$

$KE_i = 3.75 \times 10^4$ J

Step 3

Identify the known and unknown variables and the formula that relates these variables.

$m_A = 3000$ kg, $m_B = 3000$ kg, $v_f = 0.50 \text{ m s}^{-1}$, $KE_f = ?$

$KE = \frac{1}{2}mv^2$

Step 4

Substitute values into the formula and solve for the total final kinetic energy of the trains.

$KE_f = \frac{1}{2}(m_A + m_B) \times v_f^2$

$KE_f = \frac{1}{2} \times (3000 + 3000) \times 0.50^2$

$KE_f = 750 = 7.5 \times 10^2$ J

Step 5

Compare the initial and final kinetic energies of the trains to determine if the collisions were elastic or inelastic.

Since $KE_i \neq KE_f$, it was an inelastic collision.

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PROGRESS QUESTIONS

Question 1

Select the row that best describes types of collisions.

	Collision	Momentum	Kinetic energy
A.	Elastic Inelastic	Conserved Conserved	Conserved Conserved
B.	Elastic Inelastic	Conserved Conserved	Conserved Not conserved
C.	Elastic Inelastic	Not conserved Conserved	Conserved Not conserved
D.	Elastic Inelastic	Conserved Conserved	Not conserved Conserved

Question 2

In a collision between two football players, kinetic energy is not conserved. Which of the following is not true?

A. The collision was elastic.

B. Momentum is conserved.

C. The collision was inelastic.

D. The final kinetic energy is less than the initial kinetic energy.

Energy dissipation 3.1.9.2

During collisions where kinetic energy is not conserved (inelastic collisions), the kinetic energy lost must be transformed into other forms of energy, according to the conservation of energy.

Where does energy in inelastic collisions go?

Energy dissipation occurs when the usable kinetic energy of an object is transformed into other forms. During inelastic collisions, the kinetic energy lost may be dissipated from the objects involved in the collision in the form of heat, sound, and the deformation of the objects themselves.[1,2]

Imagine a tennis ball bouncing along the floor (Figure 2).

- With each bounce the ball bounces to a lower height. This is the tennis ball losing kinetic energy.
- When the ball bounces, a sound is produced. The energy required to produce this sound comes from the kinetic energy of the ball.
- Additionally, there will be friction between the tennis ball and the ground, which generates heat. This heat energy is also transformed from the kinetic energy of the ball.
- Finally, with each bounce energy is transformed into the deformation of the tennis ball (changing its shape).
- Energy has not been destroyed. The kinetic energy of the ball has been dissipated as the energy is now in the form of sound and heat, which are generally considered unusable.

KEEN TO INVESTIGATE?

1 **How many slaps does it take to cook a chicken?**
Search YouTube: How many slaps does it take to cook a chicken?

2 **How does energy dissipation help cricket umpires?**
Search YouTube: Umpiring simplified: how does the hot spot function?

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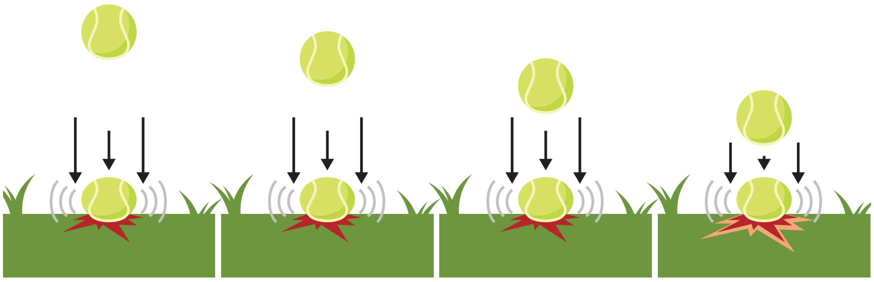

Figure 2 Kinetic energy dissipating from a tennis ball as it bounces on the ground

USEFUL TIP

To observe energy dissipation, we can rub our hands together. The kinetic energy of our hands will be transformed into heat energy due to friction.

PROGRESS QUESTIONS

Question 3

In a game of pool, the white ball initially has 3 J of kinetic energy. After it collides with the stationary black ball, both balls roll off with a combined total kinetic energy of 2 J. How much energy was dissipated?

A. 0 J **B.** 1 J **C.** 2 J **D.** 3 J

Question 4

Two football players collide during a game. Initially the total kinetic energy of both players was 4.0 kJ. During the collision, sound was produced. Is this collision elastic or inelastic?

A. Elastic, no kinetic energy is dissipated.

B. Inelastic, no kinetic energy is dissipated.

C. Elastic, kinetic energy is dissipated to sound.

D. Inelastic, kinetic energy is dissipated to sound.

Theory summary

- The total momentum is conserved in all collisions.
- Kinetic energy is conserved in elastic collisions.
- Kinetic energy is not conserved (decreases) in inelastic collisions.
- When energy is not conserved, it may be dissipated in the form of heat, sound or object deformation.

2B Questions

Mild 🌶 Medium 🌶🌶 Spicy 🌶🌶🌶

Deconstructed exam-style

Use the following information to answer questions 5–8.

Two whitetail bucks (male deers) are charging towards each other and collide head on during a territorial fight. Before the collision, buck *A* has a mass of 110 kg and is moving at 8.00 m s^{-1} to the right, while buck *B* is 130 kg and is moving at 5.00 m s^{-1} to the left. The total initial kinetic energy of the two bucks is 5.15×10^3 J. After the collision buck *A* and *B* are locked together.

Question 5 🌶 (1 MARK)

What is the magnitude and direction of the total momentum of the system before the bucks collide?

A. 2.30×10^2 kg m s^{-1} to the right

B. 4.90×10^2 kg m s^{-1} to the right

C. 1.53×10^3 kg m s^{-1} to the right

D. 3.12×10^3 kg m s^{-1} to the right

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Question 6 (1 MARK)

After the collision, when the two bucks are locked together, what is their speed?

A. 0.958 m s^{-1}

B. 1.76 m s^{-1}

C. 2.09 m s^{-1}

D. 13.0 m s^{-1}

Question 7 (1 MARK)

What is the final kinetic energy after the collision?

A. 1.10×10^2 J

B. 1.15×10^2 J

C. 2.20×10^2 J

D. 5.15×10^3 J

Question 8 (4 MARKS)

Is the collision elastic or inelastic? Justify your answer.

Exam-style

Question 9 (1 MARK)

Dodgem car *A* is travelling at 2.0 m s^{-1} and collides with a stationary dodgem car *B*. When they collide, the rubber around the base of the cars deforms and a thud can be heard. The collisions between the dodgems is best described as one where

A. both kinetic energy and momentum are conserved.

B. neither kinetic energy nor momentum is conserved.

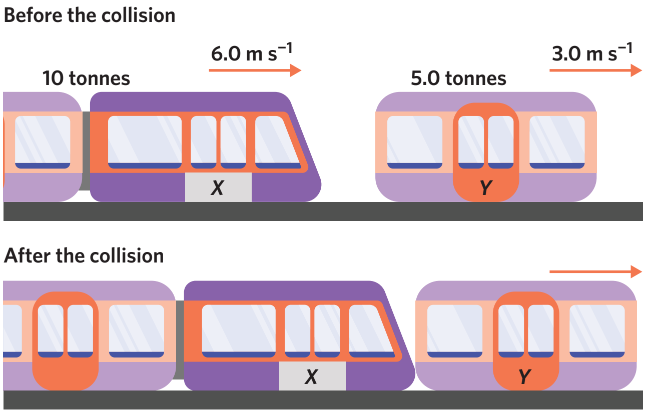
C. kinetic energy is not conserved but momentum is conserved.

D. kinetic energy is conserved but momentum is not conserved.

Adapted from VCAA 2018 exam Multiple choice Q9

Question 10 (7 MARKS)

Two runaway train cars collide and join together.



a. Calculate the final speed of the joined cars. — 3 MARKS

Adapted from VCAA 2018 exam Multiple choice Q8

b. Is the collision elastic or inelastic? Use calculations to support your answer. — 3 MARKS

c. State one potential source of energy dissipation in this collision. — 1 MARK

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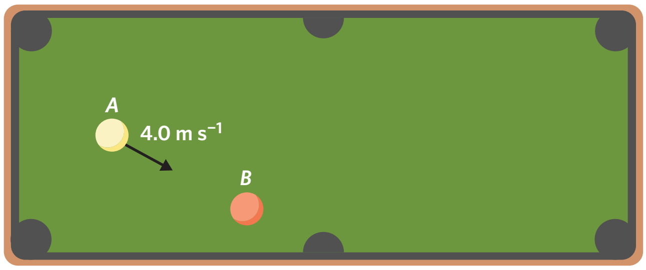
Question 11 (3 MARKS)

Two billiard balls collide during a game of pool. They each have a mass of 0.35 kg and ball *A* has an initial speed of 4.0 m s^{-1} before it hits the stationary ball *B*.

After the collision ball *A* is stationary. Find the final speed of ball *B* and determine, using calculations, if the collision is elastic or inelastic.



Question 12 (8 MARKS)

A group of students are dropping a tennis ball on the floor of their classroom and recording the height of several successive bounces.

They obtain the following data points with an uncertainty of ± 0.05 m.

Bounce	1	2	3	4
Height (m)	1.20	0.78	0.49	0.31

a. *Key science skill*
Use the data set to plot bounce height against the number of bounces. Be sure to include: 4 MARKS

- axis labels and units
- an appropriate scale
- error bars

FROM LESSON 12D

b. Explain why the ball doesn't return to the same height after each bounce. 2 MARKS

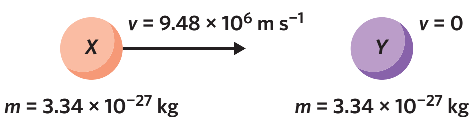
c. *Key science skill*
One student suggests that they repeat the experiment again and average their results from both trails. What effect will this have on the accuracy of the data and why? 2 MARKS

FROM LESSON 12C

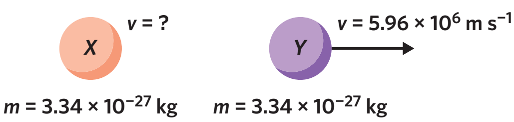
Question 13 (10 MARKS)

Sadie designs a computer simulation program as part of her practical investigation into the physics of particle collisions. She simulates colliding particles, both of mass 3.34×10^{-27} kg. Particle *X* travels at 9.48×10^{6} m s^{-1} towards particle *Y* which is initially stationary. After the collision, Particle *Y* moves to the right at 5.96×10^{6} m s^{-1}.

Before collision



After collision



a. Calculate the magnitude and direction of the velocity of particle *X* after the collision. 4 MARKS

b. Show that this collision is inelastic. 3 MARKS

c. Does this violate the law of conservation of energy? Justify your answer. 3 MARKS

Adapted from VCAA 2020 exam Short answer Q10

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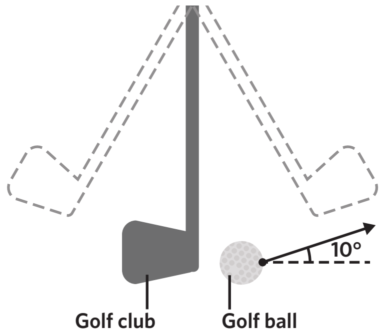
Question 14 🌶🌶🌶 (4 MARKS)

The behaviour of a golf ball and the club used to strike it is being investigated. Treat the impact as an elastic collision between the head of the golf club and the golf ball.

The following measurements are recorded.

Mass of golf ball	48 g
Initial speed of golf club head	30.00 m s^{-1}
Final speed of golf club head	24.74 m s^{-1}
Final speed of golf ball	54.74 m s^{-1}



Given that the golf ball was stationary before being hit, calculate the mass of the golf club head. Give your answer in grams.

Adapted from VCAA 2019 NHT exam Short answer Q7c

Previous lessons

Question 15 🌶 (2 MARKS)

A ball of mass 0.40 kg is attached to a string of length 0.75 m and spun horizontally on a frictionless surface. The string will break if the tension force is greater than 12 N. The speed of the ball is gradually increased. What is the speed of the ball when the string breaks?

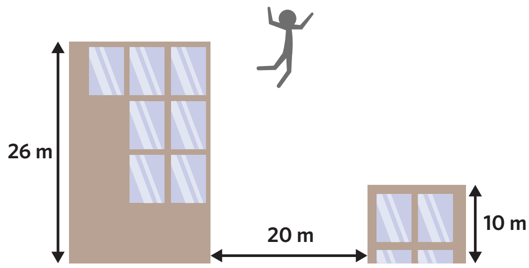
FROM LESSON 1E

Question 16 🌶🌶 (2 MARKS)

Jim is jumping between buildings in his role as a stunt performer. He jumps a 20 m gap from a building that is 26 m tall onto a building that is 10 m tall. He jumps with an initial velocity of 17 m s^{-1} horizontally to the right. It takes him 1.8 seconds to fall to a height of 10 m.

Will Jim make the jump by landing on the 10 m tall building? Use calculations to support your answer.

FROM LESSON 1H



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2C Gravitational potential energy

Image: Doug Lemke/Shutterstock.com

How do roller coaster carts operate without an engine or power source?

The thrill of a roller coaster ride is almost as exciting as the physics behind its operation. After being pulled to the top of a big hill, the gravitational potential energy (GPE) of the cart is converted into kinetic energy (KE). So we don't feel out of the loop, this lesson will explore the concepts of gravitational potential energy and conservation of energy.

STUDY DESIGN DOT POINT

- analyse transformations of energy between kinetic energy, elastic potential energy, gravitational potential energy and energy dissipated to the environment (considered as a combination of heat, sound and deformation of material):
  - kinetic energy at low speeds: $E_k = \frac{1}{2}mv^2$; elastic and inelastic collisions with reference to conservation of kinetic energy
  - strain potential energy: area under force-distance graph including ideal springs obeying Hooke's Law: $E_s = \frac{1}{2}m\Delta x^2$
  - gravitational potential energy: $E_g = mg\Delta h$ or from area under a force-distance graph and area under a field-distance graph multiplied by mass

2A 2B 2C 2D 2E

3.1.9.3 Gravitational potential energy

3.1.9.4 Conservation of energy

KEY TERMS AND DEFINITIONS

gravitational potential energy (GPE) the stored energy associated with the position of an object in a gravitational field

FORMULAS

- **kinetic energy** $KE = \frac{1}{2}mv^2$
- **work** $W = Fs$
- **gravitational potential energy** $\Delta GPE = mg\Delta h$

ESSENTIAL PRIOR KNOWLEDGE

2A Work

2A Kinetic energy

See questions 26–27.

Gravitational potential energy 3.1.9.3

Gravitational potential energy (GPE) represents an object's potential to do work due to its height in a gravitational field. The higher the object is, the more gravitational potential energy it has.[1] We can calculate the change in gravitational potential energy for an object which changes its height within a gravitational field.

KEEN TO INVESTIGATE?

[1] **How fast do you fall from space?** Search YouTube: I jumped from space (world record supersonic freefall)

How can we calculate gravitational potential energy?

Recall from Lesson 2A that work is done whenever a force moves an object over a distance, such as the force due to gravity acting on a falling apple. Work can be calculated using the equation $W = \Delta E = Fs$, or by calculating the area under a force-distance graph.

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USEFUL TIP

Even though energy is a scalar, we still need to be consistent with our sign convention.

- If an object is gaining energy then this change in energy should be positive.
- If an object is losing energy then this change in energy should be negative.

For example, if an object is losing GPE but gaining KE then these should have opposite signs. This is particularly important when using conservation of energy to calculate the velocity of an object.

For a uniform gravitational field, the force due to gravity acting on a given object is constant. Figure 1 shows a force-height graph for an object moving in a uniform gravitational field of strength 9.8 N kg^{-1}. It's important to note that:

- The force due to gravity remains constant ($F = mg$), so the graph is a horizontal line.
- The shaded area represents the work done, or the change in gravitational potential energy, $W = \Delta GPE = Fs$, between 1 m and 8 m.
- Work is only done on or by the gravitational field when the object changes its height. The change in height of the object is $\Delta h = h_f - h_i$:
  - If the object increases its height, $\Delta h > 0$, then the object gains GPE.
  - If the object decreases its height, $\Delta h < 0$, then the object loses GPE.
- Since the area under the graph is a rectangle, we can multiply the force, mg, by the change in height, Δh, to get the change in gravitational potential energy.

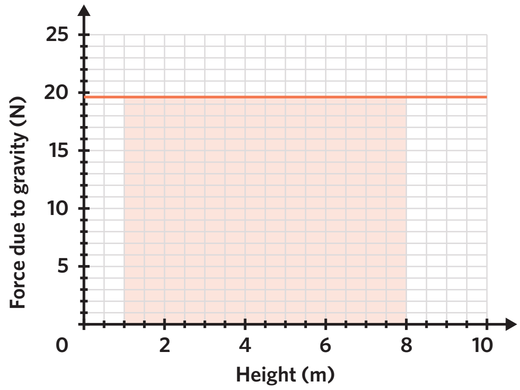


Figure 1 A force-height graph for an object in a uniform gravitational field.

FORMULA

$$\Delta GPE = mg\Delta h$$

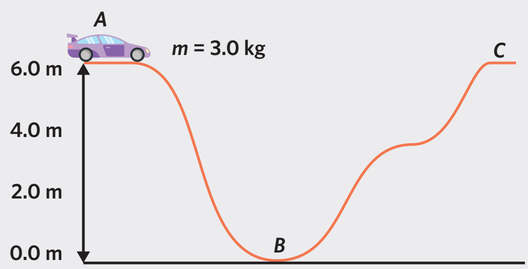
ΔGPE = change in gravitational potential energy (J)
m = mass (kg)
g = acceleration due to gravity (m s^{-2})
Δh = change in height (m)

USEFUL TIP

Note that the VCE Physics Study Design uses the abbreviation E_g for gravitational potential energy.

WORKED EXAMPLE 1

A 3.0 kg toy car is released from the top of a track with an initial height of 6.0 m, as shown in the diagram. Take the acceleration due to gravity to be 9.8 m s^{-2} downwards. Assume friction is negligible.



a. Calculate the change in gravitational potential energy of the toy car from point A to point B.

Step 1

Identify the known and unknown variables and the formula that relates them.

Note that the initial height is position A, and the final height is position B.

$h_i = 6.0$ m, $h_f = 0.0$ m, $m = 3.0$ kg, $g = 9.8$ m s^{-2}, $\Delta GPE = ?$

$\Delta GPE = mg\Delta h$

Continues →

Step 2

Substitute in the values and solve for the change in gravitational potential energy.

$\Delta GPE = 3.0 \times 9.8 \times (0.0 - 6.0)$

$\Delta GPE = -1.76 \times 10^2 = -1.8 \times 10^2$ J

Note that since the height decreased, the toy car lost GPE.

b. What is the change in gravitational potential energy of the toy car from point *A* to point *C*?

Step 1

Identify the known and unknown variables and the formula that relates them.

$h_i = 6.0$ m, $h_f = 6.0$ m, $m = 3.0$ kg, $g = 9.8$ m s^{-2}, $\Delta GPE = ?$

$\Delta GPE = mg\Delta h$

Step 2

Substitute in the values and solve for the change in gravitational potential energy.

$\Delta GPE = 3 \times 9.8 \times (6.0 - 6.0)$

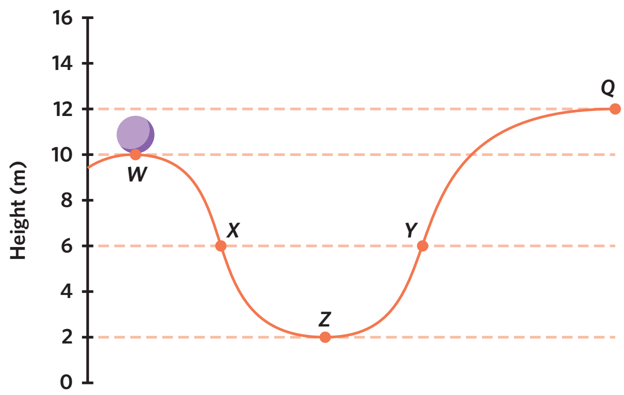
$\Delta GPE = 0.0$ J

Note that as position *A* and position *C* are at the same height there is no change in GPE between them.

PROGRESS QUESTIONS

Use the following information to answer questions 1–3.

A 15 kg ball, which is initially at rest at point *W*, rolls along the frictionless track shown in the diagram.



Question 1

Which of the following calculations could be used to find the change in gravitational potential energy as the ball rolls from point *W* to point *X*?

A. $15 \times 6 \times g$

B. $15 \times 10 \times g$

C. $15 \times (6 - 10) \times g$

D. $15 \times (2 - 10) \times g$

Question 2

At which two points does the ball have the same gravitational potential energy?

A. *X* and *Y* **B.** *X* and *Z* **C.** *Y* and *Z* **D.** *W* and *Q*

Question 3

What is the change in gravitational potential energy as the ball rolls from point *X* to point *Z*?

A. -2.9×10^2 J **B.** -5.9×10^2 J **C.** -8.8×10^2 J **D.** -1.5×10^3 J

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Conservation of energy 3.1.9.4

Energy is always conserved. This means that energy can be transformed from one type to another but can never be created nor destroyed. Hence, the total energy in a system will remain constant.

How do we analyse transformations of energy?

To find the total energy of a system, we must add together all the different types of energy in the system.

Consider the ball in Figure 2, that starts off stationary then rolls down a hill (take the bottom of the hill as the position with zero GPE):

- When the ball is at the top of the hill (Point *A*), all the ball's energy is in GPE.
- As the ball rolls down the hill, GPE is transformed to KE and the ball speeds up.
- When the ball is at the bottom of the hill (Point *B*), all the ball's energy is in KE.
- If the ball then rolls up a second hill, some of its KE would get transformed back to GPE as it gains height and loses speed.

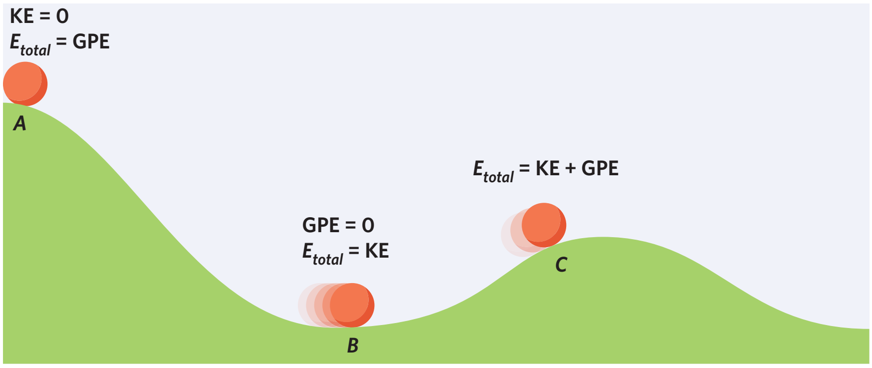

Figure 2 How GPE and KE change as a ball rolls down a hill.

This means that at any given point, the total energy of the ball remains constant (Figure 3), and is given by:

$$E_{total} = KE + GPE$$

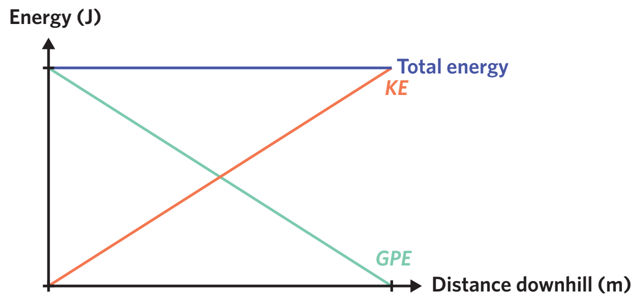

Figure 3 Graph of how energy is transformed as a ball rolls down a hill from point *A* to point *B*

Since energy is conserved, we can equate the initial and final state giving us:

$$KE_i + GPE_i = KE_f + GPE_f$$

It's important to note that one or more of these terms are often equal to zero. For example, when a ball starts off stationary and rolls to the bottom of a hill, this equation simplifies to $GPE_i = KE_f$

Substituting the formulas for gravitational potential energy and kinetic energy, gives us:

$$\frac{1}{2}mu^2 + mgh_i = \frac{1}{2}mv^2 + mgh_f$$

When finding GPE_i or GPE_f we are finding the GPE at a particular point, so we can use the formulae $GPE = mgh$, where h is the height taken from a reference point.

USEFUL TIP

While the ground is usually used as a reference point for zero GPE ($h = 0$), other reference points can be used – like the top of a table (Figure 4). However, the reference point must remain consistent and all heights have to be calculated from the same reference point.

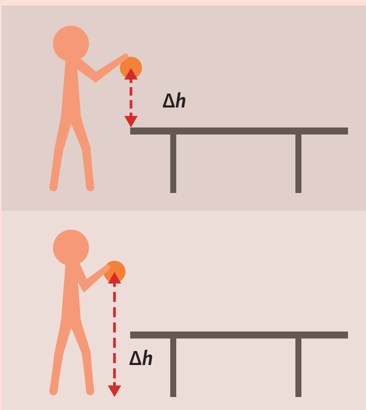

Figure 4 Defining the points of reference for change in height

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WORKED EXAMPLE 2

A 990 kg car starts at rest from the top of a 50 m hill. Take the bottom of the hill as the position with zero GPE.

a. Calculate the gravitational potential energy of the car when it's at the top of the hill.

Step 1

Identify the known and unknown variables and the formula that relates them.

$m = 990$ kg, $g = 9.8$ m s^{-2}, $h = 50$ m

$GPE_i = mgh$

Step 2

Substitute values into the formula and solve for the GPE of the car.

$GPE_i = 990 \times 9.8 \times 50$

$GPE_i = 4.85 \times 10^5 = 4.9 \times 10^5$ J

b. Calculate the kinetic energy of the car when it is at the bottom of the hill.

Step 1

Identify the known and unknown variables and the formula that relates them.

Note that due to conservation of energy, the GPE of the car at the top of the hill is equal to the kinetic energy of the car at the bottom of the hill.

$GPE_i = 4.85 \times 10^5$ J, $KE_f = ?$

$GPE_i = KE_f$

Step 2

Substitute values into the formula and solve for the kinetic energy of the car.

$KE_f = 4.85 \times 10^5 = 4.9 \times 10^5$ J

c. Calculate the speed of the car when it is at the bottom of the hill.

Step 1

Identify the known and unknown variables and the formula that relates them.

$KE_f = 4.85 \times 10^5$ J, $m = 990$ kg, $v = ?$

$KE = \frac{1}{2}mv^2$

Step 2

Substitute values into the formula and solve for the speed of the car.

$4.85 \times 10^5 = \frac{1}{2} \times 990 \times v^2$

$v = 31.3 = 31$ m s^{-1}

USEFUL TIP

If gravitational potential energy and kinetic energy are the only relevant types of energy in a question, the final speed of the object can be calculated using:

$$v = \sqrt{u^2 - 2g\Delta h}$$

In our examples, we assume that all of the energy is transformed from GPE to KE and vice versa. However, in reality no energy transformation is 100% efficient and some energy will always be transformed into other types, like thermal energy (heat), sound energy, and deformation of the material.[2] This is called energy dissipation, and it does not violate the conservation of energy principle.

KEEN TO INVESTIGATE?

[2] **How is energy conserved?**
Search: Energy skate park simulation

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PROGRESS QUESTIONS

Question 4

A ball with 12 J of GPE is initially at rest at the top of a hill. How much kinetic energy will the ball have after it has rolled to the bottom? Take the bottom of the hill as the position with zero GPE.

A. 0 J **B.** 6 J **C.** 12 J **D.** 24 J

Question 5

A roller coaster cart is initially at the top of a hill with 5 kJ of kinetic energy and 58.8 kJ of GPE. How much KE will the cart have at the bottom of the hill? Take the bottom of the hill as the position with zero GPE.

A. 5 kJ **B.** 53.8 kJ **C.** 58.8 kJ **D.** 63.8 kJ

Question 6

A car of mass 800 kg is stationary at the top of a 30 m tall hill. The driver takes the hand brake off and rolls to the bottom of the hill. Calculate the car's final speed at the bottom.

A. 17 m s^{-1} **B.** 24 m s^{-1} **C.** 27 m s^{-1} **D.** 89 m s^{-1}

Theory summary

- A change in gravitational potential energy can be calculated from
  - the area under a gravitational force-height graph.
  - the equation $\Delta GPE = mg\Delta h$ where $\Delta h = h_f - h_i$.
- Energy is always conserved.
  - The initial energy equals the final energy of the system. For a system involving only kinetic energy and gravitational potential energy, this gives us: $KE_i + GPE_i = KE_f + GPE_f$
  - One or more of these terms are often equal to zero.
- In the real world, energy is often transformed into other forms such as thermal energy and sound. This is called energy dissipation.

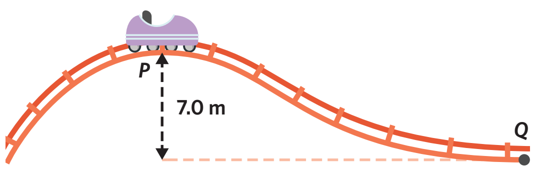
2C Questions

Mild Medium Spicy

Deconstructed exam-style

Use the following information to answer questions 7–9.

A roller coaster cart of mass 100 kg, is on the track shown. It starts from rest at point *P* before rolling down to point *Q*. Take point *Q* as the position with zero GPE.



Question 7 (1 MARK)

What is the gravitational potential energy of the cart at point *P*?

A. 0 J

B. 7.0×10^2 J

C. 6.9×10^3 J

D. 7.2×10^3 J

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Question 8 (1 MARK)

What is the kinetic energy of the car at point Q?

A. 0 J

B. 7.0×10^2 J

C. 6.9×10^3 J

D. 7.2×10^3 J

Question 9 (3 MARKS)

Calculate the speed of the cart at point Q.

Adapted from VCAA 2017 exam Short answer Q8b

Exam-style

Question 10 (1 MARK)

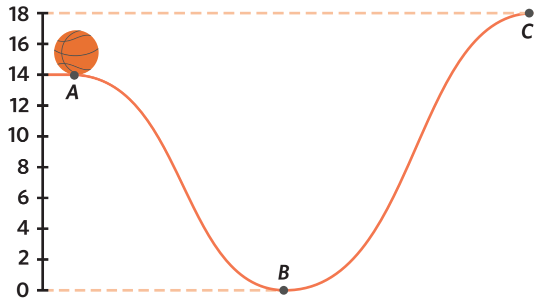
Assume the basketball starts from rest and that there is no friction. Which of the following options best explains why the basketball will never reach point C?

A. The horizontal distance to point C is too far.

B. It would violate the law of conservation of mass.

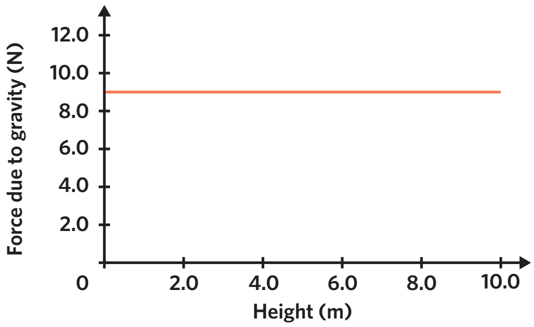
C. The ball does not have enough mass to make it to point C.

D. The GPE at point C is greater than the initial GPE of the ball.



Question 11 (3 MARKS)

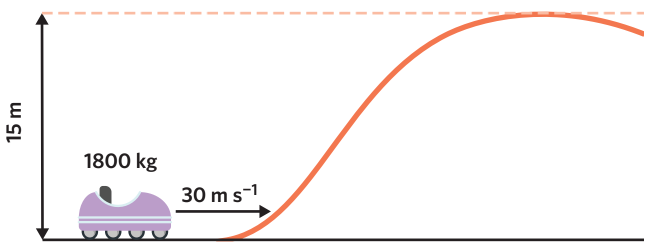
The graph shows the force-height graph for a small rock being launched from a catapult.



a. Determine the change in GPE as the rock is launched from the ground to a height of 8 m. 1 MARK

b. Calculate the mass of the rock. 2 MARKS

Question 12 (6 MARKS)



A 1800 kg roller coaster car is travelling at 30 m s^{-1} at the bottom of a 15 m hill. Assume there is no friction acting on the car and take the bottom of the hill as the position with zero GPE.

a. Calculate the kinetic energy of the car at the bottom of the hill. 2 MARKS

b. Calculate the gravitational potential energy of the car when it reaches the top of the hill. 2 MARKS

c. Calculate the speed the car is travelling when it reaches the top of the hill. 2 MARKS

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Question 13 (8 MARKS)

Students drop a 0.50 kg ball from rest at varying heights and record the final kinetic energy of the ball just before it hits the ground. Take the ground as the position with zero GPE.

a. Use the mass of the ball and the height from which it was dropped to calculate the values for the initial gravitational potential energy. 2 MARKS

Height from which the ball is dropped (m)	Initial gravitational potential energy (J)	Final kinetic energy (J)
2		9.5
4		18
6		27
8		35

b. *Key science skill*

Draw a graph of the final kinetic energy on the vertical axis versus the initial gravitational potential energy on the horizontal axis using the data from the table in part **a**. On your graph include: 4 MARKS

- axes labels and appropriate scale
- units on each axis
- a line of best fit

FROM LESSON 12D

c. Was any energy dissipated as the ball fell? Justify your answer. 2 MARKS

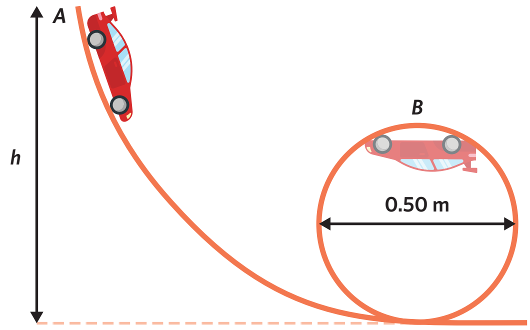
Question 14 (3 MARKS)

A 300 g toy car performs a loop in the set up shown.

The car starts from rest at point *A* and travels along the track without any air resistance or frictional forces. The radius of the loop is 0.25 m. When the car reaches point *B* it is travelling at a speed of 4.0 m s^{-1}.

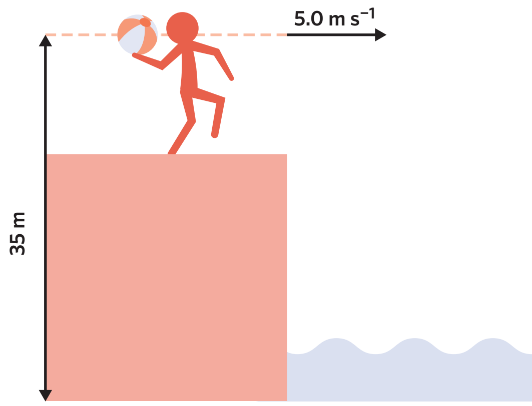
Calculate the value of *h*. Show your working.

Adapted from VCAA 2019 exam Short answer Q8a



Question 15 (6 MARKS)

Tom throws a 0.50 kg ball at 5.0 m s^{-1} horizontally from a height of 35 m into a lake. Take the gravitational potential energy at the water to be zero. Take the water as the position with zero GPE.



a. Calculate the total energy of the ball when it is thrown. 2 MARKS

b. What is the kinetic energy of the ball when it impacts the water? 2 MARKS

c. What is the speed of the ball when it is 10 m above the water? 2 MARKS

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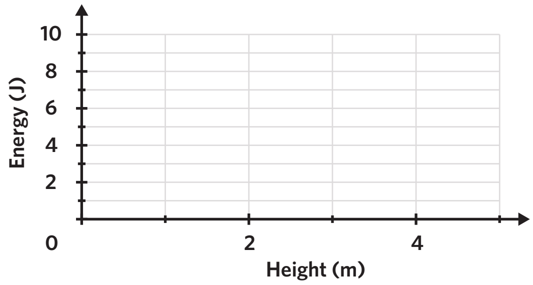
Question 16 🌶🌶 (3 MARKS)

A probe of mass 1.5 kg, which is initially at rest, drops from a height of 4.0 m above the surface of the Moon. Take the Moon to have a gravitational field strength, g, of 1.5 m s^{-2}.

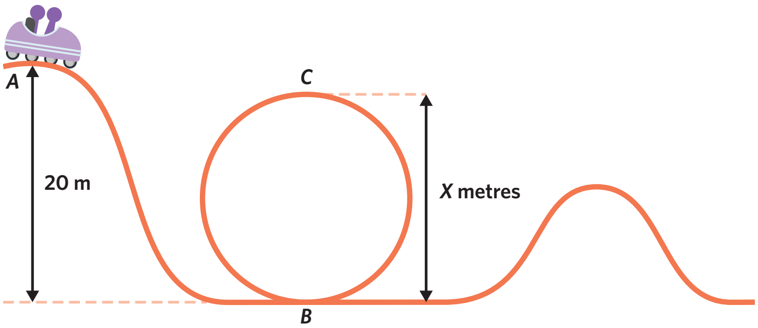
Using the axis, sketch a graph of the gravitational potential energy, kinetic energy, and total energy as a function of height above the Moon's surface. Take the surface of the Moon as the position with zero GPE.

FROM LESSON 12D



Question 17 (5 MARKS)

Maria and Robert are about to go on a roller coaster ride that has a loop-the-loop. The radius of the loop, CB, is r.



The cart starts from rest at the highest point, A, which is 20 m above point B. Assume that there is negligible friction between the cart and the track.

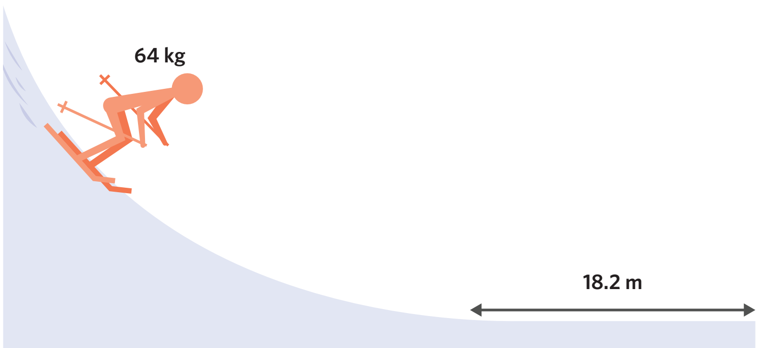
If we were to consider the forces acting on the cart, the condition for the cart to just remain in contact with the track at point C is given by $v^2 = rg$.

a. What is the speed of the cart at point B? 🌶🌶 2 MARKS

b. What is the maximum height of the loop (X metres) that will ensure that the cart stays in contact with the track at point C? 🌶🌶🌶 3 MARKS

Adapted from VCAA 2021 exam Short answer Q9

Question 18 (5 MARKS)



Lucie, a 64 kg skier rides down a frictionless mountain side until she reaches a dirt patch at the bottom. The dirt slows Lucie to a complete stop with a force of 560 N applied over 18.2 m.

a. What is the height of the hill Lucie skied down? 🌶🌶🌶 3 MARKS

b. Is energy conserved when moving over the dirt patch? Explain your answer. 🌶🌶 2 MARKS

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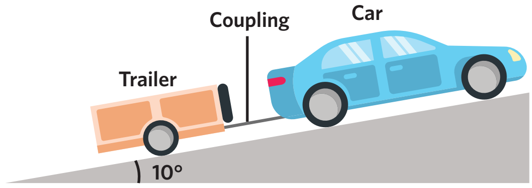
Question 19 🌶🌶🌶 (1 MARK)

A car is driving up a uniform slope with a trailer attached, as shown. The slope is angled 10° to the horizontal. The trailer has a mass of 250 kg and the car has a mass of 810 kg. Ignore friction.



What is the gravitational potential energy gained by the car and trailer when they have travelled 90 m along the slope?

A. 1.24×10^5 J

B. 1.62×10^5 J

C. 7.14×10^5 J

D. 9.35×10^5 J

Adapted from VCAA 2021 NHT exam Short answer Q8c

Previous lessons

Question 20 (4 MARKS)

A motorcycle rider drives around a banked circular track which is angled at 25° to the horizontal. The rider's circular path has a radius of 50 m.

a. Calculate the speed they should drive at so that they do not experience a sideways frictional force while maintaining this path. 🌶 2 MARKS

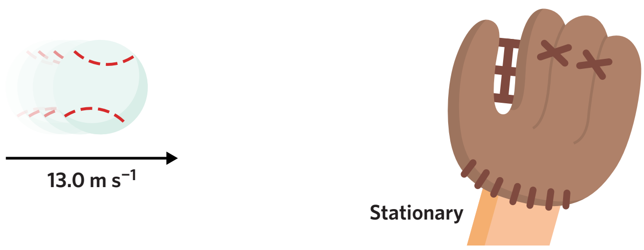
b. Calculate the required angle of the banked track for there to be no sideways frictional force if the rider drives at 30 m s^{-1} along the same circular path. 🌶 2 MARKS

FROM LESSON 1F

Question 21 (3 MARKS)

A baseball fielder attempts to catch a ball. The ball has a mass of 0.250 kg.

Speed of ball before collision	13.0 m s^{-1}
Speed of ball after collision	0 m s^{-1}
Time in contact with the ball	0.150 s



a. Show that the magnitude of the impulse given by the glove to the ball is 3.25 kg m s^{-1}. 🌶 1 MARK

b. Calculate the magnitude of the average force by the glove on the ball during the collision. Show your working. 🌶🌶 2 MARKS

FROM LESSON 1I

Adapted from VCAA 2019 NHT exam Short answer Q7

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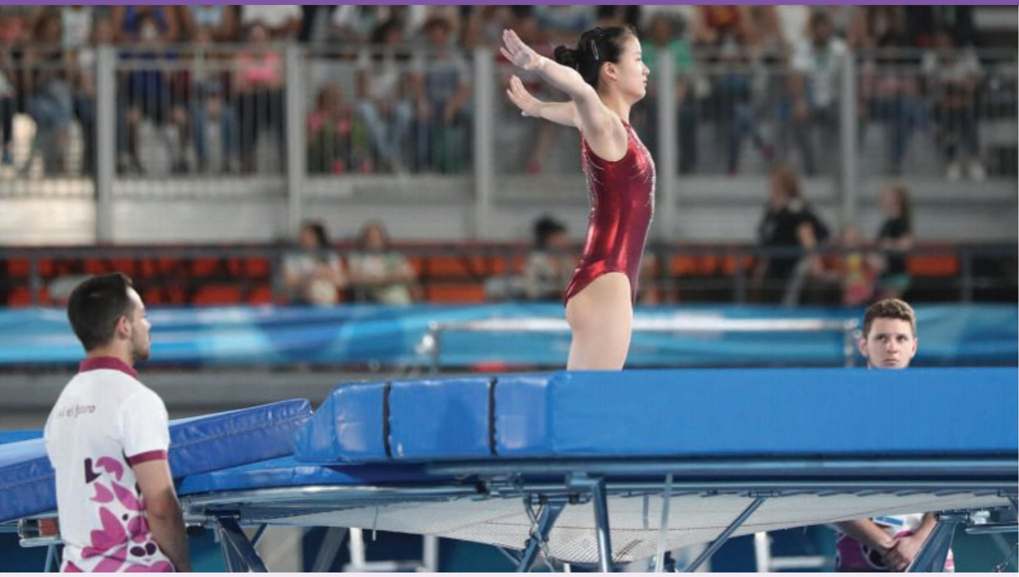
2D Strain potential energy



How can we calculate the force that the trampoline applies on a gymnast?

When we are thinking about forces produced by springs, Hooke's law springs to mind! A spring will always produce a force to return to its natural length. The graph of this force plotted against the displacement of the spring can be used to calculate strain potential energy. Strain potential energy will be used in conservation of energy calculations alongside gravitational potential energy and kinetic energy.

STUDY DESIGN DOT POINT

- analyse transformations of energy between kinetic energy, strain potential energy, gravitational potential energy and energy dissipated to the environment (considered as a combination of heat, sound and deformation of material):
  - kinetic energy at low speeds: $E_k = \frac{1}{2}mv^2$; elastic and inelastic collisions with reference to conservation of kinetic energy
  - strain potential energy: area under force-distance graph including ideal springs obeying Hooke's Law: $E_s = \frac{1}{2}k\Delta x^2$
  - gravitational potential energy: $E_g = mg\Delta h$ or from area under a force-distance graph and area under a field-distance graph multiplied by mass

2A 2B 2C **2D** 2E

3.1.9.5 Hooke's law

3.1.9.6 Strain potential energy

ESSENTIAL PRIOR KNOWLEDGE

1A Displacement
2A Work
2A Kinetic energy
2C Gravitational potential energy
See questions 28–31.

KEY TERMS AND DEFINITIONS

ideal spring a spring that obeys Hooke's law, such that the force it exerts is proportional to its change in length

compression (spring) the process of decreasing an object's length

extension the process of increasing an object's length

natural length the length of a spring when no external forces are acting on it

spring constant a value that describes the stiffness of a spring

strain potential energy (SPE) the energy stored by the deformation of an object; also known as elastic potential energy or spring potential energy

FORMULAS

- **Hooke's law**
  $F_s = -k\Delta x$
- **strain potential energy**
  $SPE = \frac{1}{2}k(\Delta x)^2$

Hooke's law 3.1.9.5

Hooke's law describes the linear relationship between the force and displacement of an **ideal spring**. The spring constant, k, represents the stiffness of a spring and determines the amount of force needed to compress or extend a spring.

How can we apply Hooke's law to an ideal spring?

Hooke's law is used to calculate the restoring force that an ideal spring applies when it is **compressed** or **extended**.[1]

KEEN TO INVESTIGATE?

[1] How can we calculate the spring force in a non-ideal spring?
Search: Non-ideal spring forces

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FORMULA

$F_s = -k\Delta x$

F_s = spring restoring force (N)
k = spring constant (N m^{-1})
Δx = displacement from natural position (m)

MISCONCEPTION

'The variable Δx represents the length of the spring.'

The variable Δx refers to the displacement of the spring, that is how the position of the string has changed.

USEFUL TIP

In VCE Physics it is common to deal with the magnitudes of forces, in which case the negative sign in Hooke's law can be excluded.

A spring will always produce a force in the opposite direction to its displacement to return to its **natural length**, which is represented by the negative sign in the formula. For this reason it is referred to as a spring restoring force. When a spring is at its natural position ($x = 0$) it will not exert a force ($F_s = -k\Delta x = 0$).

The **spring constant** is a property of each spring and it is equal to the gradient of a spring's force-displacement graph (Figure 1). Many elastic objects besides springs may obey Hooke's law, but springs will be the most common example in VCE Physics.

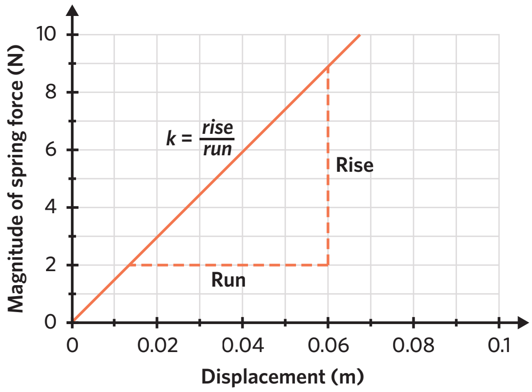


Figure 1 The magnitude of the spring's restoring force against displacement of the spring

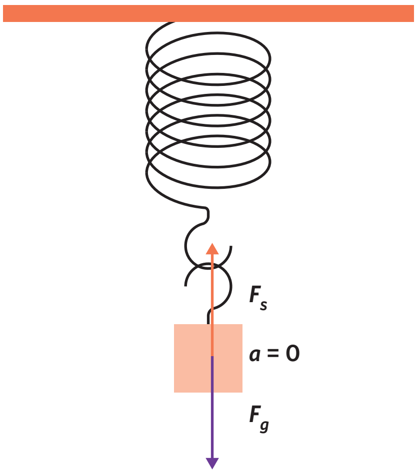


Figure 2 A mass on a spring in its equilibrium position where its acceleration is zero

Equilibrium involving springs

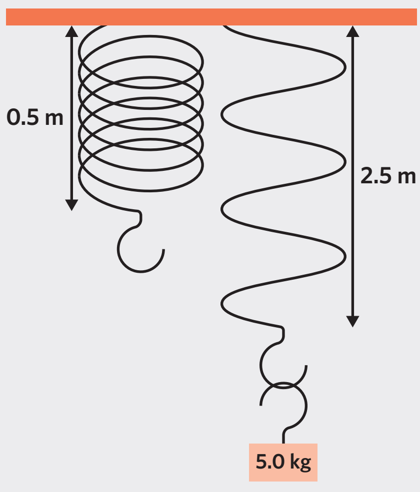
For an object attached to a vertical spring:

- When the force due to gravity acting on the object has the same magnitude as the restoring force of the spring, $mg = k\Delta x$, the net force on the object is zero (Figure 2). This is often called the equilibrium position, as this is the point at which the mass is not accelerating.
- When dropped from a height, the equilibrium position is where the object reaches its maximum speed. This is the only position where an object can remain stationary over time.

Note that if the velocity of a mass is zero, it does not necessarily mean that the spring is in equilibrium. This will be covered in more detail in Lesson 2E.

WORKED EXAMPLE 1

To determine the spring constant of a spring, students attached a block with a mass of 5.0 kg to a hanging spring. The left hand side of the diagram shows the uncompressed spring and the right hand side of the diagram shows the spring with the block hanging on the spring. Assume the block is not accelerating.



Continues →

a. What is the magnitude of the displacement, Δx, of the spring from its natural state?

Step 1

Identify known and unknown variables and write down the formula that relates these variables.

$L_{natural} = 0.50$ m, $L_{stretched} = 2.5$ m, $\Delta x = ?$

$\Delta x = L_{stretched} - L_{natural}$

Step 2

Substitute values into the formula and solve for the displacement of the spring.

$\Delta x = 2.5 - 0.50$

$\Delta x = 2.0$ m

---

b. Find the spring constant, k.

Step 1

Identify known and unknown variables and write down the formula that relates these variables.

Note that since the mass is in equilibrium, the gravitational force is equal to the spring force.

$m = 5.0$ kg, $\Delta x = 2.0$ m, $k = ?$

$F_g = F_s$

$mg = k\Delta x$

Step 2

Substitute values into the formula and solve for the spring constant.

$5.0 \times 9.8 = k \times 2.0$

$k = \frac{5.0 \times 9.8}{2.0} = 24.5 = 25 \text{ N m}^{-1}$

PROGRESS QUESTIONS

Question 1

The shape of a force-displacement graph for an ideal spring is

A. hyperbolic.

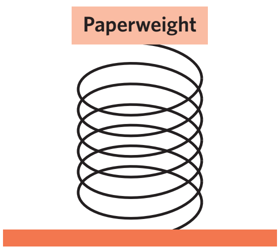
B. exponential.

C. linear and diagonal.

D. linear and horizontal.

Question 2

A spring is being compressed by a paperweight resting on top of it.



If only the mass of the paperweight, m, was known, which equation would best be used to calculate the magnitude of the spring's restoring force?

A. $F_s = mg$

B. $F_s = k\Delta x$

C. $F_s = \frac{1}{2}k(\Delta x)^2$

D. $F_s = mgk\Delta x$

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Strain potential energy 3.1.9.6

Strain potential energy is equal to the area under a force-displacement graph for a spring and it represents the energy that is stored in the spring.

How can we analyse the energy stored in a spring?

Recall from Lesson 2A, that work is done whenever a force is applied to an object in a parallel direction to its motion. It is equal to the area under a force-displacement graph.

- As the spring force always acts parallel to the direction it is displaced, the area under a spring force-displacement graph is the work done on the spring at that displacement.
- This is equivalent to the strain potential energy stored in the spring (Figure 3).

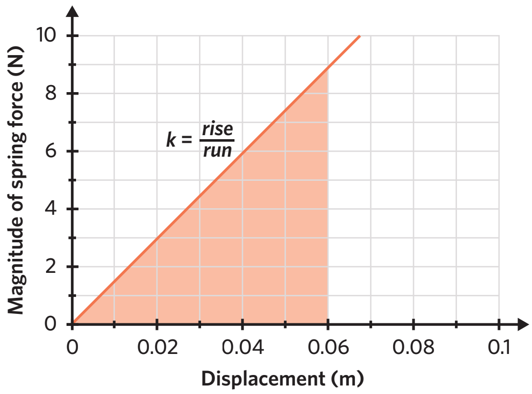

Figure 3 The shaded area shows the strain potential energy when the displacement of the spring is 0.06 m.

USEFUL TIP

When calculating the area underneath a force-displacement graph to find the strain potential energy, ensure that the labels and units of the axes are displacement in 'm' and spring force in 'N'. Otherwise, the value for strain potential energy will not be in the unit of 'J'.

We also know from Lesson 2A that the work done is equal to the change in energy of an object caused by a force.

- Strain potential energy represents the spring's potential to do work as it returns to its natural length.
- The area under the force-displacement graph for a spring will give us the change in strain potential energy ($W = \Delta SPE$).
- When the spring is stretched or compressed from its natural length, the area under the graph is a triangle. It can be calculated using $\frac{1}{2} \times base \times height = \frac{1}{2} \times \Delta x \times F_s$.
- By substituting $k\Delta x$ in the place of F_s, we arrive at the following formula for the strain potential energy:

USEFUL TIP

The VCE Physics study design uses the abbreviation E_s for strain potential energy. For the purposes of making an obvious distinction between different forms of energy, this book will usually use SPE. Strain potential energy may also be referred to as spring potential energy or elastic potential energy.

FORMULA

$$SPE = \frac{1}{2}k(\Delta x)^2$$

SPE = strain potential energy (J)
k = spring constant (N m^{-1})
Δx = displacement from natural position (m)

Conservation of energy

Recall from Lesson 2A, the total mechanical energy of a closed system is always conserved if there is no form of energy lost. This means we can equate the total energy of the initial state of a spring-mass system with the total energy of the final state of the system to determine unknown quantities.

$$KE_i + GPE_i + SPE_i = KE_f + GPE_f + SPE_f$$

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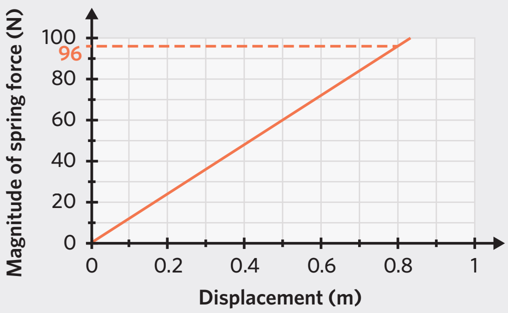
STRATEGY

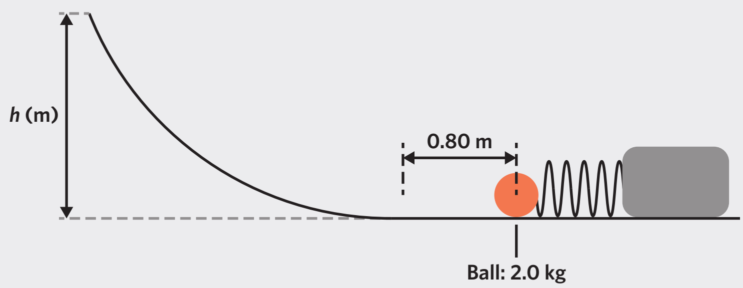
How to solve a problem using conservation of energy, assuming no mechanical energy is lost in the system:

1. Write out the conservation of energy statement:
   $KE_i + GPE_i + SPE_i = KE_f + GPE_f + SPE_f$
2. Find the terms that are equal to zero
   - When $v = 0$ then $KE = 0$
   - When $h = 0$ then $GPE = 0$
   - When $\Delta x = 0$ then $SPE = 0$
3. Rewrite the equation but ignore the terms that equal zero.
   For example: $SPE_i = KE_f + GPE_f$
4. Substitute the formulas for the unknown energies:
   For example: $\frac{1}{2}k(\Delta x_i)^2 = \frac{1}{2}mv^2 + mgh_f$
5. Substitute the remaining values into the equation and solve.

WORKED EXAMPLE 2

A compressed spring is used to launch a 2.0 kg ball on a frictionless horizontal surface. The ball then continues to roll up a ramp which is also frictionless. The spring is initially compressed by 0.80 m and its force-displacement characteristics are shown in the graph.





a. Use the graph to calculate the spring constant, k.

Step 1

Identify two points on the force-displacement graph and write down the formula that relates these variables.

$x_1 = 0\text{ m}, y_1 = 0\text{ N}, x_2 = 0.80\text{ m}, y_2 = 96\text{ N}$

$k = gradient = \frac{rise}{run}$

Step 2

Substitute values into the formula and solve for the spring constant, k.

$k = \frac{96 - 0}{0.80 - 0}$

$k = 1.20 \times 10^2 = 1.2 \times 10^2\text{ N m}^{-1}$

b. Calculate the height the ball reaches above its point of release.

Step 1

Identify known and unknown variables and write down the formula that relates these variables.

Note that the maximum height occurs when the velocity of the ball is 0 m s^{-1}.

$\Delta x = 0.80\text{ m}, k = 1.20 \times 10^2\text{ N m}^{-1}, m = 5.0\text{ kg},$

$\Delta h = ?$

Conservation of energy:

$SPE_i = GPE_f$

$\frac{1}{2}k(\Delta x)^2 = mg\Delta h$

Step 2

Substitute values into the formula and solve for the change in height of the ball.

$\frac{1}{2} \times 1.20 \times 10^2 \times 0.80^2 = 5.0 \times 9.8 \times \Delta h$

$\Delta h = 1.96 = 2.0\text{ m}$

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PROGRESS QUESTIONS

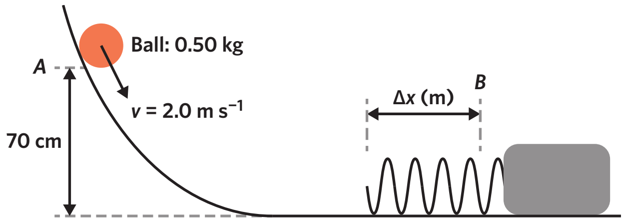
Question 3

An ideal spring, with a spring constant 3.5 N m^{-1} is compressed so that it has a strain potential energy of 1.6 J. The compression of the spring is closest to

A. 0.96 m. **B.** 1.2 m. **C.** 1.9 m. **D.** 2.8 m.

Use the following information to answer questions 4 and 5.

A ball travelling at 2.0 m s^{-1} rolls down a ramp 70 cm above the ground, and compresses a spring as it comes to rest on a flat horizontal track. Assume the track is frictionless.



Question 4

Which of the following conservation of energy equations correctly equates the energy of the ball at position *A* and position *B*?

A. $KE_A = SPE_B$ **B.** $KE_A = SPE_B$

C. $KE_A + GPE_A = SPE_B$ **D.** $KE_A + GPE_A = GPE_A + SPE_B$

Question 5

The strain potential energy stored in the spring is closest to

A. 4.4 J. **B.** 6.6 J. **C.** 8.8 J. **D.** 18 J.

Theory summary

- Hooke's law relates the spring force to the displacement of a spring: $F_s = -k\Delta x$.
- When a block of mass m is hanging on a spring in equilibrium, $mg = k\Delta x$.
- Strain potential energy can be calculated by $SPE = \frac{1}{2}k(\Delta x)^2$
- For a force-displacement graph for an ideal spring:

Table 1 Features of a spring force-displacement graph

Feature	Description	Quantity
Individual coordinates	Lie on a straight line	Spring force, F_s, at a particular displacement, x
Gradient	Constant, and passing through the origin	Spring constant, k
Area under graph	Always in the shape of a triangle	Strain potential energy, SPE

- Conservation of energy
  - Energy can be transformed between kinetic, gravitational and strain potential energy or dissipated as heat and sound but the total energy in a system must remain constant.
  - When no energy is lost: $KE_i + GPE_i + SPE_i = KE_f + GPE_f + SPE_f$

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2D Questions

Mild 🌶 Medium 🌶🌶 Spicy 🌶🌶🌶

Deconstructed exam-style

Use the following information to answer questions 6–9.

A gymnast of mass 64 kg on a trampoline, with spring constant $k = 4.3 \times 10^5$ N m^{-1}, reaches a maximum height above the trampoline of 6.0 m. Take the maximum height of the gymnast as the initial point, and the bottom of the gymnast's motion as the reference height and final point. Assume the change in height of the trampoline is negligible.

Question 6 (1 MARK)

State the form(s) of energy present when the gymnast is at their maximum height.

Question 7 (1 MARK)

State the form(s) of energy present when the gymnast is at the bottom of their motion.

Question 8 (1 MARK)

The conservation of energy equation for the situation is

A. $KE_i = SPE_f$

B. $GPE_i = SPE_f$

C. $GPE_i + SPE_i = SPE_f$

D. $KE_i + GPE_i = GPE_f + SPE_B$

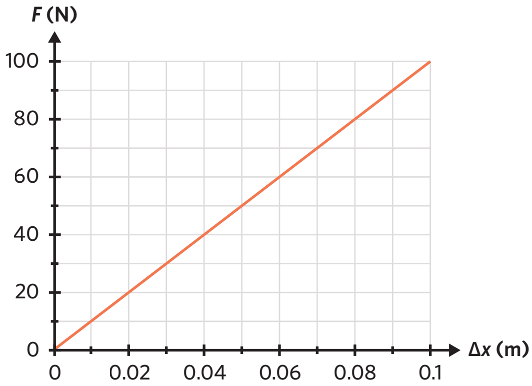
Question 9 (3 MARKS)

Calculate the extension of the trampoline at its lowest point.

Exam-style

Question 10 (5 MARKS)

The force-displacement graph for an ideal spring is as shown.



a. *Key science skill*

Use the graph to determine the spring constant, k. 🌶 2 MARKS

FROM LESSON 12E

Adapted from VCAA 2021 exam Multiple choice Q11

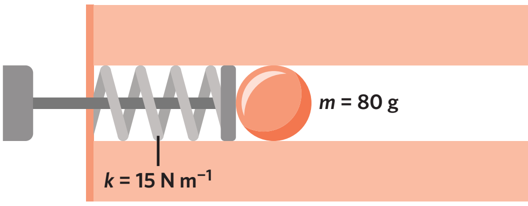
b. Given that a force of 40 N is applied to the spring, what is the magnitude of the compression, Δx, of the spring? Assume the spring is stationary. 🌶 1 MARK

c. Calculate the strain potential energy when a force of 40 N is applied to the spring. Assume the spring is stationary. 🌶 2 MARKS

Adapted from VCAA 2021 exam Multiple choice Q12

Question 11 (4 MARKS)

An initially stationary 80 g ball is shot from the spring with $k = 15.0\ \text{N m}^{-1}$. The spring is compressed by 0.010 m before being released.

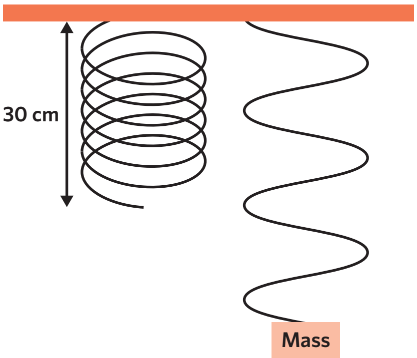


a. Calculate the magnitude of the force of the spring on the ball, before the spring is released. 2 MARKS

b. Calculate the speed of the ball when it leaves the spring. 2 MARKS

Question 12 (4 MARKS)

A spring-mass system has been set up. The spring has an unstretched length of 30 cm.



In order to determine the spring constant, *k*, students progressively place 25 g masses onto an unstretched spring and measure the resultant length.

Number of masses	0	1	2	3
Length of spring	30 cm	40 cm	50 cm	60 cm

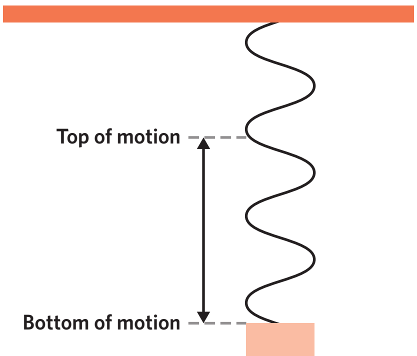
a. Show that the spring constant is equal to $2.5\ \text{N m}^{-1}$. 2 MARKS

Adapted from VCAA 2014 exam Short answer Q2a

b. What is the strain potential energy when the spring is loaded with two masses? 2 MARKS

Question 13 (1 MARK)

A mass at the end of an ideal spring is oscillating freely up and down.



Which one of the following best describes the motion of this oscillating mass?

A. Its speed is a minimum only at the top of the motion.

B. Its speed is a maximum when its acceleration is a maximum.

C. Its acceleration has a minimum value at both the top and the bottom of the motion.

D. Its acceleration has a maximum value upward when the mass is stationary at the bottom.

Adapted from VCAA 2021 NHT exam Multiple choice Q12

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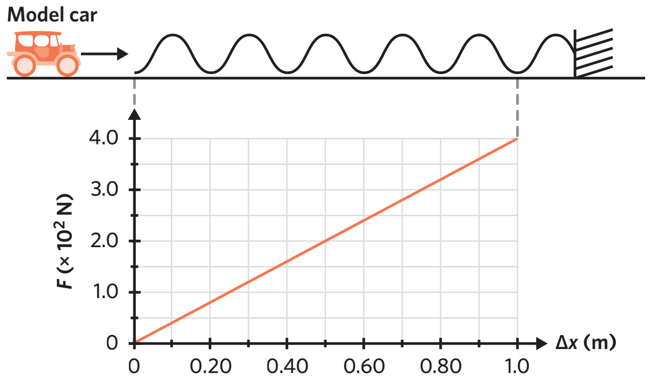
Use the following information to answer questions 14 and 15.

A model car of mass 1.25 kg is on a track and moving to the right. It collides with and compresses a spring that is considered ideal, as shown in the diagram below. The car compresses the spring to 0.50 m when the car momentarily comes to rest. The force–displacement graph for the spring is also shown below. Assume that friction is negligible.



Question 14 (1 MARK)

Key science skill

What is the initial kinetic energy of the car?

A. 0.50 J

B. 10 J

C. 50 J

D. 1.0×10^2 J

FROM LESSON 12D

Adapted from VCAA 2017 exam Multiple choice Q13

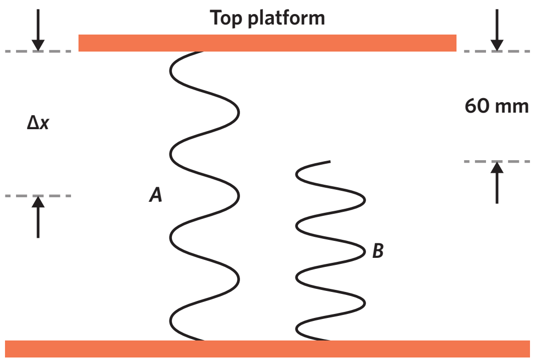
Question 15 (3 MARKS)

After the car comes to a rest, the spring pushes the car back. Calculate the magnitude and direction of the velocity of the car after the spring returns to its natural length.

Question 16 (13 MARKS)

As part of their practical investigation, some students investigate a spring system consisting of two springs, A and B, and a top platform, as shown.

The students place various masses on the top platform. Assume that the top platform has negligible mass. With no masses on the top platform of the spring system, the distance between the uncompressed spring A and the top of spring B is 60 mm. The students place various masses on the top platform of the spring system and note the vertical compression, Δx, of the spring system. They use a ruler with millimetre gradations to take readings of the compression of the spring(s), Δx, with an uncertainty of $\pm$ 2 mm. The results of their investigation are shown in the table. Use $g = 10$ N kg^{-1} for the value of the gravitational field strength.



Mass (g)	Compression, Δx (mm)
0	0
300	21
600	40
900	60
1300	68
1700	75
1900	80

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a. *Key science skill*

- Plot a graph of force (F) versus compression (Δx) for the spring system
- Include scales and units on each axis
- Insert appropriate uncertainty bars for the compression values on the graph
- Draw lines that best fit the data for:
  - the effect of spring A alone.
  - the effect of spring A and spring B.

6 MARKS

FROM LESSON 12D

b. *Key science skill*
Determine the work done to compress spring A when the spring system is compressed by 80 mm. 2 MARKS

FROM LESSON 12D

c. *Key science skill*
Determine the work done to compress spring B when the spring system is compressed by 80 mm. 3 MARKS

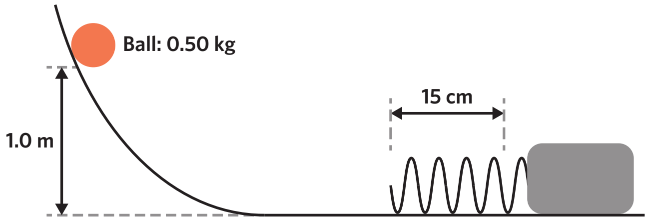
FROM LESSON 12D

d. Explain how this type of spring system could be used in car spring suspension systems to enable the car to negotiate small bumps and more severe bumps in the road. 2 MARKS

Adapted from VCAA 2019 exam Short answer Q19

Question 17 (4 MARKS)

Key science skill



A 0.50 kg ball is dropped down a ramp from a height of 1.0 m before compressing a horizontal spring by 15 cm from its uncompressed state. Draw an energy-distance graph showing how the three forms of energy and the total energy of the system change during the ball's motion. Values are not required.

FROM LESSON 12D

Previous lessons

Question 18 (1 MARK)

The normal force acting on a car travelling at the design speed on a banked track is

A. smaller in magnitude than the gravitational force, and acts down the track it is travelling on.

B. greater in magnitude than the gravitational force, and acts down the track it is travelling on.

C. smaller in magnitude than the gravitational force, and acts perpendicular to the track it is travelling on.

D. greater in magnitude than the gravitational force, and acts perpendicular to the track it is travelling on.

FROM LESSON 1F

Question 19 (2 MARKS)

When an object undergoes uniform circular motion its velocity is constantly changing, but its speed is not. Describe how the kinetic energy of the object changes.

FROM LESSON 2A

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2E Vertical spring-mass systems


Image: Aboubakar Malipula/Shutterstock.com

How is energy transformed as a bungee jumper falls?

So far, Chapter 2 has introduced kinetic energy, gravitational potential energy, and strain potential energy, and explored how they can be transformed using the law of conservation of energy. This lesson builds on that knowledge and examines how it can be used to analyse the energy transformations taking place when a bungee jumper takes a leap of faith. So let's spring into action and extend ourselves as we learn about vertical-spring mass systems.

STUDY DESIGN DOT POINT

- analyse transformations of energy between kinetic energy, strain potential energy, gravitational potential energy and energy dissipated to the environment (considered as a combination of heat, sound and deformation of material):
  - kinetic energy at low speeds: $E_k = \frac{1}{2}mv^2$; elastic and inelastic collisions with reference to conservation of kinetic energy
  - strain potential energy: area under force-distance graph including ideal springs obeying Hooke's Law: $E_s = \frac{1}{2}k\Delta x^2$
  - gravitational potential energy: $E_g = mg\Delta h$ or from area under a force-distance graph and area under a field-distance graph multiplied by mass

2A 2B 2C 2D 2E

3.1.9.7 Vertical spring-mass systems

ESSENTIAL PRIOR KNOWLEDGE

2A Kinetic energy
2C Gravitational potential energy
2D Strain potential energy
2D Conservation of energy

See questions 32–35.

KEY TERMS AND DEFINITIONS

spring-mass system the combination of a spring and a mass attached to one end

equilibrium position (spring-mass system) the position of the mass at which the net force on the mass is zero

oscillate move repetitively about a fixed position

FORMULAS

- **Newton's second law of motion** $F_{net} = ma$
- **force due to gravity** $F = mg$
- **kinetic energy** $KE = \frac{1}{2}mv^2$
- **gravitational potential energy** $\Delta GPE = mg\Delta h$
- **Hooke's law** $F_s = -k\Delta x$
- **strain potential energy** $SPE = \frac{1}{2}k(\Delta x)^2$

Vertical spring-mass systems 3.1.9.7

When a vertical spring stretches or compresses with the motion of an object, the energy of the system transforms between kinetic energy, gravitational potential energy, and strain potential energy.

Vertical **spring-mass systems** include both hanging springs and standing springs (Figure 1).

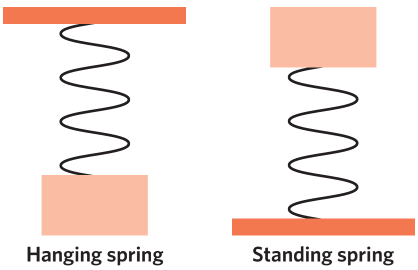

Figure 1 Hanging and standing vertical spring-mass systems

How do we analyse energy transformations in standing spring-mass systems?

Most standing spring-mass systems involve either:

- dropping a mass onto a standing spring
- using a standing spring to launch a mass upwards.

For both these scenarios it is often easiest to take zero gravitational potential energy to be the top of the spring when it's at maximum compression.

When a mass is held stationary at a height, h, above a standing spring and released (Figure 2):

- The gravitational potential energy at height, h, is a maximum and is equal to the total energy of the system, $GPE = E_{total}$.
- The mass reaches its maximum speed when its acceleration is zero. This occurs at its **equilibrium position** – when the force due to gravity is equal and opposite to the spring force, $k\Delta x = mg$.
- The mass stops for an instant when the spring is at maximum compression, the strain potential energy is equal to the total energy of the system, $SPE = E_{total}$.

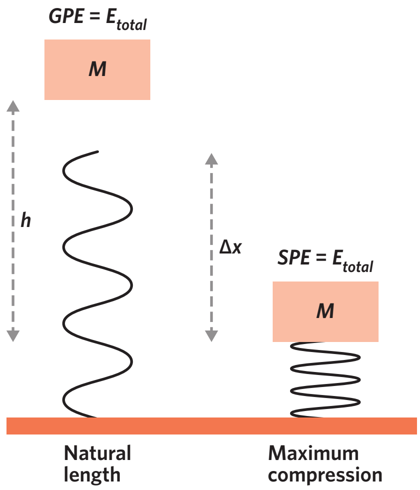

Figure 2 Dropping a mass onto a standing spring

When a mass is held stationary on a compressed spring and released (Figure 3):

- When the spring is at maximum compression, the strain potential energy is equal to the total energy of the system, $SPE = E_{total}$.
- The mass reaches its maximum speed when its acceleration is zero. This occurs at its equilibrium position – when the force due to gravity is equal and opposite to the spring force, $k\Delta x = mg$.
- Assume the spring was compressed enough such that the mass will be released. When the mass reaches its maximum height, h, the gravitational potential energy is a maximum and is equal to the total energy of the system, $GPE = E_{total}$.

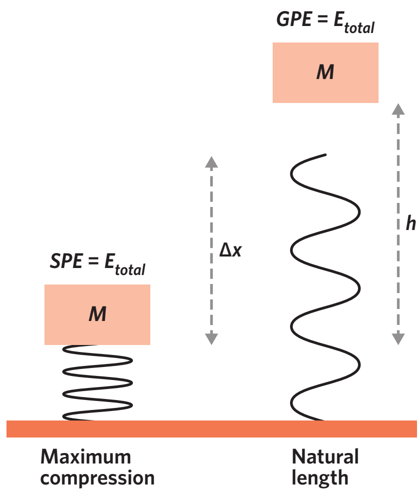

Figure 3 Using a standing spring to launch a mass upwards

Applying the law of energy conservation (and assuming energy is not dissipated from the system) we can conclude that the sum of these three energies must be the same at all stages of the motion: $GPE_i + SPE_i + KE_i = GPE_f + SPE_f + KE_f$

PROGRESS QUESTIONS

Use the following information to answer questions 1–3.

A mass of 1.50 kg is dropped onto a vertical spring with a spring constant of 100 N m^{-1}. The spring compresses 0.350 m before the mass momentarily comes to rest. Take the acceleration due to gravity to be 9.8 m s^{-2}.

Question 1

What is the energy stored in the spring at maximum compression?

A. 6.13 J **B.** 12.3 J **C.** 17.5 J **D.** 35.0 J

Question 2

What is the initial GPE of the mass?

A. 6.13 J **B.** 12.3 J **C.** 17.5 J **D.** 35.0 J

Question 3

Which of the following gives the equilibrium position of the standing spring-mass system?

A. 0.15 m **B.** 0.29 m **C.** 0.38 m **D.** 6.8 m

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How do we analyse energy transformations in hanging spring-mass systems?

When a mass is attached to a hanging spring, the mass has the ability to **oscillate** up and down, alternating between the points of maximum and minimum extension of the spring.

The equilibrium position is where the net force acting on the mass is zero, and is equally distanced from the points of maximum and minimum extension of the spring (Figure 4). At this point, the force of gravity acting on the mass is balanced by the restoring force of the stretched spring acting in the opposite direction.

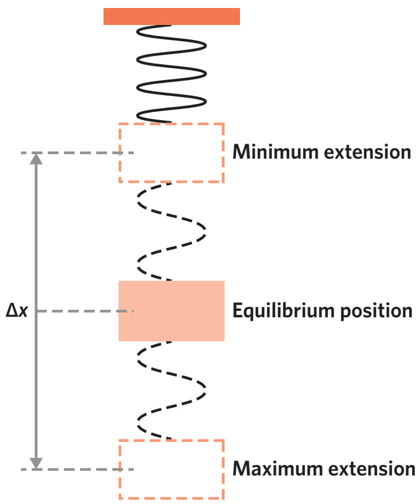


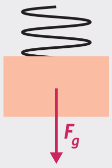
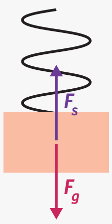
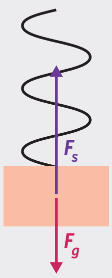
Figure 4 The top and bottom of oscillation as well as the equilibrium position for a hanging spring mass system

USEFUL TIP

When the mass is attached to the spring, the equilibrium position will be the midpoint between the top and bottom of the oscillation. This is also where the mass would eventually come to rest, given enough time.

We can understand the oscillations of a hanging spring-mass system by analysing the forces acting on the mass in three positions – the top of the oscillation, the equilibrium position, and the bottom of the oscillation. (Table 1). Assume the mass is held stationary at the unstretched position before being released and allowed to oscillate.

Table 1 Analysing the forces acting on a hanging spring mass system.

	Free body diagram	Net force	Speed
Top		• Maximum and downwards • The spring force is zero, so it is smaller than the force due to gravity.	• Zero • Even though the net force and acceleration are maximum, the mass momentarily stops as it changes direction.
Middle (equilibrium position)		• Zero • The force due to gravity is equal and opposite to the spring force • $(k\Delta x = mg)$	• Maximum • Although the acceleration is zero, the mass has maximum speed and kinetic energy.
Bottom		• Maximum and upwards • The spring force is larger than the force due to gravity.	• Zero • Even though the net force and acceleration are maximum, the mass momentarily stops as it changes direction.

USEFUL TIP

The force due to gravity acting on the mass, F_g, does not change throughout the oscillation. As the spring oscillates between maximum and minimum extension, the magnitude of the spring force also oscillates between maximum and minimum.

For a hanging oscillating spring-mass system there are three relevant forms of energy:

- Gravitational potential energy of the mass: ***GPE***
- Strain potential energy of the spring: ***SPE***
- Kinetic energy of the mass: ***KE***

We can also analyse the energy transformations taking place between these three forms of energy at the same three positions (Figure 5). Assume the mass is held stationary at the unstretched position before being released and allowed to oscillate.

MISCONCEPTION

'The mass always has no *GPE* at the spring's maximum extension.'

GPE is always measured relative to another height. Only if the reference height is set at the position of maximum extension is the *GPE* of the mass zero at this point.

Top

(Unstretched position, zero extension)

- The top of the oscillation is the position of minimum extension. The spring is at its natural length. Therefore $\Delta x = 0$.
- As the mass is at the top of its oscillation, the gravitational potential energy is a maximum and is equal to the total energy of the system, $GPE = E_{total}$.
- This means there is no strain potential energy stored in the spring, $SPE = 0$.
- The mass is momentarily stationary as it changes direction. This means that the kinetic energy of the mass is zero, $KE = 0$.

Middle (equilibrium position)

(Equilibrium position $F_{net} = 0$)

- The mass is halfway between the top and bottom of its oscillation. The spring force is equal and opposite to the force due to gravity, $k\Delta x = mg$.
- As the mass is in the middle of its oscillation, the gravitational potential energy is a half of its maximum and is equal to half the total energy of the system, $GPE = 0.5 \times E_{total}$.
- The spring is halfway between its maximum and minimum extension, therefore a quarter of the total energy is stored as strain potential energy, $SPE = 0.25 \times E_{total}$.
- The mass is moving at a maximum speed. This means the kinetic energy is at a maximum and accounts for one quarter of the total energy of the system, $KE = 0.25 \times E_{total}$.

Bottom

(Maximum extension)

- The mass is at the bottom of its oscillation. The spring is at its maximum extension.
- As the mass is at the bottom of its oscillation, the gravitational potential energy is zero, $GPE = 0$.
- This means the strain potential energy is at a maximum and is equal to the total energy of the system, $SPE = E_{total}$.
- The mass is momentarily stationary as it changes direction. This means that the kinetic energy of the mass is zero, $KE = 0$.

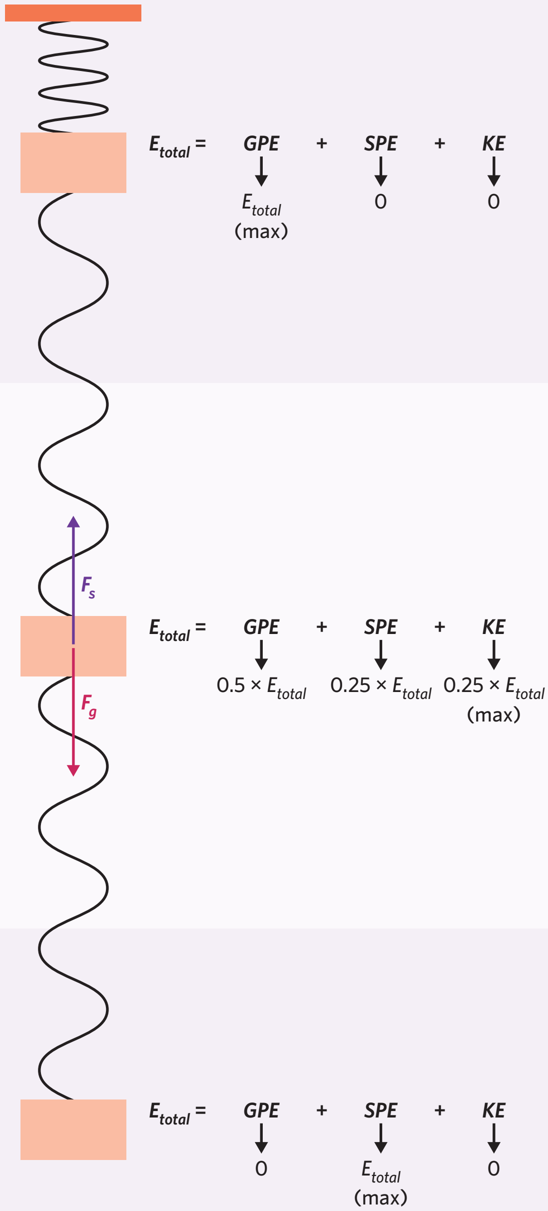


Figure 5 The energy distributions at the top, middle, and bottom for a hanging spring-mass system.

Applying the law of energy conservation (and assuming energy is not dissipated from the system) we can conclude that the sum of these three energies must be the same at all stages of the motion (Figure 6):
$GPE_i + SPE_i + KE_i = GPE_f + SPE_f + KE_f$

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The strain potential energy, gravitational potential energy and kinetic energy of a hanging oscillating spring-mass system each vary with displacement, but the total energy is constant.[1]

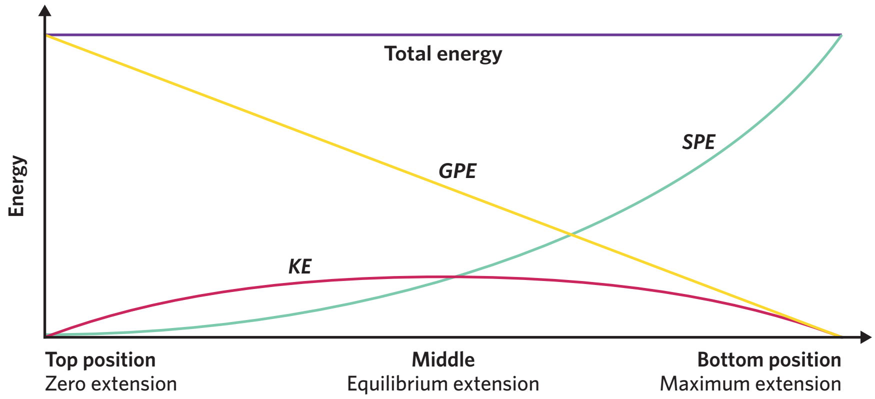

Figure 6 Graph of the energy forms and the total energy in a hanging spring-mass system

KEEN TO INVESTIGATE?

[1] **How do we graph the energy of a bungee jump?**
Search: Bungee jumping with energy conservation

USEFUL TIP

The *SPE* is only zero at the top if the mass is released from the unstretched length. Similarly, the *KE* is only zero at the top if the mass is stationary before being released.

WORKED EXAMPLE 1

A block of mass 0.050 kg is attached to the end of a hanging spring with a spring constant of 10 N m^{-1}. The mass is initially held so that the spring is unstretched. It is then released and allowed to oscillate. Take gravitational potential energy to be zero at the point of maximum extension.

a. Calculate the maximum extension of the spring.

Step 1

Identify known and unknown variables and write down the formula that relates these variables.

Note that in the unstretched position $KE_i = 0$ and SP $E_i = 0$, and in the maximum stretched position $KE_f = 0$ and $GPE_f = 0$.

$m = 0.050$ kg, $g = 9.8$ m s^{-2}, $k = 10$ N m^{-1}, $\Delta x = ?$

$GPE_i = SPE_f \Rightarrow mgh = \frac{1}{2}k(\Delta x)^2$

Step 2

Substitute values into the formula and solve for the maximum extension of the spring.

Note that $h = \Delta x$ because the top of the oscillation is at the unstretched position.

$mg\Delta x = \frac{1}{2}k(\Delta x)^2$

$0.050 \times 9.8 \times \Delta x = \frac{1}{2} \times 10 \times (\Delta x)^2$

$\Delta x = 0.098 = 0.10$ m

b. Calculate the extension of the spring at which the mass would eventually come to rest if the energy in the system was gradually lost.

Step 1

Identify known and unknown variables and write down the formula that relates these variables.

Note that the mass would come to rest at the equilibrium position, which is halfway between the top and bottom of the oscillation.

$m = 0.050$ kg, $g = 9.8$ m s^{-2}, $k = 10$ N m^{-1}, $\Delta x = ?$

$mg = k\Delta x$

OR

$\Delta x_{max} = 0.098$ m, $equilibrium\ position = ?$

$equilibrium\ position = \frac{1}{2}\Delta x_{max}$

Step 2

Substitute values into the formula and solve for the equilibrium position.

$0.050 \times 9.8 = 10 \times \Delta x$

$\Delta x = 0.049 = 0.050$ m

OR

$equilibrium\ position = \frac{1}{2} \times 0.098$

$equilibrium\ position = 0.049 = 0.050$ m

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PROGRESS QUESTIONS

Question 4

At which position is the strain potential energy a maximum in a hanging spring-mass system?

A. at the top of oscillation
B. at the equilibrium position
C. at the bottom of oscillation
D. strain potential energy is equal throughout oscillation

Question 5

At which position is the kinetic energy a maximum in a hanging spring-mass system?

A. at the top of oscillation
B. at the equilibrium position
C. at the bottom of oscillation
D. kinetic energy is equal throughout oscillation

Theory summary

- Total energy must be conserved for an isolated vertical spring-mass system:
  - $GPE_i + SPE_i + KE_i = GPE_f + SPE_f + KE_f$
- For a standing vertical spring-mass system:
  - The total energy of the system is in *GPE* when the mass is stationary at its maximum height.
  - The mass reaches its maximum speed and *KE* when it reaches its equilibrium position, $mg = k\Delta x$.
  - The total energy of the system is in *SPE* when the mass is stationary and the spring is at maximum compression.
- For a hanging spring-mass system released from the spring's unstretched position:
  - At the top of its oscillation all the energy of the system is in gravitational potential energy, $GPE = E_{total}$.
  - At the equilibrium position:
    - The net force on the mass is zero, $mg = k\Delta x$.
    - The mass is halfway between the top and bottom positions of the oscillating spring.
    - The mass is travelling at its maximum speed.
  - At the bottom of its oscillation all the energy of the system is in strain potential energy, $SPE = E_{total}$.

2E Questions

Mild 🌶 Medium 🌶🌶 Spicy 🌶🌶🌶

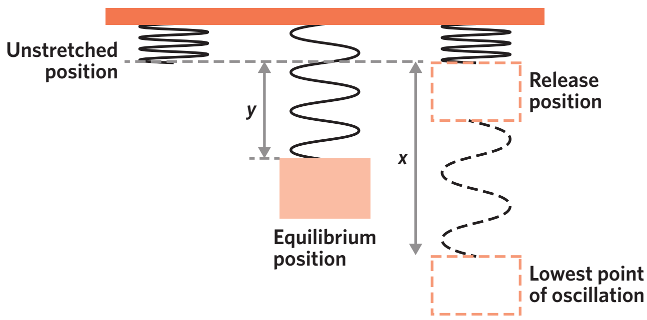
Deconstructed exam-style

Use the following information to answer questions 6–9.

Students conduct an experiment in which a mass of 2.50 kg is suspended from a spring with a spring constant of 98.0 N m^{-1}, as shown. Ignore the mass of the spring.

The mass is raised to the unstretched length of the spring and released so that it oscillates vertically.

The lowest point of its oscillation is $x = 0.500$ m. Take gravitational potential energy to be zero at this point.



Question 6 (1 MARK)

Which of the following is closest to the total energy of the system?

A. 6.13 J

B. 12.3 J

C. 24.5 J

D. 49.0 J

Question 7 (1 MARK)

Which of the following is closest to the gravitational potential energy of the mass at the equilibrium position?

A. 3.06 J

B. 6.13 J

C. 12.3 J

D. 24.5 J

Question 8 (1 MARK)

Which of the following is closest to the strain potential energy at the equilibrium position?

A. 3.06 J

B. 6.13 J

C. 12.3 J

D. 24.5 J

Question 9 (4 MARKS)

Calculate the maximum speed of the mass. Show your working.

Adapted from VCAA 2019 NHT exam Short answer Q5bii

Exam-style

Question 10 (2 MARK)

A hanging mass is attached to a spring. The mass is held at the springs natural length and released, allowing it to oscillate. When the spring is at its natural length, the total energy of the system is 12 J.

a. Determine the GPE at the top of the oscillation. 1 MARK

b. Determine the SPE at the bottom of the oscillation 1 MARK

Question 11 (1 MARK)

A mass is dropped onto a vertical standing spring with characteristics shown in the graph. The mass causes a compression of 0.3 m in the spring when the mass is travelling its maximum speed. Take gravity to be 10 m s^{-2}.

Which of the following gives the mass in kg?

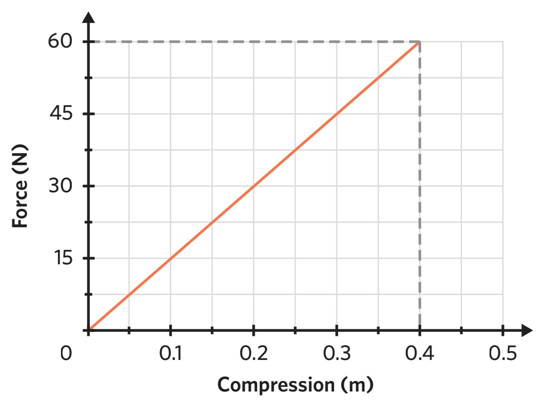
A. 4.5 kg

B. 6.0 kg

C. 30 kg

D. 45 kg

Adapted from VCAA 2022 exam Multiple choice Q8



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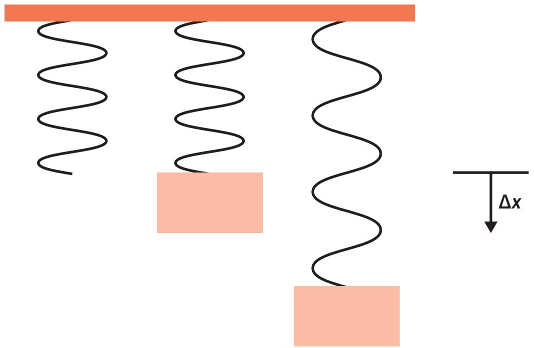
Question 12 (9 MARKS)

Ryle and Rushil hang a mass of 0.800 kg on the end of a spring with a spring constant of 12 N m^{-1}. They initially hold the mass at the unstretched length of the spring and then release it.



a. Determine how far the spring stretches until the mass comes to rest, before moving upwards again. 3 MARKS

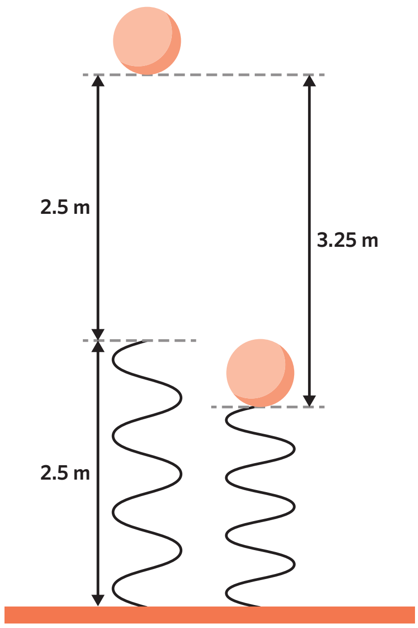
b. Calculate the maximum speed of the mass. 3 MARKS

c. *Key science skill*
Draw a graph showing the acceleration of the mass as it moves from the highest point to the lowest point, where upwards is the positive direction. The acceleration should be shown on the vertical axis and the extension of the spring should be shown on the horizontal axis. Include units and an appropriate scale on your graph. 3 MARKS

FROM LESSON 12D

Question 13 (7 MARKS)

A ball of mass 3.0 kg is dropped from a height of 2.5 m above a spring, as shown. The spring has an uncompressed length of 2.5 m. The ball and the spring come to rest when they are at a distance of 0.75 m below the uncompressed position of the spring.



a. Show that the spring constant, k, is equal to 340 N m^{-1}. Show your working. 3 MARKS

b. Determine the acceleration of the ball when it reaches its maximum speed. Explain your answer. 2 MARKS

c. Calculate the compression of the spring when the ball reaches its maximum speed. Show your working. 2 MARKS

Adapted from VCAA 2018 exam Short answer Q6

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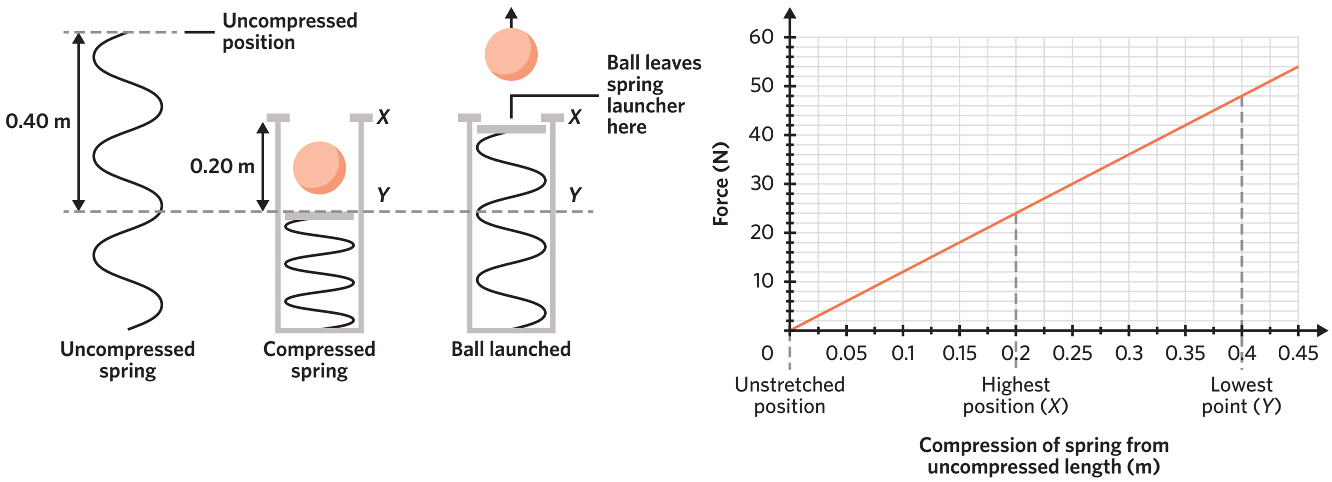
Question 14 (13 MARKS)

A spring launcher is used to project a 0.50 kg ball vertically upwards. When the spring reaches the top point X it is held stationary, but still partly compressed. Assume the spring has no mass.



a. *Key science skill*

Use the graph to show that the spring constant, k, is 120 N m^{-1}. 1 MARK

Adapted from VCAA 2018 NHT exam Short answer Q9a

FROM LESSON 12D

b. Show that the change in strain potential energy as the spring goes from its lowest to its highest point is 7.2 J. 2 MARKS

Adapted from VCAA 2018 NHT exam Short answer Q9b

c. Determine the maximum height above the lowest point (Y) that the ball reaches after being launched. 3 MARKS

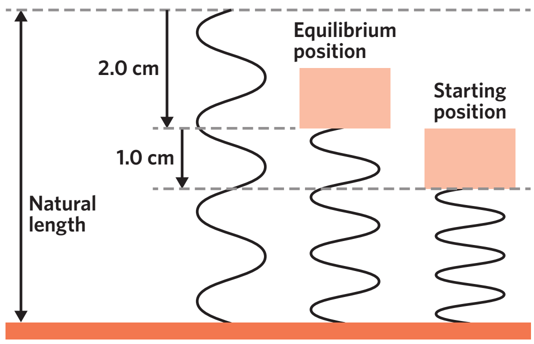
d. Calculate the speed of the ball at point X. 3 MARKS

Adapted from VCAA 2018 NHT exam Short answer Q9c

e. Describe how the three forms of energy and the total energy of the mass-spring system change as the ball moves from the lowest point Y to the highest point X. 4 MARKS

Question 15 (3 MARKS)

Yokabit, Valeriy, and JL are conducting an experiment with a mass attached to a standing spring. When at rest, the mass compresses the spring by 2.0 cm. They intend to compress the spring by a further 1.0 cm (total compression of 3.0 cm) and measure the maximum height that the mass reaches when it oscillates. Assume the spring-mass system is able to oscillate up and down without any horizontal motion.



Each of the students has a different suggestion for the maximum height that the mass will reach:

- Yokabit suggests that the highest position will be the equilibrium position because the net force would act downwards if the mass was any higher;
- Valeriy suggests that the highest position will be the position at which the spring is uncompressed because the spring force would act downwards on the mass if the mass was any higher;
- JL suggests that the highest position will be 3.0 cm above the natural length (uncompressed position) because energy conservation suggests that the highest and lowest positions should be the same distance from the uncompressed position.

Evaluate each of these students' suggestions with supporting explanations. State the correct height that the mass will reach.

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Question 16 🌶🌶🌶 (3 MARKS)

Students design a hanging oscillating spring-mass system. They set up the system so that the mass is released from 20 cm below the unstretched spring length. They assume that

- at the point of release, the system has zero strain potential energy and zero kinetic energy;
- at the bottom of the oscillation, the system has zero gravitational potential energy and zero kinetic energy.

However their calculations for total energy ($KE + GPE + SPE$) give different values when comparing these two positions.

Explain the mistake that the students have made.

Adapted from VCAA 2013 exam Short answer Q6c

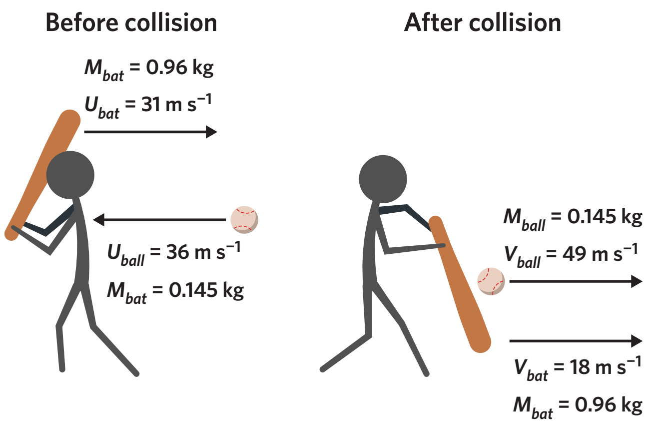
Previous lessons

Question 17 🌶🌶 (3 MARKS)

An aerobatics pilot with a mass of 60.0 kg completes a loop the loop in her plane which has a mass of 1000 kg. At the top of the loop she has a speed of 80.0 m s^{-1} and there is no normal force acting on her. At the bottom of the loop she is travelling at 100 m s^{-1}. Assuming that the loop is a perfect circle, calculate the magnitude of the normal force acting on her at the bottom of the loop.

FROM LESSON 1G

Question 18 🌶🌶 (3 MARKS)



A game of baseball is being played. The pitcher throws the ball towards the batter at 36 m s^{-1} who swings their bat at 31 m s^{-1}. After hitting the ball, the bat is moving at 18 m s^{-1} and the ball is moving at 49 m s^{-1}. The mass of the bat is 960 g, and the ball 145 g.

Is the collision elastic or inelastic? Justify your answer with calculations.

FROM LESSON 2B

Chapter 2 review

Mild 🌶 Medium 🌶🌶 Spicy 🌶🌶🌶

These questions are typical of one hour's worth of questions on the VCE Physics Exam.

Total marks: 50

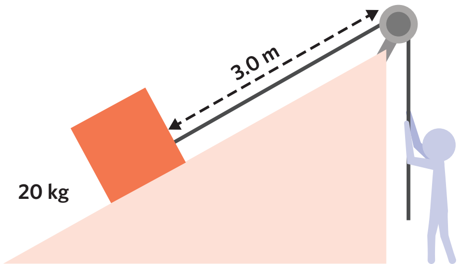
Section A

All questions in this section are worth one mark.

Unless otherwise indicated, the diagrams in this book are not drawn to scale.

Question 1 🌶

A worker pulls a 20 kg block a distance of 3.0 m up a ramp using a force of 100 N.



How much work does the worker do on the block?

A. 60 J

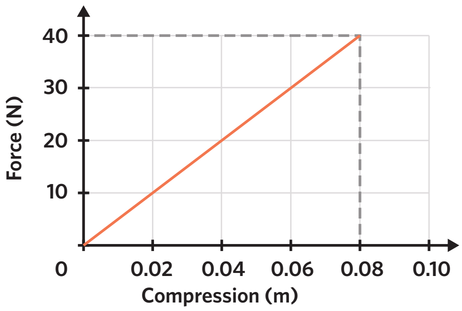
B. 5.9×10^2 N m s^{-1}

C. 3.0×10^2 J

D. 5.9×10^2 J

Use the following information to answer questions 2 and 3.

The graph shows force vs. compression for a spring used in a physics investigation.



Question 2 🌶

Which of the following is closest to the spring constant of the spring?

A. 3.2 N m^{-1}

B. 40 N m^{-1}

C. 500 N m^{-1}

D. 6250 N m^{-1}

Adapted from VCAA 2021 exam Multiple choice Q11

Question 3 🌶🌶

Which one of the following is closest to the compression required to store 0.9 J of potential energy in the spring?

A. 0.05 m

B. 0.06 m

C. 0.07 m

D. 0.08 m

Taken from VCAA 2022 exam Multiple choice Q8

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Question 4

A block with mass of 15.0 kg, moving at 50.0 m s^{-1} to the right, collides with a block with mass of 40.0 kg, moving at 4.00 m s^{-1} to the left. After the collision they stick together, and move off at 10.7 m s^{-1} to the right. Assume there are no frictional forces. What percentage of the initial kinetic energy is conserved in the collision?

A. 11.5%

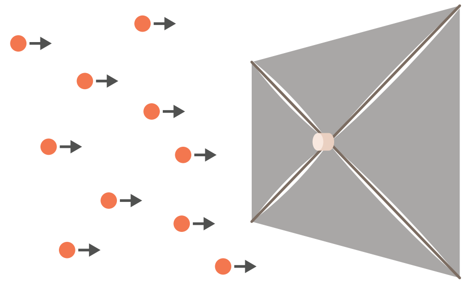
B. 16.5%

C. 65.3%

D. 100%

Question 5

A "space sail" mounted on a tiny interstellar probe relies on the momentum of photons from a nearby star for propulsion, as shown.



The photons strike the sail at 90° and reflect elastically. Which of the following is the expression for the momentum the sail gains from one photon collision?

A. $\Delta p_{sail} = p_{ph}$

B. $\Delta p_{sail} = 2p_{ph}$

C. $\Delta p_{sail} = E_{ph}$

D. $\Delta p_{sail} = 2E_{ph}$

Adapted from VCAA 2021 exam Short answer Q17b

Section B

In questions where more than one mark is available, appropriate working must be shown.

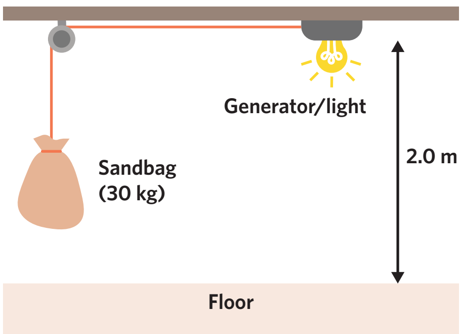
Unless otherwise indicated, the diagrams in this book are not drawn to scale.

Question 6 (2 MARKS)

A PE teacher is holding up a heavy book above her head. She states that she is doing a lot of work on the book to hold it there. Evaluate this statement.

Question 7 (4 MARKS)

Engineers set up a gravity light as shown. The energy from a falling sandbag with a mass of 30 kg is converted to electricity by an electrical generator and is used to power an LED light. The LED light uses 1.5 W. The maximum height of the sandbag is 2.0 m from the floor. Assume no energy is lost in the generator or the LED light.



a. How much energy can the sandbag deliver to the LED by falling from the maximum height to the ground? Ignore resistance forces and assume the bag is at rest when it reaches the ground. 2 MARKS

b. How long will the light be able to stay on using the energy from the sandbag? 2 MARKS

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Question 8 (7 MARKS)

A football with a mass of 0.50 kg is thrown downwards, with an initial kinetic energy of 6.25 J, from the Sydney Harbour Bridge. The ball impacts the water with a speed of 31 m s^{-1}.

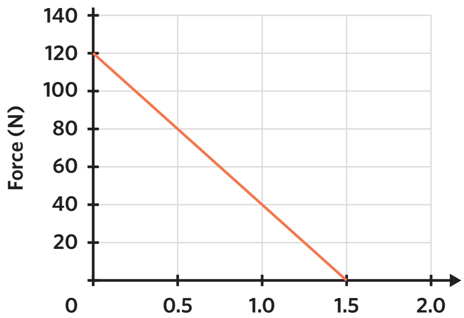
a. Calculate the height of the bridge. Ignore the effects of resistance forces. 2 MARKS

b. In the water, the ball slows to a speed of 5.0 m s^{-1}. It then collides with a 0.70 kg shoe, initially at rest. They both move off at a speed of 2.1 m s^{-1}. Calculate the energy dissipated into the environment. 3 MARKS

c. Was the collision with the shoe an elastic or inelastic collision? Justify your response. 2 MARKS

Question 9 (4 MARKS)

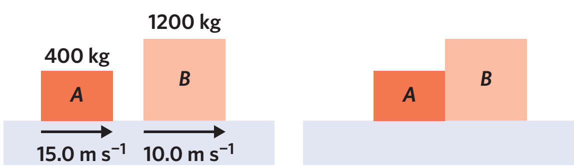
The graph shows the force that a baseball pitcher applies in a horizontal direction to a 450 g baseball over a distance of 1.5 m. The ball starts from rest.



a. Determine the work done on the baseball by the pitcher. 2 MARKS

b. What is the speed of the ball as it leaves the pitcher's hand? 2 MARKS

Question 10 (4 MARKS)



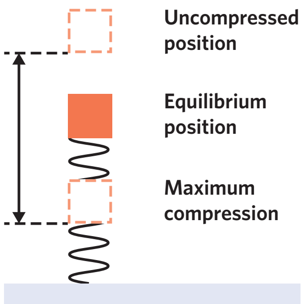
Two blocks are travelling to the right on a frictionless surface. Block *A* has an initial speed of 15.0 m s^{-1} and block *B* has an initial speed of 10.0 m s^{-1}. After they collide, the masses attach together. Using calculations, determine whether the collision is elastic or inelastic.

Adapted from 2017 VCAA exam Short answer Q12

Question 11 (6 MARKS)

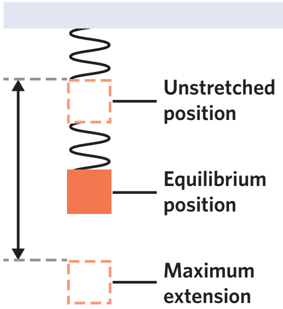
A mass is attached to a standing spring at its unstretched length and released, allowing it to oscillate.

a. Explain how the three forms of energy involved, and the total energy of the system, vary as the mass descends from top to bottom. Calculations are not required. 4 MARKS



Adapted from 2017 VCAA exam Short answer Q13b

b. A different spring is hung from the roof with a 4.8 kg mass attached. It is released from the unstretched position and allowed to oscillate. The spring constant is 50 N m^{-1}. Calculate the magnitude of the maximum extension of the spring. 🌶🌶 2 MARKS



Question 12 (7 MARKS)

A swimmer is competing in a 200 m race, consisting of four laps of a 50 m long pool. While swimming, they have a maximum speed of 1.0 m s^{-1}. When they reach the end of the pool, the swimmer turns around and pushes off the wall using their legs (tumble-turn). They push themselves with an average force of 60 N for 0.65 m before losing contact with the wall.

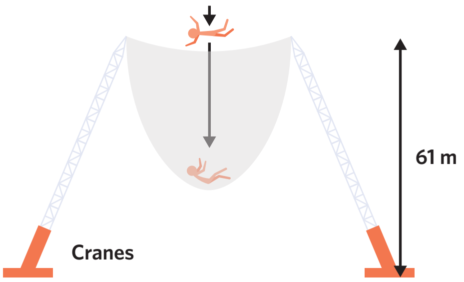
a. What is the amount of work they do during this push? 🌶 2 MARKS

b. If we were to model the swimmer's legs as a single ideal spring, calculate the spring constant during the turn. 🌶🌶 2 MARKS

c. While swimming at their maximum speed, the swimmer uses energy at a rate of 1800 W. How much of the swimmer's energy is dissipated over a 25 m distance? Assume they maintain their maximum speed. 🌶🌶 3 MARKS

Question 13 (4 MARKS)

In 2016, Luke Aikins (70.0 kg) skydived out of a plane, at 7661 m above the ground, without a parachute. Due to air resistance, Aikins reached a terminal (maximum) velocity of 240 km h^{-1}. He opted to land in an enormous net. Assume that the net follows Hooke's law. The net was set up on 61 m tall cranes and it was initially flat before Aikins landed on the net.



a. How much of Aikins' initial gravitational potential energy was dissipated to air resistance in his skydive by the time he hit the top of the net? 🌶🌶 2 MARKS

b. What must the minimum spring constant of the net be so that Aikins does not hit the ground? 🌶🌶🌶 2 MARKS

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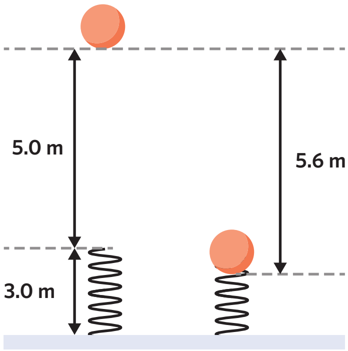
Question 14 (7 MARKS)

A ball of 1.5 kg is dropped from a height of 5.0 m above an uncompressed spring 3.0 m tall. The ball comes to rest 5.6 m below its original position. Take the spring constant to be $k = 457 \text{ N m}^{-1}$.



a. What is the spring potential energy in the spring when the ball has come to a complete stop? 2 MARKS

b. How far has the spring been compressed when the ball reaches its maximum speed? 3 MARKS

Adapted from 2018 VCAA exam Short answer Q6

c. The spring is replaced by a different one with a spring constant of 200 N m^{-1}. For this new spring, the ball is again dropped from a height 5.0 m above the spring, and it reaches its maximum speed when the spring is compressed by 7.35×10^{-2} m. Find the maximum kinetic energy of the ball. 2 MARKS

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Unit 3 AOS 1 review

Mild 🌶 Medium 🌶🌶 Spicy 🌶🌶🌶

These questions are typical of one hour's worth of questions on the VCE Physics Exam.

Total marks: 50

Section A

All questions in this section are worth one mark.

Unless otherwise indicated, the diagrams in this book are not drawn to scale.

Question 1 🌶

A train travelling to the left at 12 m s^{-1} applies the brakes and decelerates at 2.0 m s^{-2}. Calculate the magnitude of the train's displacement after 6.0 seconds.

A. 2.4×10^1 m **B.** 3.6×10^1 m **C.** 1.1×10^2 m **D.** 1.4×10^2 m

Adapted from VCAA 2016 exam Short answer Q1a

Question 2 🌶🌶

Which of these objects is not accelerating?

A. a plane speeding up as it travels down a runway

B. a train travelling straight at a constant speed of 50 m s^{-1}

C. a car driving around a corner at a constant speed of 20 m s^{-1}

D. an apple falling from a tree under the influence of gravity (ignoring air resistance)

Question 3 🌶🌶

Which of the following is the best description of the law of conservation of energy?

A. Energy is conserved in all situations.

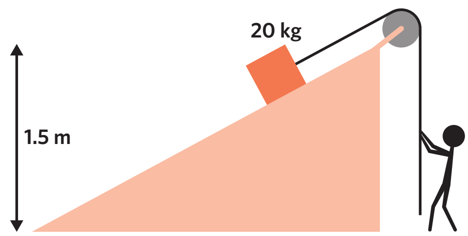
B. There is no situation in which energy is conserved.

C. Energy is only conserved in systems where elastic collisions take place.

D. Energy is only conserved in systems where there are non-contact forces present.

Question 4 🌶🌶

While holding a 20 kg block at the top of a 1.5 m high ramp, a worker is distracted by a loud noise and releases the rope. Which option is closest to the speed of the block at the bottom of the ramp? Ignore any frictional forces.



A. 2.5 m s^{-1} **B.** 5.4 m s^{-1}

C. 8.6 m s^{-1} **D.** 10 m s^{-1}

Question 5 🌶🌶

The ISS is travelling around the Earth in a stable circular orbit. Which of the following statements is correct concerning the momentum and kinetic energy of the ISS?

A. Both the momentum and the kinetic energy vary along the orbital path.

B. Both the momentum and the kinetic energy are constant along the orbital path.

C. The momentum is constant, but the kinetic energy changes throughout the orbital path.

D. The momentum changes, but the kinetic energy remains constant throughout the orbital path.

Adapted from VCAA 2020 exam Multiple choice Q11

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Section B

In questions where more than one mark is available, appropriate working must be shown.

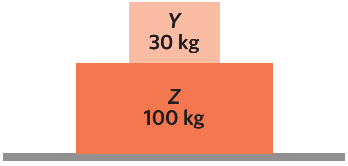
Unless otherwise indicated, the diagrams in this book are not drawn to scale.

Question 6 (2 MARKS)

Block Y has a mass of 30 kg and rests on top of block Z, which has a mass of 100 kg.

Calculate the magnitude of the force on block Y by block Z.

Adapted from VCAA 2018 exam Short answer Q8a



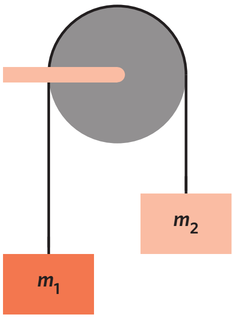
Question 7 (3 MARKS)

A cannonball, of mass 2.0 kg, is moving directly upwards at 50 m s^{-1} when it is at an altitude of 530 m above the ground. After reaching its maximum altitude, the cannonball falls straight back down.

Find the maximum kinetic energy of the cannonball before it hits the ground. Ignore the effects of air resistance in your calculations.

Question 8 (6 MARKS)

Darren and Joey utilise a classic experimental setup, an 'Atwood machine', to examine the concept of acceleration. They attach two masses, m_1, with a mass of 500 g, and m_2, with a mass of 300 g, to a string with negligible mass running over a frictionless pulley.



a. Calculate the magnitude of the gravitational forces acting on m_1 and m_2. 2 MARKS

b. Calculate the magnitude of the acceleration of m_1. 2 MARKS

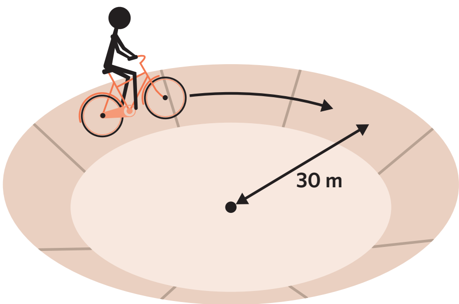
Adapted from VCAA 2015 exam Short answer Q2a

c. Calculate the magnitude of the tension in the string. 2 MARKS

Adapted from VCAA 2015 exam Short answer Q2b

Question 9 (7 MARKS)

A bicycle and its rider have a total mass of 120 kg and travel around a circular banked track with a 30 m radius. The track is banked at an angle 37.4°.



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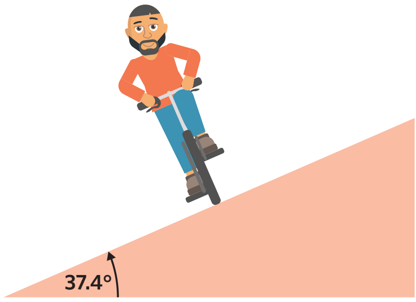
a. On a copy of the diagram, draw all the forces acting on the rider and bicycle. Draw the net force as a dashed line. Consider the bicycle and rider as a single object. 🌶🌶 — 2 MARKS



Adapted from VCAA 2015 exam Short answer Q4a

b. Calculate the kinetic energy of the bicycle required for there to be no sideways frictional force acting on it. 🌶🌶🌶 — 3 MARKS

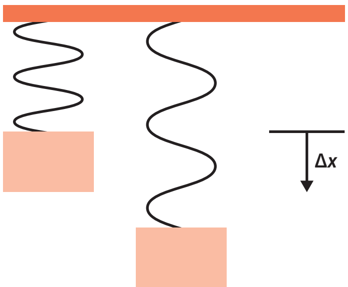
c. *Key science skill*

The angle of inclination of the banked track is slightly raised for a new competition. Does the rider now have to travel faster, at the same speed, or slower than before, in order to maintain no sideways frictional force on their bicycle? Justify your answer. 🌶🌶 — 2 MARKS

Question 10 🌶🌶🌶 — (4 MARKS)

Key science skill

Jeremy and Talia hang a mass on the end of a spring. They hold the mass at the unstretched length of the spring and release it, allowing it to fall.



Draw an energy-displacement graph showing how the three forms of energy involved vary as the mass falls from top to bottom. Include the total energy of the system as a dotted line. Calculations are not required.

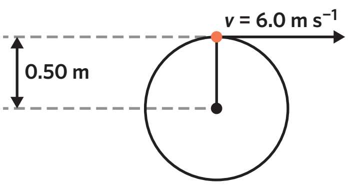
Adapted from VCAA 2017 exam Short answer Q13b

FROM LESSON 12D

Question 11 — (6 MARKS)

Students perform an experiment where a ball of mass 1.5 kg is moving in a vertical circle at the end of a string.

The string has a length of 0.5 m. At the top of the arc, the ball is moving at 6.0 m s^{-1}.



a. Does the ball have a great enough speed at the top of the arc so that the string remains tight (under tension)? Support your answer with calculations. 🌶🌶 — 3 MARKS

b. Calculate the speed of the ball at the lowest point. 🌶🌶 — 3 MARKS

Adapted from VCAA 2018 NHT exam Short answer Q8

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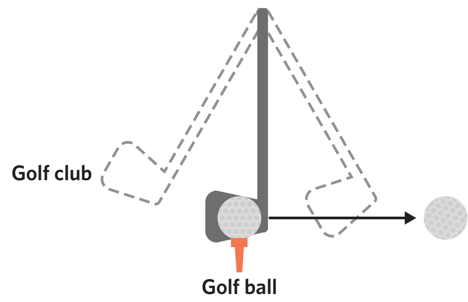
Question 12 (4 MARKS)

Students are studying a golf club hitting a stationary golf ball. They treat it as a collision between the head of the golf club and golf ball only.



The students take the following measurements

Mass of the head of the golf club	330 g
Mass of golf ball	45 g
Initial velocity of golf club	70 m s^{-1} to the right
Final velocity of golf club after hitting golf ball	60 m s^{-1} to the right

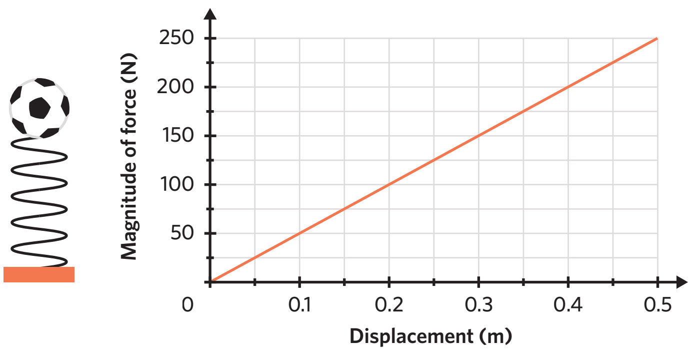
a. Show that the ball's speed after the collision is 73 m s^{-1}. 1 MARK

b. Use calculations to determine whether or not the collision was elastic. 3 MARKS

Adapted from VCAA 2018 NHT exam Short answer Q7

Question 13 (7 MARKS)

A soccer ball is launched vertically upward using a spring, as shown. The characteristics of the spring are shown in the graph. The spring is initially compressed by 0.40 m before the ball is launched. Take the mass of the soccer ball to be 0.40 kg.



a. *Key science skill*

Use the graph to determine the spring constant, *k*. 2 MARKS

FROM LESSON 12D

b. What is the elastic potential energy of the spring before the soccer ball is launched? 2 MARKS

c. What is the maximum height that the soccer ball reaches above the top of the launcher? 3 MARKS

Question 14 (6 MARKS)

A tennis ball, of mass 58 g, is launched at a speed of 25 m s^{-1}, at an angle of 14° to the horizontal. The air resistance acting on the ball can be modelled quantitatively as a force of magnitude $1.0 \times 10^{-3} \times v^2$.

a. Calculate the magnitude of the net force acting on the projectile, just as it is launched. 5 MARKS

b. Identify what is the reaction force to air resistance on the projectile. 1 MARK

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UNIT 3 AOS 2

How do things move without contact?

Field models are used to explain the behaviour of objects when there is no apparent contact. In this area of study, students examine the similarities and differences between three fields: gravitational, electric and magnetic. Students explore how positions in fields determine the potential energy of, and the force on, an object. They investigate how concepts related to field models can be applied to construct motors, maintain satellite orbits and to accelerate particles including in a synchrotron.

Outcome 1

On completion of this unit the student should be able to analyse gravitational, electric and magnetic fields, and apply these to explain the operation of motors and particle accelerators, and the orbits of satellites.

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3

CHAPTER 3

Gravitational fields

STUDY DESIGN DOT POINTS

- describe gravitation, magnetism and electricity using a field model
- investigate and compare theoretically and practically gravitational, magnetic and electric fields, including directions and shapes of fields, attractive and repulsive effects, and the existence of dipoles and monopoles
- investigate and compare theoretically and practically gravitational fields and electrical fields about a point mass or charge (positive or negative) with reference to:
  - the direction of the field
  - the shape of the field
  - the use of the inverse square law to determine the magnitude of the field
  - potential energy changes (qualitative) associated with a point mass or charge moving in the field
- identify fields as static or changing, and as uniform or non-uniform
- analyse the use of gravitational fields to accelerate mass, including:
  - gravitational field and gravitational force concepts: $g = G\frac{M}{r^2}$ and $F_g = G\frac{m_1 m_2}{r^2}$
  - potential energy changes in a uniform gravitational field: $E_g = mg\Delta h$
- analyse the change in gravitational potential energy from area under a force vs distance graph and area under a field vs distance graph multiplied by mass
- apply the concepts of force due to gravity and normal force including in relation to satellites in orbit where the orbits are assumed to be uniform and circular
- model satellite motion (artificial, Moon, planet) as uniform circular orbital motion: $a = \frac{v^2}{r} = \frac{4\pi^2 r}{T^2}$
- describe the interaction of two fields, allowing that electric charges, magnetic poles and current carrying conductors can either attract or repel, whereas masses only attract each other

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LESSONS

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3A Gravitational fields and forces


Image: PRILL/Shutterstock.com

STUDY DESIGN DOT POINTS

- describe gravitation, magnetism and electricity using a field model
- investigate and compare theoretically and practically gravitational fields and electrical fields about a point mass or charge (positive or negative) with reference to:
  - the direction of the field
  - the shape of the field
  - the use of the inverse square law to determine the magnitude of the field
  - potential energy changes (qualitative) associated with a point mass or charge moving in the field
- analyse the use of gravitational fields to accelerate mass, including:
  - gravitational field and gravitational force concepts: $g = G\frac{M}{r^2}$ and $F_g = G\frac{m_1 m_2}{r^2}$
  - potential energy changes in a uniform gravitational field: $E_g = mg\Delta h$
- describe the interaction of two fields, allowing that electric charges, magnetic poles and current carrying conductors can either attract or repel, whereas masses only attract each other

3A 3B 3C

3.2.1.1 & 3.2.3.1 & 3.2.12.3 The field model of gravity

3.2.8.1 Gravitational force and field strength

3.2.3.2 The inverse square law

ESSENTIAL PRIOR KNOWLEDGE

1B Newton's third law of motion

1B Gravitational force

See questions 36–37.

How can we calculate the mass of the earth?

You may experience an attraction to someone, but not in the way that you think. Every object with mass produces its own gravitational field, attracting all other objects to it. We experience gravitational fields and forces every day even if we don't always feel them. This lesson will explore the gravitational fields associated with the mass of different objects, and gravitational forces that act between masses.

KEY TERMS AND DEFINITIONS

field a region of space in which each point is subject to a non-contact force

non-contact force a force applied to an object by another body not in contact with it

monopole a type of field in which all field lines either point towards or away from the object(s) generating the field

uniform field a field that has the same magnitude and direction at all locations in space

non-uniform field a field that varies in magnitude or direction at different locations in space

gravitational field strength a measure of the gravitational force acting on each unit of mass at a point in space

altitude the height of an object in relation to the surface of the planet

FORMULAS

- **force due to gravity**
  $F_g = mg$
- **Newton's law of universal gravitation**
  $F_g = G\frac{m_1 m_2}{r^2}$
- **gravitational field strength**
  $g = G\frac{M}{r^2}$
- **inverse square law for gravitation**
  $g_2 = g_1\left(\frac{r_1}{r_2}\right)^2$

The field model of gravity 3.2.1.1 & 3.2.3.1 & 3.2.12.3

A **field** is a way of modelling a region of space in which each point is subject to a **non-contact force**. The gravitational fields of objects can be modelled using field diagrams. All objects with mass have an associated gravitational field that attracts all other objects with mass.

How can we represent gravitational fields?

There are three non-contact forces we need to consider in VCE Physics:

- gravitational force
- electric force
- magnetic force.

These non-contact forces can be modelled as fields, which are depicted using field lines.

Fields have the following characteristics:

- Field lines can be represented by vectors, with the direction of the arrows indicating the direction of the field.
- Field lines that are closer together indicate a stronger field.
- Field lines that are further apart indicate a weaker field.
- Field lines never intersect or touch – if they did, then it would indicate a point where the field (and therefore the force) points in two different directions.

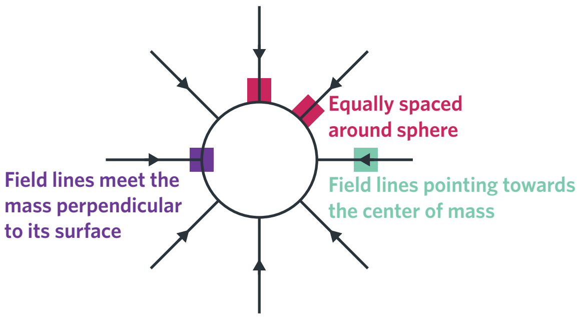

Figure 1 Gravitational field conventions

Gravitational fields are considered **monopoles**, since gravitational field lines always point towards the centre of mass. Monopoles and dipoles are discussed in more detail in Lessons 4A and 4B. Gravitational field lines have the following conventions (Figure 1):

- Gravity is always attractive – field lines are straight and point towards the centre of mass, never away from it.
- For spherical objects, field lines should be equally spaced around the sphere and meet the surface at 90°.
- Gravitational fields extend infinitely far out into space, so the gravitational field lines should be drawn with an appropriate length to represent that.

Fields can be classified as **uniform** or **non-uniform**.

- A uniform field is a field that has a constant magnitude and direction at all points. It is represented by evenly spaced, parallel lines.
- In a non-uniform field, the magnitude and direction of the field varies depending on the location. Non-uniform field lines point in different directions and have inconsistent spacings in various regions of the field.

Figure 2 shows that a planet's gravitational field is non-uniform as it is stronger on the surface and gets weaker the further away you travel. However, Figure 3 shows that the gravitational field near the surface of a planet can be approximated as uniform when dealing with everyday objects – this is why we can approximate the acceleration due to the gravity on the surface of Earth as a constant 9.8 m s^{-2}.

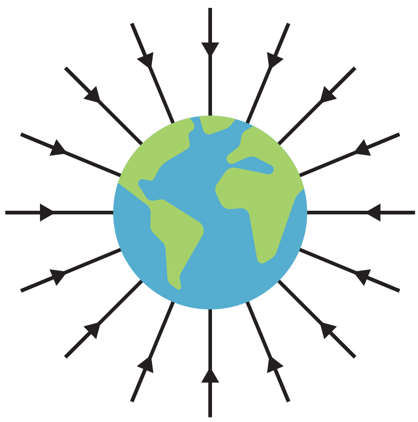

Figure 2 Gravitational field lines show the gravitational field as non-uniform

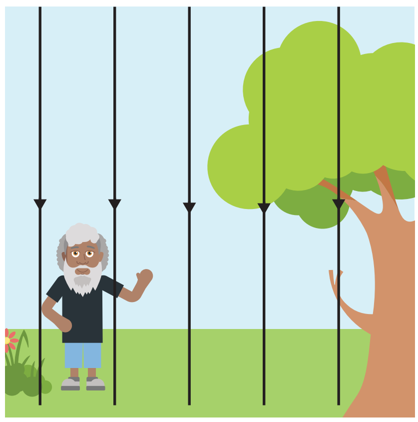

Figure 3 Gravitational field lines appear uniform near the surface of the Earth

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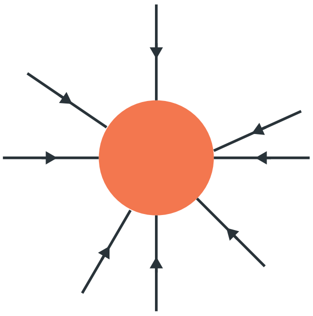
PROGRESS QUESTIONS

Question 1

Which gravitational field line convention is not followed in the diagram?



A. Field lines never intersect or touch.

B. Field lines are evenly spaced apart.

C. Field lines point towards the centre of mass.

D. Field lines have arrows to indicate the direction of the field.

Question 2

Which of the following statements is false?

A. Gravitational force is always repulsive.

B. Gravitational force is a non-contact force.

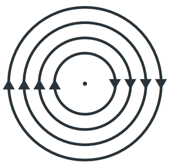
C. All objects with mass create gravitational fields.

D. Acceleration due to gravity is the same for all objects within a uniform gravitational field.

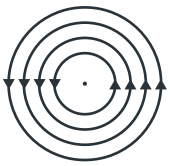
Question 3

Which of the following best represents the gravitational field around a planet?

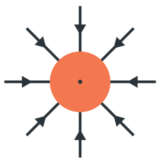
A.



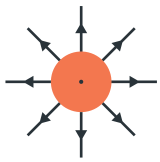
B.



C.



D.



Gravitational force and field strength 3.2.8.1

We can use Newton's law of universal gravitation to calculate the gravitational force between masses and the **gravitational field strength** at any distance from a mass.

How can we calculate gravitational forces and the strength of a gravitational field?

Gravitational forces are always attractive. Newton's law of universal gravitation states that the gravitational force between two objects with mass can be calculated using:

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FORMULA

$$F_g = G\frac{m_1 m_2}{r^2}$$

F_g = force due to gravity (N)
G = universal gravitational constant (6.67×10^{-11} N m^2 kg^{-2})
m_1 = mass of one object (kg)
m_2 = mass of another object (kg)
r = distance between the centres of the two objects (m)

USEFUL TIP

G is the universal gravitational constant. It always has the same value of 6.67×10^{-11} N m^2 kg^{-2} and is used to relate different quantities involving gravitation.[1]

KEEN TO INVESTIGATE?

[1] **How do we know the value of the universal gravitational constant?**
Search YouTube: Gravitational constant explained

According to Newton's third law of motion, the gravitational force between two objects with mass will be equal and opposite (Figure 4).

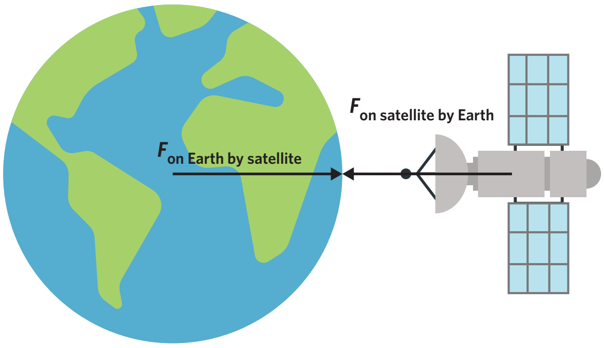

Figure 4 The force of the Earth's gravity acting on the satellite and the force of the satellite's gravity acting on the Earth are an action-reaction pair.

USEFUL TIP

It does not matter which object is m_1 or m_2 when using Newton's law of universal gravitation, as the gravitational force between the two objects is always equal and opposite.

The gravitational force that an object, with mass m, experiences is due to the gravitational field of another object, M. Rearranging $F_g = mg = G\frac{mM}{r^2}$, shows us that the gravitational field due to the mass M is given by:

FORMULA

$$g = G\frac{M}{r^2}$$

g = gravitational field strength (N kg^{-1} or m s^{-2})
G = universal gravitational constant (6.67×10^{-11} N m^2 kg^{-2})
M = mass of object creating gravitational field (kg)
r = distance from centre of object (m)

There are some points to note about this relationship:

- The gravitational field strength depends on only the mass creating the field – larger masses have larger gravitational field strengths at the same distance from their centres.
- In VCE Physics, the gravitational field of an object will always originate from the centre of mass.
- As distance increases, gravitational field strength decreases (Figure 5).[2]

KEEN TO INVESTIGATE?

[2] **How does mass affect orbit**
Search: Gravity and orbits simulation

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USEFUL TIP

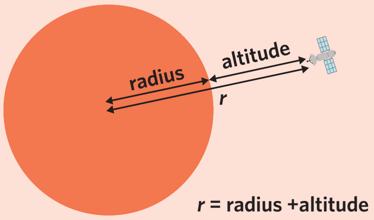

Figure 6 Finding r given the radius and altitude

When calculating gravitational field strength and gravitational force, *r* refers to the distance from the centre of the object to the location we are considering. Words like '**altitude**' and 'height' refer to the distance from the surface of the object. If given the altitude, remember to add the radius of the object to this value (Figure 6).

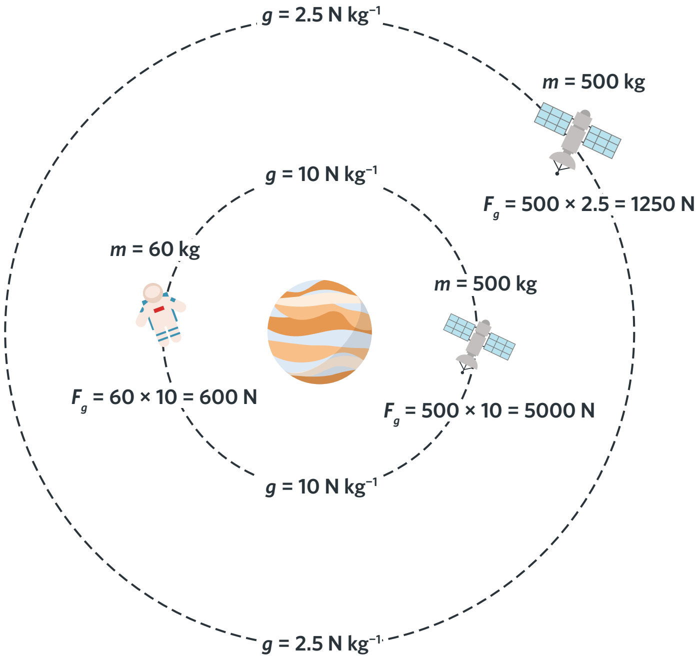

Figure 5 Objects experience different forces depending on their distances away.

KEEN TO INVESTIGATE?

[3] **Do heavier objects fall faster?**
Search YouTube: Misconceptions about falling objects

The units of gravitational field strength can be N kg^{-1} or m s^{-2}. This indicates that gravitational field strength is a measure of how quickly an object speeds up towards the centre of the body generating the gravitational field (assuming there is no air resistance acting on the object). This is also known as the acceleration ($g = a$).[3]

WORKED EXAMPLE 1

Use the data table to answer the following questions.

Mass of Jupiter	1.90×10^{27} kg
Mass of Io	8.93×10^{22} kg
Orbital radius of Io from the surface of Jupiter	3.52×10^{8} m
Radius of Jupiter	6.99×10^{7} m
Universal gravitational constant	6.67×10^{-11} N m^2 kg^{-2}

a. Calculate Jupiter's gravitational field strength at Io.

Step 1

Identify known and unknown variables and write down the formula that relates these variables.

$G = 6.67 \times 10^{-11}$ N m^2 kg^{-2}, $M_J = 1.90 \times 10^{27}$ kg,
$r = 3.52 \times 10^{8} + 6.99 \times 10^{7} = 4.22 \times 10^{8}$ m, $g = ?$

Note that *r* is the sum of the radius of Jupiter and the distance to Io from Jupiter's surface. As we are trying to find the gravitational field strength of Jupiter, we use the mass of Jupiter.

$$g = G\frac{M_J}{r^2}$$

Step 2

Substitute values into the formula and solve for the gravitational field strength.

$$g = 6.67 \times 10^{-11} \times \frac{1.90 \times 10^{27}}{(4.22 \times 10^{8})^2}$$

$$g = 7.116 \times 10^{-1} = 7.12 \times 10^{-1} \text{ N kg}^{-1} \text{ or m s}^{-2}$$

Continues →

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b. Calculate the magnitude of the force due to gravity on Io by Jupiter.

Step 1

Identify known and unknown variables and write down the formula that relates these variables.

$G = 6.67 \times 10^{-11}$ N m^2 kg^{-2}, $M_J = 1.90 \times 10^{27}$ kg, $m_I = 8.93 \times 10^{22}$ kg, $r = 4.22 \times 10^8$ m, $F = ?$

$$F = G\frac{m_J m_I}{r^2}$$

OR

$m_I = 8.93 \times 10^{22}$ kg, $g = 7.116 \times 10^{-1}$ N kg^{-1}

$$F = m_I g$$

Step 2

Substitute values into the formula and solve for the gravitational field strength.

$$F = 6.67 \times 10^{-11} \times \frac{1.90 \times 10^{27} \times 8.93 \times 10^{22}}{(4.22 \times 10^8)^2}$$

$F = 6.3548 \times 10^{22} = 6.35 \times 10^{22}$ N

OR

$F = 8.93 \times 10^{22} \times 7.116 \times 10^{-1}$

$F = 6.3545 \times 10^{22} = 6.35 \times 10^{22}$ N

---

c. Calculate the magnitude of the force due to gravity on Jupiter by Io.

Step 1

Identify known and unknown variables and write down the formula that relates these variables.

$F_{on\ I\ by\ J} = 6.35 \times 10^{22}$ N, $F_{on\ J\ by\ I} = ?$

$F_{on\ A\ by\ B} = -F_{on\ B\ by\ A}$

Step 2

Substitute values into the formula and solve for the magnitude of the force due to gravity on Jupiter by Io

$F_{on\ I\ by\ J} = -F_{on\ J\ by\ I}$

$-F_{on\ J\ by\ I} = -6.35 \times 10^{22}$ N

The magnitude of $F_{on\ J\ by\ I}$ is 6.35×10^{22} N

PROGRESS QUESTIONS

Use the following information to answer questions 4 and 5.

A satellite of mass 2.11×10^3 kg orbits a planet of mass 3.45×10^{25} kg. The distance between the centres of the two objects is 7.91×10^7 m. Take $G = 6.67 \times 10^{-11}$ N m^2 kg^{-2}.

Question 4

What is the magnitude of the planet's gravitational field strength at the satellite's distance?

A. 3.68×10^{-1} N kg^{-1} **B.** 2.91×10^0 N kg^{-1} **C.** 3.68×10^6 N kg^{-1} **D.** 2.91×10^7 N kg^{-1}

Question 5

What is the magnitude of the gravitational force between the satellite and the planet?

A. 7.76×10^2 N **B.** 6.14×10^3 N **C.** 7.76×10^9 N **D.** 6.14×10^{10} N

Question 6

Planet A has a radius of 6.5×10^5 m and planet B has a radius of 1.3×10^5 m. The distance between the surfaces of these planets is 2.4×10^6. Which of the following correctly gives the value of r in $F = G\frac{m_1 m_2}{r^2}$?

A. 7.8×10^5 m **B.** 1.3×10^5 m **C.** 2.4×10^6 m **D.** 3.2×10^6 m

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The inverse square law 3.2.3.2

When we do not know the mass of the object creating the gravitational field, the inverse square law can be helpful for finding relationships between the gravitational field strength and the distance from source.

How can we use the inverse square law of gravitation?

Given that the mass remains constant, the gravitational field strength of an object decreases with the square of the distance from the body creating the field: $g = G\frac{M}{r^2}$. This is known as an inverse square law.

- If the distance from the centre of a planet doubles, the gravitational field strength due to that planet becomes four times smaller (Figure 7).
- This is because the area that g is spread over increases.
- The inverse square law is useful for relating the field strength due to the same object at two different locations.

FORMULA

$$g_2 = g_1\left(\frac{r_1}{r_2}\right)^2$$

g_2 = gravitational field strength at position 2 (N kg^{-1} or m s^{-2})
g_1 = gravitational field strength at position 1 (N kg^{-1} or m s^{-2})
r_2 = distance from source centre at position 2 (m)
r_1 = distance from source centre at position 1 (m)

USEFUL TIP

If we are told that a different variable other than mass is kept constant, we can still use the relevant formulas to find the relationships between variables.

For example, if the gravitational field strength is kept constant but radius and mass change:

$$g = G\frac{M}{r^2} \Rightarrow \frac{M_1}{{r_1}^2} = \frac{M_2}{{r_2}^2}$$

If the mass of the object 'experiencing' the gravitational field is also constant, then the inverse square law applies to gravitational force as well as field strength.

$$F_2 = F_1\left(\frac{r_1}{r_2}\right)^2$$

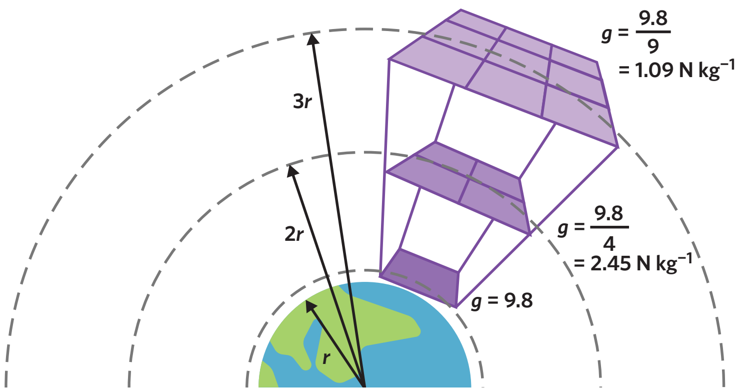


Figure 7 The gravitational field strength decreases with the square of the distance from the body.

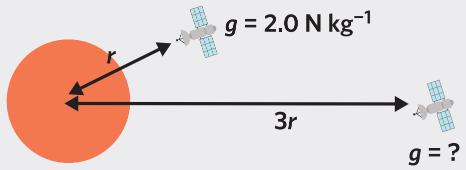
MISCONCEPTION

'There is no gravitational force in space.'

There is at least a small amount of gravitational force everywhere in space. As we get further away from objects with mass, the gravitational field strength decreases but never reaches 0.

WORKED EXAMPLE 2

A satellite experiences a gravitational field strength of 2.0 N kg^{-1} at a distance of r from a nearby planet. Determine the value of the gravitational field strength experienced by the satellite if it moved to a distance of $3r$.



Step 1

Identify known and unknown variables and write down the formula that relates these variables.

$g_1 = 2.0 \text{ N kg}^{-1}, r_1 = r, r_2 = 3r\, g_2 = ?$

$g_2 = g_1\left(\frac{r_1}{r_2}\right)^2$

Step 2

Substitute values into the formula and solve for the gravitational field strength at the new location.

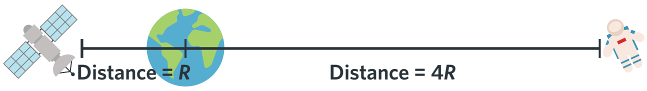
Note that we do not need to know the value of r as it cancels out in the fraction.

$g_2 = 2.0 \times \frac{r^2}{(3r)^2}$

$g_2 = 0.222 = 0.22 \text{ N kg}^{-1}$

PROGRESS QUESTIONS

Question 7



Which of the following statements is true?

A. The gravitational force on the astronaut by Earth is $\frac{1}{4}$ the Earth's gravitational force on the satellite.

B. The gravitational force on the astronaut by Earth is $\frac{1}{16}$ the Earth's gravitational force on the satellite.

C. We must know the masses of all three objects to compare the gravitational field strength of Earth on the astronaut.

D. The gravitational field strength due to Earth at the position of the astronaut is $\frac{1}{16}$ of the gravitational field strength at the position of the satellite.

Question 8

An astronaut, Theo, is at a location with a gravitational field strength due to Mars of 1.5 N kg^{-1}. If Theo moves closer so he is now half the distance from the centre of Mars he originally was, what is the value of the gravitational field strength Theo experiences?

A. 0.38 N kg^{-1} **B.** 1.5 N kg^{-1} **C.** 3.0 N kg^{-1} **D.** 6.0 N kg^{-1}

Question 9

The radius of an asteroid is 2.0×10^5 m. On the surface, the gravitational field strength is 0.1 N kg^{-1}. How far away from the centre of the asteroid would you have to be to experience a gravitational field strength of 0.05 N kg^{-1}?

A. 1.4×10^5 m **B.** 2.8×10^5 m **C.** 8.0×10^5 m **D.** 2.8×10^{10} m

Theory summary

- Fields are a way of modelling non-contact forces.
  - All objects with mass have an associated gravitational field.
  - The strength and direction of a field are represented with field lines.
- The force due to gravity acting on an object can be calculated using Newton's law of universal gravitation.
  - $F_g = G\frac{m_1 m_2}{r^2} = mg$
  - The two objects exert a force on each other that is equal in magnitude but opposite in direction.
- The gravitational field strength can be calculated using $g = G\frac{M}{r^2}$.
  - It can be measured in N kg^{-1} or m s^{-2}.
  - When there are no other forces acting on an object, its acceleration due to gravity is equivalent to the gravitational field strength at the object's position.
- The inverse square law can be used to calculate the field strength or the radius of objects without knowing their mass.
  - $g_2 = g_1\left(\frac{r_1}{r_2}\right)^2$.

3A Questions

Mild 🌶 Medium 🌶🌶 Spicy 🌶🌶🌶

Deconstructed exam-style

Use the following information to answer questions 10–12.

Mass of International Space Station (ISS)	4.19×10^5 kg
Radius of Earth	6.37×10^6 m
Altitude of the ISS	4.00×10^5 m
Gravitational force between ISS and Earth	3.65×10^6 N
Universal gravitational constant	6.67×10^{-11} N m^2 kg^{-2}

Question 10 🌶 (1 MARK)

What is the distance from the centre of the Earth to the ISS?

A. 4.00×10^5 m

B. 3.65×10^6 N

C. 6.37×10^6 m

D. 6.77×10^6 m

Question 11 🌶 (1 MARK)

Which of the following can be used to find the mass of the Earth?

A. $F = g\frac{m_1 m_2}{r}$

B. $F = G\frac{m_1 m_2}{r}$

C. $F = G\frac{m_1 m_2}{r^2}$

D. $g_2 = g_1\left(\frac{r_1}{r_2}\right)^2$

Question 12 (3 MARKS)

Calculate the mass of the Earth.

Exam-style

Question 13 (1 MARK)

Earth's moon has a mass of 7.34×10^{22} kg and a radius of 1.74×10^{6} m. Which of the following is the closest to the magnitude of the gravitational field strength on the surface of the moon? Take $G = 6.67 \times 10^{-11}$ N m^2 kg^{-2}.

A. 0.162 m s^{-2}

B. 1.62 m s^{-2}

C. 2.81 m s^{-2}

D. 9.81 m s^{-2}

Adapted from VCAA 2020 exam Multiple choice Q2

Question 14 (4 MARKS)

A spacecraft has a mass of 480 kg. It is orbiting Earth at a radius of 7.00×10^{6} m from its centre. Earth has a mass of 5.98×10^{24} kg. Take $G = 6.67 \times 10^{-11}$ N m^2 kg^{-2}.

a. Calculate the magnitude of the force that the spacecraft exerts on Earth. 2 MARKS

b. Calculate the magnitude of the acceleration due to the gravity of Earth on the spacecraft. 2 MARKS

Question 15 (2 MARKS)

The gravitational force on a satellite by a planet is 50 N. The satellite has a mass of 250 kg and is at a distance of 4.0×10^{6} m from the centre of the planet. Calculate the mass of the planet. Take $G = 6.67 \times 10^{-11}$ N m^2 kg^{-2}.

Question 16 (6 MARKS)

In 2003, the European Space Agency (ESA) launched a space probe to study Mars. The probe is currently in orbit around Mars. Assume the probe maintains the same distance from the planet's centre.

Mass of Mars	6.39×10^{23} kg
Mass of space probe	1.12×10^{3} kg
Radius of Mars	3.39×10^{6} m
Altitude of space probe's orbit	3.00×10^{5} m
Gravitational constant	6.67×10^{-11} N m^2 kg^{-2}

a. Draw a field diagram showing the gravitational field around Mars. 1 MARK

b. Show that the magnitude of the acceleration due to gravity that the probe experiences is equal to 3.13 m s^{-2}. 1 MARK

c. Calculate the magnitude of the gravitational force acting on the probe. 2 MARKS

d. Calculate the magnitude of the gravitational force someone with a mass of 80 kg would experience on the surface of Mars. 2 MARKS

Question 17 (3 MARKS)

The Earth has a mass of 5.98×10^{24} kg and a radius of 6.37×10^{6} m. A satellite of mass of 2.00×10^{3} kg experiences a gravitational force of 340 N while orbiting Earth. Calculate the altitude of the satellite.

Adapted from VCAA 2022 exam Short answer Q2b

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Question 18 (9 MARKS)

Measurements of the Moon's gravitational field strength at a range of distances are shown in the table. Assume there is an uncertainty of ± 0.05 N kg^{-1} in the measurements of the field strength. Take $G = 6.67 \times 10^{-11}$ N m^2 kg^{-2}.

Distance from surface of moon (10^3 km)	Gravitational field strength (N kg^{-1})
1.80	1.5
2.50	0.8
3.40	0.4
5.60	0.2
8.20	0.1

a. *Key science skill*

Plot the data from the table with distance on the horizontal axis and gravitational field strength on the vertical axis. Ensure you include: 🌶🌶 6 MARKS

- scales and units on each axis
- uncertainty bars for the gravitational field strength
- a non-linear line of best fit

FROM LESSON 12D

b. *Key science skill*

Using the gravitational field strength recorded at 1.8×10^3 km, calculate the maximum possible mass of the Moon when considering the uncertainty in the measurements. 🌶🌶 3 MARKS

FROM LESSON 12D

Question 19 (4 MARKS)

Mariner 10 is orbiting Mercury. In its first orbit, it experiences a gravitational field strength of 0.80 N kg^{-1}. Over two years, Mariner changes the altitude of its orbit. At its new altitude, the gravitational field strength is 0.089 N kg^{-1}.

a. Did Mariner 10 increase or decrease in altitude? 🌶 1 MARK

b. By what factor did Mariner 10 change its distance from the centre of Mercury? Give your answer to the nearest whole number. 🌶🌶🌶 3 MARKS

Question 20 🌶🌶🌶 (1 MARK)

Tulia is a planet that has a mass that is five times that of the Earth. The gravitational field strength at the surface of Tulia is 1.5 m s^{-2}.

If Earth has a radius r, which one of the following is the closest to the radius of Tulia?

A. $0.6r$

B. $1.8r$

C. r

D. $5r$

Adapted from VCAA 2021 exam Multiple choice Q4

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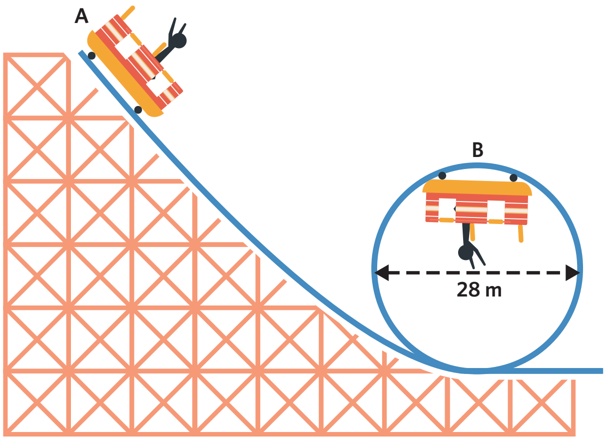
Previous lessons

Question 21 (3 MARKS)

Paige is riding a loop-the-loop roller coaster. The combined mass of Paige and the cart is 90 kg. She starts at point A from rest and when she reaches point B, her speed is 13 m s^{-1}. The diameter of the first loop is 28 m. Calculate the magnitude of the normal reaction force on Paige and the cart by the track when she reaches point B.



Adapted from VCAA 2019 exam Short answer Q8b

FROM LESSON 1G

Question 22 (2 MARKS)

A piano with a mass of 91 kg is dropped from the top of a building with a height of 24 m. What is the piano's change in gravitational potential energy if it lands on the ground below?

FROM LESSON 2C

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3B Gravitational potential energy in uniform and non-uniform fields

STUDY DESIGN DOT POINTS

- investigate and compare theoretically and practically gravitational fields and electrical fields about a point mass or charge (positive or negative) with reference to:
  - the direction of the field
  - the shape of the field
  - the use of the inverse square law to determine the magnitude of the field
  - potential energy changes (qualitative) associated with a point mass or charge moving in the field
- analyse the use of gravitational fields to accelerate mass, including:
  - gravitational field and gravitational force concepts: $g = G\frac{M}{r^2}$ and $F_g = G\frac{m_1 m_2}{r^2}$
  - potential energy changes in a uniform gravitational field: $E_g = mg\Delta h$
- analyse the change in gravitational potential energy from area under a force vs distance graph and area under a field vs distance graph multiplied by mass

3A 3B 3C

3.2.8.2 & 3.2.3.3 & 3.2.9.1 GPE in uniform and non-uniform fields

ESSENTIAL PRIOR KNOWLEDGE

2A Kinetic energy
2C Conservation of energy
3A Identifying uniform and non-uniform fields

See questions 38–40.

How much energy does it take to launch a rocket into space?

As rockets get higher and higher into the atmosphere, they gain more gravitational potential energy. Changes in gravitational potential energy are due to changes in height, changes in gravitational field strength, and changes to the mass of the rocket in this case. This lesson will explore how gravitational potential energy changes in a non-uniform field.

KEY TERMS AND DEFINITIONS

gravitational potential energy (GPE) the stored energy associated with the position of an object in a gravitational field

FORMULAS

- **gravitational potential energy (in uniform fields)**
  $\Delta GPE = mg\Delta h$

GPE in uniform and non-uniform fields 3.2.8.2 & 3.2.3.3 & 3.2.9.1

Lesson 2C discusses that changes in **gravitational potential energy (GPE)** occur due to an object's change in height across an approximately uniform gravitational field. However, as we get further away from the centre of mass of an object, the gravitational field strength decreases.

USEFUL TIP

The change in height is between two points of reference. Sometimes the ground can be taken as $h = 0$, and other times the top of a rocket could be taken as $h = 0$.

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How do we calculate the change in gravitational potential energy of an object in uniform fields?

Recall that gravitational potential energy can be calculated using:

$$\Delta GPE = mg\Delta h$$

This is applicable to gravitational fields that are uniform or approximately uniform.

- Near the Earth's surface, we say that the gravitational field is approximately uniform.
- We can also find ΔGPE by calculating the area under a force vs displacement graph.
- As we get further away from the centre of Earth, the gravitational field can no longer be approximated as uniform and we cannot use this equation to calculate ΔGPE.

USEFUL TIP

The area under a force-displacement graph represents the work done by a force. This means the area under a gravitational force-displacement graph will give us the magnitude of the change in gravitational potential energy ($W = \Delta GPE$).

PROGRESS QUESTIONS

Question 1

On the surface of Mars, the gravitational field is approximately uniform and has a value of 3.71 m s^{-2}. A spanner of mass 0.199 kg is dropped from the top of a spacecraft that is 4.00 m tall. If the spanner lands on the ground, what is the change in gravitational potential energy of the spanner?

A. 2.95 J

B. 5.68 J

C. 7.80 J

D. We cannot calculate the change in gravitational potential energy because it is in a non-uniform field.

Question 2

As Sam is drifting out in space, the gravitational force acting on them changes significantly. Can we use $\Delta GPE = mg\Delta h$ to calculate Sam's change in gravitational potential energy?

A. We can use $\Delta GPE = mg\Delta h$, because Sam is in a uniform field.

B. We cannot use $\Delta GPE = mg\Delta h$, because Sam is in a uniform field.

C. We can use $\Delta GPE = mg\Delta h$, because Sam is in a non-uniform field.

D. We cannot use $\Delta GPE = mg\Delta h$, because Sam is in a non-uniform field.

How do we calculate the change in gravitational potential energy in non-uniform fields?

In non-uniform fields, the gravitational field strength decreases as the distance from the surface of a planet increases (Figure 1).

- The gravitational field strength increases linearly from the centre of the planet to the surface, then
- decreases from the surface outwards as per the inverse square law.

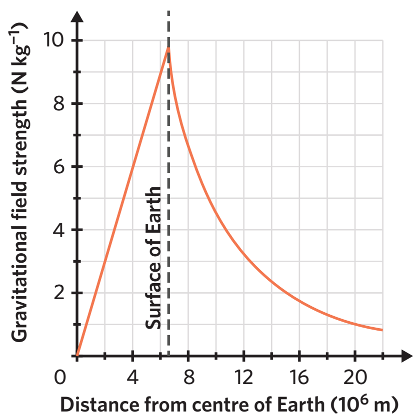
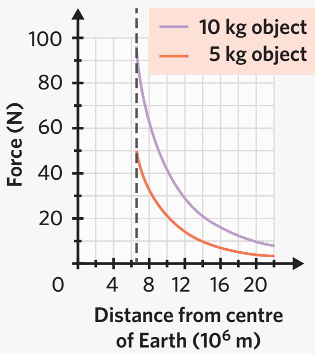
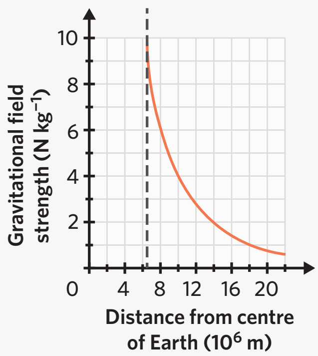


Figure 1 Gravitational field strength versus distance from centre of Earth

We can use force-distance graphs and field-distance graphs to determine the change in gravitational potential energy (Table 1) of an object moving in a non-uniform gravitational field.

Table 1 Using force-distance and field-distance graphs to calculate ΔGPE in non-uniform fields

	Force-distance graph	Field-distance graph
How do we identify the graph?	• The vertical axis is force (measured in N) • The horizontal axis is distance.	• The vertical axis is gravitational field strength (measured in N kg^{-1} or m s^{-2}) • The horizontal axis is distance.
What does it represent?	The magnitude of the force that an object with a particular mass would experience at a given distance from the centre of another body which is creating a gravitational field.	The magnitude of the gravitational field strength at a given distance from the centre of another body which is creating a gravitational field.
Which formula is used to relate the variables?	$F_g = G\frac{m_1 m_2}{r^2}$	$g = G\frac{M}{r^2}$ Note that this only depends on the mass of the body creating the gravitational field.
What is an example of a graph?	 **Figure 2** Gravitational force-distance graph for two different objects due to Earth's gravitational field	 **Figure 3** Gravitational field strength vs distance from the surface of the Earth
How can we calculate ΔGPE?	Calculate the area under the graph between two distances from the centre. *ΔGPE = area under the gravitational force-distance graph*	Calculate the area under the graph between two distances from the centre and multiply it by the mass of the object moving through the field. *ΔGPE = area under the gravitational field-distance graph × mass of object experiencing field*

USEFUL TIP

Force-distance and field-distance graphs can also be used to determine other values. We can read off a force-distance graph to find the magnitude of the force for a particular distance. Similarly with a field-distance graph we can determine the gravitational field strength for a particular distance, and vice versa.

Other things to note for force–distance graphs:

- Figure 2 shows that the shape of the force-distance graphs will have the same shape for an object with any mass, however the magnitude of the force will be different.
- When the force due to gravity is the only force acting on an object, work done, ΔGPE, and ΔKE are equal in magnitude.
  - This is because the gravitational potential energy transforms into kinetic energy as an object falls according to the law of conservation of energy ($\Delta KE = \Delta GPE$).
  - In this case, the area under a force-distance graph also provides the work done by an object to overcome the force due to gravity ($W = Fs$).

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STRATEGY

A common way of finding the area under a graph is to use the 'counting squares' method (Figure 4).

1. Count the number of squares under the graph between the two distances we are using to calculate the change in gravitational potential energy. Instead of keeping track of fractions of boxes, use the following rule:
   - If more than half of a square is under the line, include the whole square (squares 1 and 7)
   - If less than half of a square is under the line, exclude the whole square
2. Calculate the area of one square using the formula $Area = base \times height$.
   - Here, each square has dimensions of $5.0\ \text{N} \times 1.0\ \text{m} = 5.0\ \text{J}$
3. Multiply the total number of squares by the area of one square.
   - $Area = 9 \times 5.0 = 45\ \text{J}$

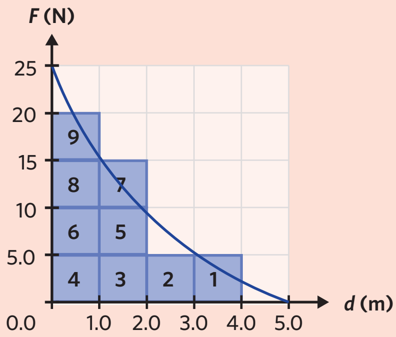


Figure 4 Counting the squares under a force-distance graph

USEFUL TIP

The units of newtons (N) multiplied by metres (m) gives the unit of joules (J). Keep this in mind when finding the area of one square on a graph to ensure the final answer is in the correct units.

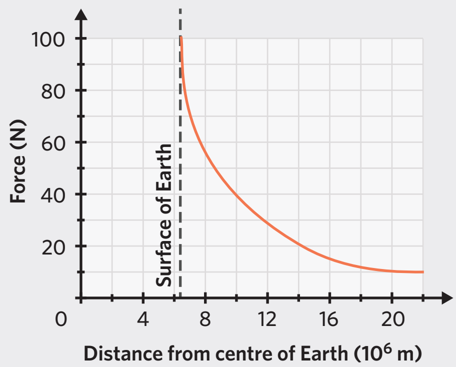
USEFUL TIP

It is a good habit to convert all units to SI units (i.e. m) whenever extracting information from a graph. It is common for an exam question to give distances in km for a force-distance or field-distance graph.

Also remember to take note of any scale factors on the axis.

WORKED EXAMPLE 1

A 10 kg object is dropped from 14×10^6 m to 8×10^6 m from the centre of the Earth. Use the graph to help answer the questions.



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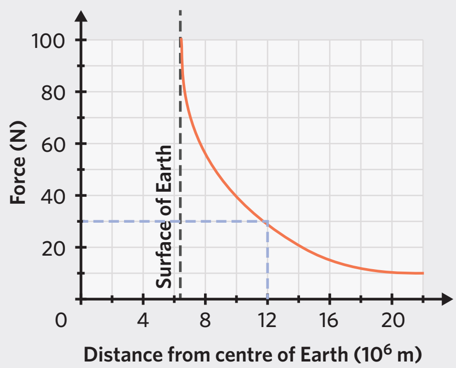
a. What is the magnitude of the force at a distance of 12×10^6 m from the centre of the Earth?

Step

Read the corresponding force of the graph for an object at a distance of 12×10^6 m.



$F_g = 30\ \text{N}$

Continues →

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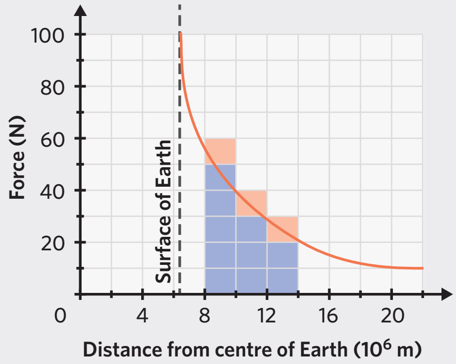
b. Calculate the magnitude of the change in the gravitational potential energy of the object.

Step 1

Identify the squares which are at least 50% below the line and in between the distances of 8×10^6 m and 14×10^6 m.



There are 10 squares under the line.

Step 2

Find the area of a single square.

$Area\ of\ square = (2 \times 10^6\ \text{m}) \times (10\ \text{N}) = 2 \times 10^7\ \text{J}$

Step 3

Multiply the number of squares by the area of each square.

$\Delta GPE = 10 \times 2 \times 10^7 = 2 \times 10^8\ \text{J}$

Note that since it is a force-distance graph, we do not need to multiply by the mass of the object. The change in gravitational potential energy is just the area under the graph.

When the scale of a graph decreases, the curved line may appear linear. We can still count squares or we can also use the area of a trapezium to calculate the area under the graph (Figure 5).

$$Area = \frac{a+b}{2} \times h$$

In relation to finding the area under a gravitational force-distance or field-distance graph:

- *a* and *b* are the two values of gravitational field force or strength
- *h* is the change in distance.

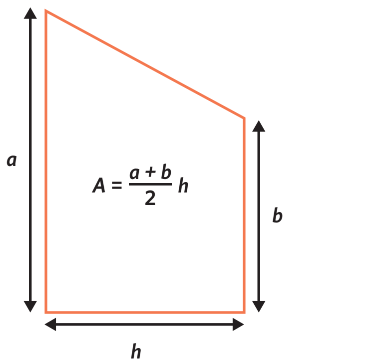


Figure 5 The area under a graph can be calculated using the area of a trapezium.

USEFUL TIP

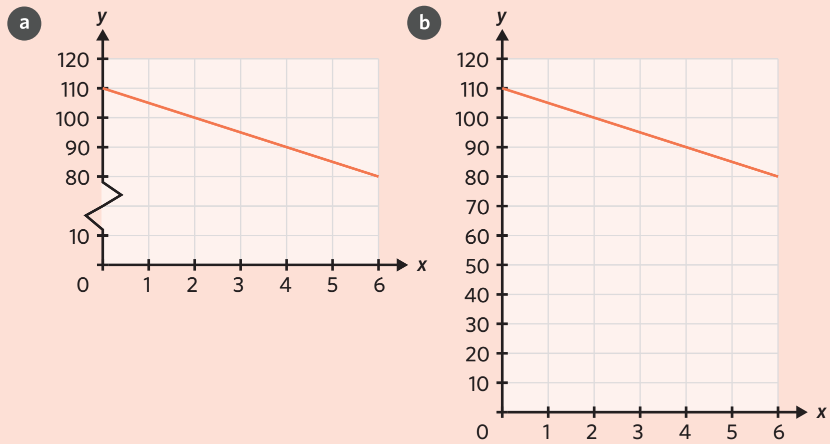


Figure 6 **(a)** A graph with a break in the data on the vertical axis and **(b)** a graph without.

A break in the data can be used to keep graphs from being unnecessarily tall or long (Figure 6).

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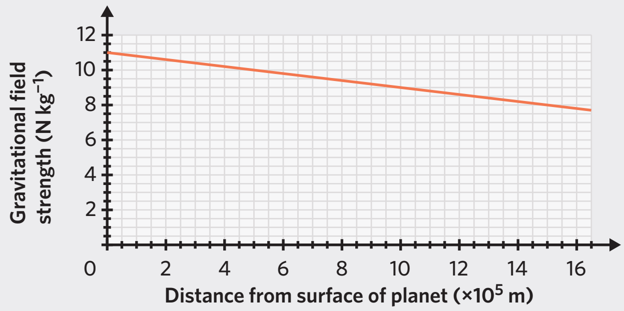
WORKED EXAMPLE 2

The graph shows the relationship between the gravitational field strength of a planet and the height from its surface.

A space probe of mass 500 kg flies to a distance of 10×10^5 m above the surface of the planet.

Use the graph to calculate the change in gravitational potential energy of the space probe.

Adapted from VCAA 2021 exam Short answer Q8c



Step 1

Calculate the area under the graph up to 10×10^5 m using the trapezoid method.

Note that the units are J kg^{-1} because N m is equivalent to J.

$$Area = \frac{a+b}{2} \times h = \frac{11+9}{2} \times 10 \times 10^5$$

$$Area = 10^7 \text{ J kg}^{-1}$$

Step 2

Identify known and unknown variables and write down the formula that relates these variables.

Note that since it is a field-distance graph, to find ΔGPE we need to multiply the area by the mass of the object experiencing the field (i.e. the space probe).

$Area = 10^7$ J kg^{-1}, $m = 500$ kg, $\Delta GPE = ?$

ΔGPE = *area under field–distance graph × mass of object experiencing field*

Step 3

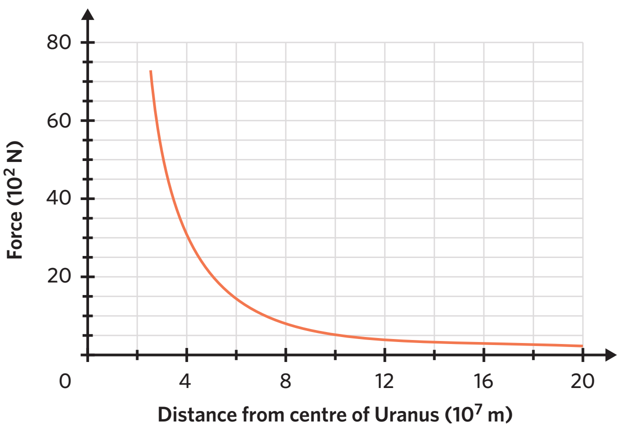
Substitute values into the formula and solve for the gravitational potential energy of the probe.

$$\Delta GPE = 10^7 \times 500$$

$$\Delta GPE = 5 \times 10^9 \text{ J}$$

PROGRESS QUESTIONS

Use the following information to answer questions 3–5.



Question 3

What is the magnitude of the gravitational force at 4×10^7 m from the centre of Uranus?

A. 4.2 N

B. 35 N

C. 3.5×10^3 N

D. 4.2×10^3 N

Continues →

Question 4

Which is closest to the number of squares under the graph between 4×10^7 m and 12×10^7 m from the centre of Uranus?

A. 4

B. 6

C. 8

D. 10

Question 5

What is the value represented by the area of one square?

A. 1.0 J

B. 10 J

C. 1.0×10^6 J

D. 1.0×10^{10} J

Question 6

If given a field vs distance graph for an object in a non-uniform field, the change in potential energy can be determined using

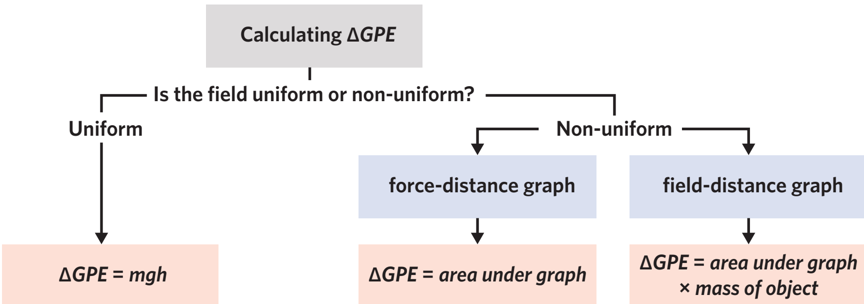
A. $\Delta GPE = mgh$.

B. ΔGPE = area under a force vs distance graph.

C. ΔGPE = area under a field vs distance graph × mass of the object in the field.

D. ΔGPE = area under a force vs distance graph × mass of the object in the field.

Theory summary



- The area under the graph can be determined by:
  - Counting squares and multiplying the number of squares by the area of each square.
  - Using the trapezoidal method: $Area = \frac{a+b}{2} \times h$
- The law of conservation of energy still applies in non-uniform fields. This means that gravitational potential energy transforms to kinetic energy as objects decrease in height.

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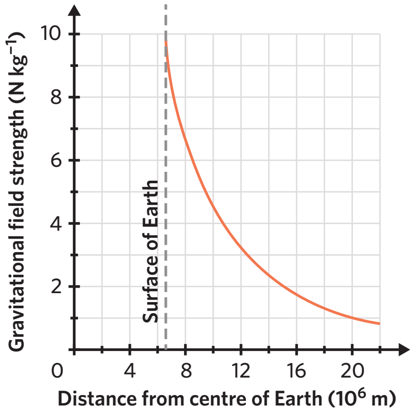
3B Questions

Mild Medium Spicy

Deconstructed exam-style

Use the following information to answer questions 7–9.

A 550 kg space probe travels from a distance of 16×10^6 to 22×10^6 m from the centre of Earth.



Question 7 (1 MARK)

How many squares are there that are 50% or more under the graph between 16×10^6 m and 22×10^6 m from the centre of Earth?

A. 1

B. 2

C. 3

D. 4

Question 8 (1 MARK)

What is the value associated with the area of one square?

A. 1 J kg^{-1}

B. 2 J kg^{-1}

C. 1×10^6 J kg^{-1}

D. 2×10^6 J kg^{-1}

Question 9 (3 MARKS)

What is the change in gravitational potential energy of the space probe?

Exam-style

Question 10 (1 MARK)

As a spacecraft decreases in altitude to land on a planet, its gravitational potential energy

A. increases.

B. remains constant.

C. is converted to kinetic energy.

D. is converted from kinetic energy.

Question 11 (2 MARKS)

Ella (75 kg) is on the surface of a planet where the gravitational field strength is only 1.9 m s^{-2}. She jumps 4.0 m above the surface of the planet. If the field can be modelled as approximately uniform, what is her change in gravitational potential energy?

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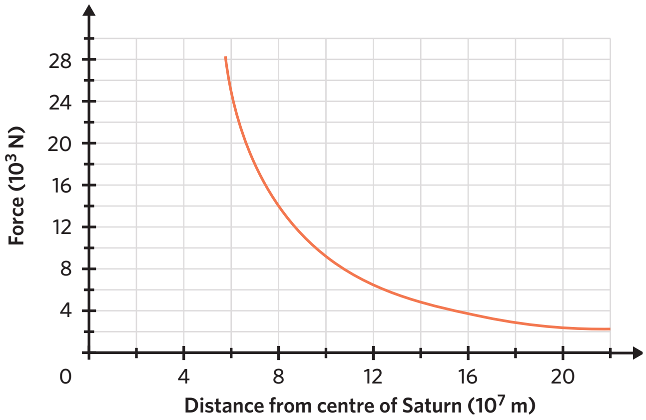
Question 12 (7 MARKS)

The spacecraft Cassini has been put into orbit around Saturn. Cassini falls from 16×10^7 m to 8.0×10^7 m from the centre of Saturn. Take Cassini's mass to be 5700 kg. A graph is used to show the gravitational force experienced by Cassini against distance from the centre of Saturn.



a. Calculate the work done by the gravitational force on Cassini when it moves from a distance of 16×10^7 m to 8.0×10^7 m from the centre of Saturn. Show your working. 🌶🌶 — 3 MARKS

b. Will the gravitational potential energy of Cassini increase, decrease, or not change as it falls closer to Saturn? Justify your answer. 🌶🌶 — 2 MARKS

c. What is the magnitude of the gravitational acceleration of Cassini at a distance of 8.0×10^7 m from the centre of Saturn? 🌶🌶 — 2 MARKS

Question 13 (5 MARKS)

Key science skill

Al and Kat both gather data on the gravitational field strength of Earth at different distances from the Earth's centre.

Distance from the centre of the Earth (m)	Gravitational field strength as measured by Al (N kg^{-1})	Gravitational field strength as measured by Kat (N kg^{-1})	True value of the gravitational field strength (N kg^{-1})
6.4×10^6	9.6	9.8	9.8
9.9×10^6	3.7	4.1	4.1
13.4×10^6	1.8	2.3	2.2
16.9×10^6	1.1	1.5	1.4
20.4×10^6	0.6	0.8	1.0

a. Plot Kat's data on a graph. Make sure to include scales and units on each axis. 🌶🌶 — 3 MARKS

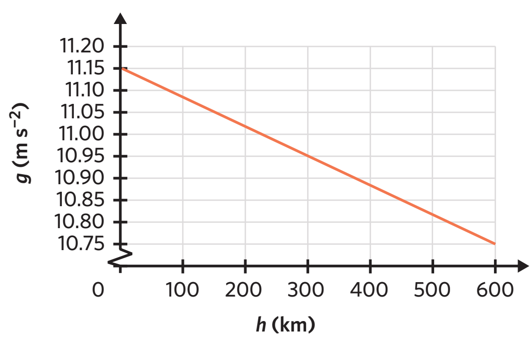
FROM LESSON 12D

b. Determine who gathered the most accurate data. Justify your answer. 🌶 — 2 MARKS

FROM LESSON 12C

Use the following information to answer questions 14 and 15.

The graph shows the strength of Neptune's gravitational field, g, vs. orbital altitude above the surface of Neptune h. The mass of the Wheeler is 311 kg.



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Question 14 (3 MARKS)

Determine the change in gravitational potential energy of the satellite, Wheeler, as it travels from the surface of Neptune to an orbital altitude of 600 km.

Adapted from VCAA 2020 exam Short answer Q4d

Question 15 (1 MARK)

At what altitude is the gravitational force on Wheeler 3.405×10^3 N?

A. 100 km

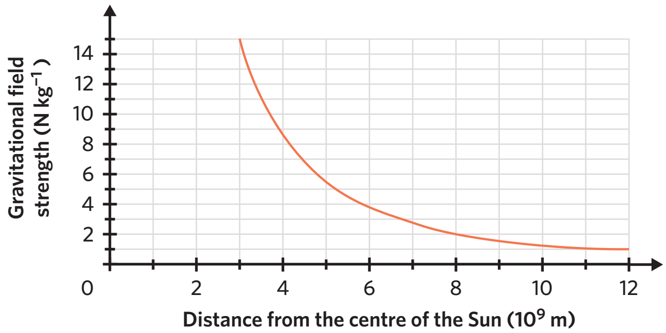
B. 200 km

C. 300 km

D. 400 km

Question 16 (5 MARKS)

The Parker Solar Probe was launched in 2018 to study the Sun. It will do this by flying closer to the Sun than any other spacecraft before. Assume the probe has a mass of 555 kg.



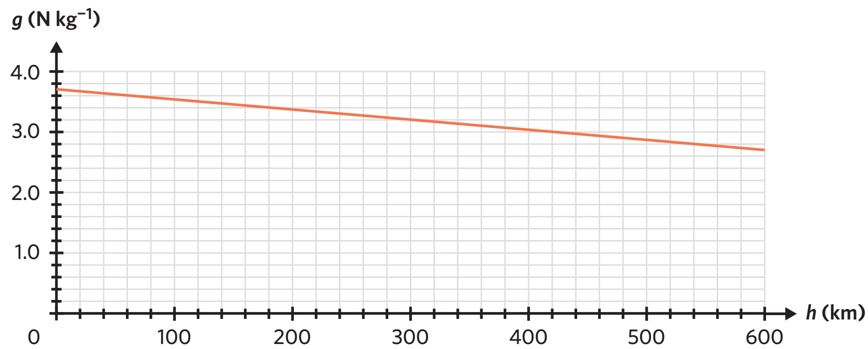
a. Use the graph to calculate the change in gravitational potential energy as the Parker Solar Probe moves from a distance of 7.0×10^9 m to 11.0×10^9 m from the centre of the Sun. 3 MARKS

b. Use the graph to find the magnitude of the gravitational force that the Parker Solar Probe experiences at a distance of 8.0×10^6 km from the centre of the Sun. 2 MARKS

Adapted from VCAA 2018 exam Short answer Q9

Question 17 (5 MARKS)

The graph shows the gravitational field strength of Mercury (g) versus altitude (h).



a. Calculate the change in gravitational potential energy of a spacecraft as it moves from 300 km to 540 km above the surface of Mercury. Take the mass of the spacecraft to be 600 kg. 2 MARKS

b. The capsule used aerodynamic braking as it descended through Mercury's atmosphere to reduce its speed from 19 000 km h^{-1} to 1500 km h^{-1}. The capsule was then at an altitude of 10 km above the surface of Mercury and had ~1.5% of its original mechanical energy remaining.

Describe how ~98.5% of the mechanical energy of the capsule was transformed and dissipated as the capsule descended from an altitude of 520 km above the surface of Mercury to an altitude of 10 km above the surface of Mercury. No calculations are required. 3 MARKS

Adapted from VCAA 2021 exam Short answer Q8

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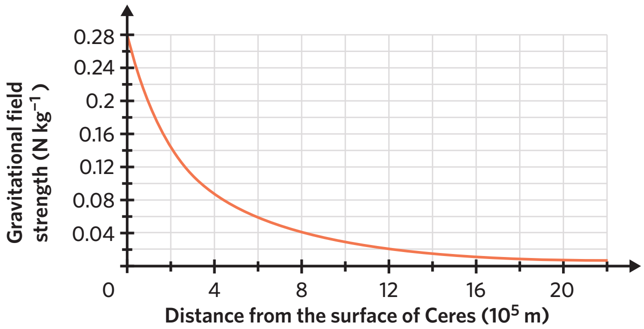
Question 18 (5 MARKS)

The graph shows the gravitational field strength versus the distance from the surface of Ceres.



a. A 500 kg object falls from 22×10^5 m onto the surface of Ceres. Calculate the amount of kinetic energy the object gains. 3 MARKS

b. Assuming that the object begins with a speed of 50.0 m s^{-1}, determine the speed at which the object will impact Ceres. 2 MARKS

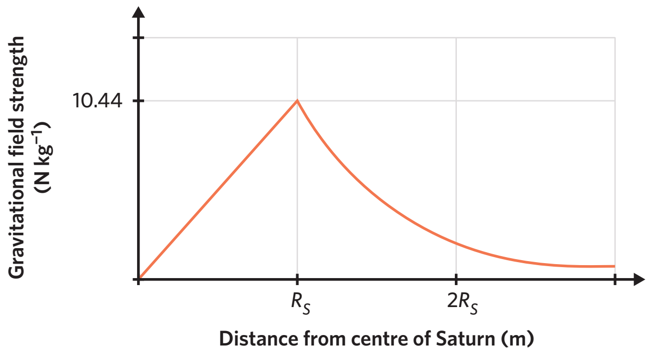
Question 19 (2 MARKS)

Assume that a journey from approximately 2 Saturn radii ($2R_S$) down to the centre of Saturn is possible. The radius of Saturn (R_S) is 5.82×10^7 m. Assume that Saturn is a sphere of constant density.

A graph of gravitational field strength versus distance from the centre of Saturn is shown.

An 80 kg person moves from the centre of Saturn to its surface. Calculate the increase in their gravitational potential energy.

Adapted from VCAA 2019 exam Short answer Q4c



Previous lessons

Question 20 (3 MARKS)

A ball is launched towards a wall which is 25 m away. The ball is launched from a height of 2.0 m at a speed of 20 m s^{-1} and angle of 40° above the horizontal. At what height above the ground will the ball hit the wall?

FROM LESSON 1H

Question 21 (2 MARKS)

The gravitational field strength on the surface of Europa is 1.214 N kg^{-1}. The 252 kg Europa Clipper lander-craft is dropped vertically 5.00 m from rest onto the surface of Europa.

Calculate the kinetic energy of Europa Clipper just before it reaches the surface.

FROM LESSON 2C

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3C Orbital motion

Image: SCStock/Shutterstock.com

How does the moon affect the tides?

As discussed in Lesson 3A, all objects with mass have associated gravitational fields. As the Moon orbits the Earth, the Moon's gravitational field causes the ocean to have high and low tides. This creates phenomena such as tidal islands – like Mont Saint-Michel, which is accessible by land during low tide but only by bridge or boat during high tide. This lesson will combine our knowledge of gravitational fields and forces with the understanding of circular motion, and introduce the mathematics necessary to describe the orbital motion of satellites.

STUDY DESIGN DOT POINTS

- apply the concepts of force due to gravity and normal force including in relation to satellites in orbit where the orbits are assumed to be uniform and circular
- model satellite motion (artificial, Moon, planet) as uniform circular orbital motion: $a = \frac{v^2}{r} = \frac{4\pi^2 r}{T^2}$
- model natural and artificial satellite motion as uniform circular motion

3A 3B 3C

3.2.10.1 & 3.1.3.1 Modelling satellites in orbit

3.2.11.1 Orbital radius, period, and speed

ESSENTIAL PRIOR KNOWLEDGE

1E Circular motion

3A Gravitational fields

See questions 41–42.

KEY TERMS AND DEFINITIONS

orbit a periodic curved path an object takes around another object

satellite any object that gravitationally orbits another body, such as a planet or star

period the time taken to complete one cycle

FORMULAS

- circular speed
  $v = \frac{2\pi r}{T}$
- centripetal acceleration
  $a = \frac{v^2}{r} = \frac{4\pi^2 r}{T^2}$
- orbital speed
  $v = \sqrt{\frac{GM}{r}}$
- Kepler's third law
  $4\pi^2 r^3 = GMT^2$

Modelling satellites in orbit 3.2.10.1 & 3.1.3.1

In VCE Physics we model **orbits** as uniform circular motion, where the gravitational force is the centripetal force acting radially inwards. Therefore, the only force causing the Moon to remain in orbit is Earth's gravitational force. The Moon, or any objects in orbit, are known as **satellites**.

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3C THEORY

How do we analyse orbital motion?

Isaac Newton was a key figure in developing the ideas for orbital mechanics. In order to understand what an orbit was he came up with a thought experiment (Figure 1). He imagined a cannon on the highest mountain on Earth, firing cannon balls horizontally at ever-increasing speeds.

Ignoring air resistance, if the cannonball is:

- launched at a speed which is too slow, the ball will hit the ground.
- launched at a speed which is too fast, the ball will 'escape' the Earth's gravitational field.
- launched at just the right speed (known as orbital speed), the ball will continuously fall towards the Earth without ever getting closer to it, due to the curvature of the Earth. Hence, the ball will orbit the Earth at a constant radius from its centre.

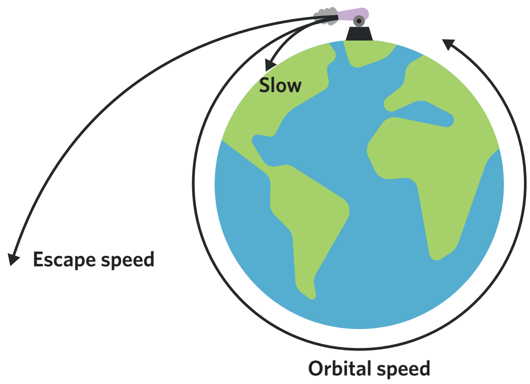

Figure 1 Isaac Newton's thought experiment of firing a cannonball around Earth

Lesson 1E discusses that for an object moving in a circular path, the net force must act radially inwards (towards the centre of the circular path). When analysing the orbits of satellites, this net force is equal to the gravitational force of the planet or star the satellite is orbiting ($F_{net} = F_g$). Therefore, for satellites in orbit the force due to gravity provides the centripetal force:

$$F_g = \frac{mv^2}{r}$$

Orbiting objects actually orbit in an elliptical path but for VCE Physics we model them as circular paths.[1]

KEEN TO INVESTIGATE?

1. **Why do planets orbit in elliptical paths?**
   Search YouTube: Solar system dynamics orbits and Kepler's laws
2. **Why do objects float in space?**
   Search YouTube: Why are astronauts weightless?
3. **How does the moon affect the tides?**
   Search: Tides NASA

STRATEGY

From Lesson 1E, recall that an object undergoes uniform circular motion if the net force acting on it is:

- constant in magnitude
- directed perpendicular to an object's velocity.

As the gravitational force acting on a satellite is constant and perpendicular to the satellite's velocity, a satellite moving at orbital speed will undergo uniform circular motion.

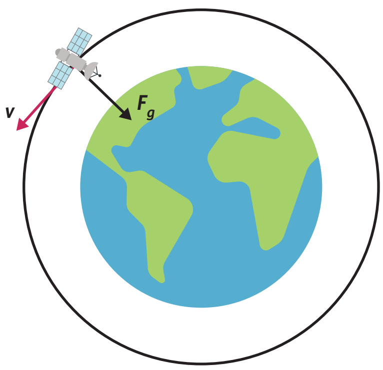

Figure 2 The direction of the centripetal force and velocity on a satellite orbiting Earth

In Figure 2, Earth's gravitational force pulls the satellite radially inwards, while the satellite's velocity vector points tangentially along its circular path. Similar to a skydiver plummeting towards Earth, the satellite and its astronauts are in constant freefall so do not experience a normal force like a person standing on the ground.[2]

Satellites still exert an equal and opposite gravitational force on the body they orbit. The effects of these forces can range from negligible in the case of small satellites, to stabilising Earth's wobble and causing ocean tides in the case of the Moon.[3]

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PROGRESS QUESTIONS

Question 1

Which of the following identifies the centripetal force acting on a satellite in orbit?

A. tension

B. normal force

C. frictional force

D. force due to gravity

Question 2

Which of the following identifies the direction of a satellite's velocity vector?

A. radially inwards

B. radially outwards

C. in the direction of the satellite's motion

D. perpendicular to the direction of the centripetal force

MISCONCEPTION

'Gravity does not act on astronauts in orbit.'

The gravitational field strength of Earth at the distance of the ISS is still about 90% of that on the surface. However, the astronauts appear to float because they and the satellite they're in are in a state of free fall. Since the astronauts and the satellite fall at the same rate, they are effectively weightless relative to each other.

Orbital radius, period, and speed 3.2.11.1

The laws of planetary motion can be used to calculate the radius, **period**, and speed of an object in a circular orbit. For a satellite orbiting at a constant radius around a central body, there is only one allowable orbital period and speed.

How do we model orbital velocity?

Since we model the orbits of satellites as circular, we can use our knowledge of circular motion to understand the motion of satellites. From Lesson 1E, recall that an equation to calculate circular speed is $v = \frac{2\pi r}{T}$. We can translate this into the context of orbital motion to arrive at the formula:

FORMULA

$$v = \frac{2\pi r}{T}$$

v = orbital speed (m s^{-1})
r = radius of orbit (m)
T = orbital period (s)

We can then equate the acceleration due to gravity of the central body, $g = G\frac{M}{r^2}$, to the centripetal acceleration formula introduced in Lesson 1E, $a = \frac{v^2}{r}$ to arrive at $G\frac{M}{r^2} = \frac{v^2}{r}$. It's important to note that the orbital radius, r, is measured from the centre of both the central body and the satellite orbiting. However, the radius of small artificial satellites, like the International Space Station, are often considered negligible when compared to the radius of planets and stars.

USEFUL TIP

The mass of the satellite in orbit does not affect its orbital speed.

This relationship can be rearranged to give the orbital speed of a satellite at a given orbital radius:

FORMULA

$$v = \sqrt{\frac{GM}{r}}$$

v = orbital speed (m s^{-1})
G = gravitational constant (6.67×10^{-11} N m^2 kg^{-2})
M = mass of body being orbited (kg)
r = radius of orbit (m)

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WORKED EXAMPLE 1

A spacecraft is in a stable orbit around Earth.

Mass of Earth	5.98×10^{24} kg
Orbital radius	2.28×10^{7} m
Gravitational constant	6.67×10^{-11} N m^2 kg^{-2}

Use the data provided to calculate the speed of the spacecraft.

Step 1

Identify known and unknown variables and write down the formula that relates these variables.

$G = 6.67 \times 10^{-11}$ N m^2 kg^{-2}, $M = 5.98 \times 10^{24}$ kg, $r = 2.28 \times 10^{7}$ m, $v = ?$

$$v = \sqrt{\frac{GM}{r}}$$

Step 2

Substitute values into the formula and solve for the speed of the spacecraft.

$$v = \sqrt{\frac{6.67 \times 10^{-11} \times 5.98 \times 10^{24}}{2.28 \times 10^{7}}}$$

$v = 4.183 \times 10^{3} = 4.18 \times 10^{3}$ m s^{-1}

PROGRESS QUESTIONS

Question 3

A satellite orbits the Earth at a radius of 4.56×10^{7} m. Take the mass of the Earth to be 5.98×10^{24} kg and $G = 6.67 \times 10^{-11}$ N m^2 kg^{-2}. What speed is the satellite travelling at?

A. 4.38×10^{-1} m s^{-1}

B. 2.96×10^{3} m s^{-1}

C. 4.18×10^{3} m s^{-1}

D. 1.82×10^{22} m s^{-1}

Question 4

A satellite orbits the moon at a radius of 8.05×10^{6} m with a speed of 1.59×10^{3} m s^{-1}. Calculate the magnitude of the acceleration of the satellite.

A. 2.45×10^{-11} m s^{-2}

B. 1.97×10^{-4} m s^{-2}

C. 1.97×10^{-1} m s^{-2}

D. 3.14×10^{-1} m s^{-2}

How do we model orbital periods?

Using the formula for centripetal acceleration, $a = \frac{4\pi^2 r}{T^2}$, we can establish another relationship for the uniform circular motion of satellites: $\frac{4\pi^2 r}{T^2} = G\frac{M}{r^2}$.

When rearranged and simplified, this gives us:

FORMULA

$$4\pi^2 r^3 = GMT^2$$

r = radius of orbit (m)
G = gravitational constant (6.67×10^{-11} N m^2 kg^{-2})
M = mass of object being orbited (kg)
T = orbital period (s)

USEFUL TIP

Rearranging the formula to the form $\frac{T^2}{r^3} = \frac{4\pi^2}{GM}$, shows that for any satellites orbiting the same central body, the ratio $\frac{T^2}{r^3}$ is constant. Therefore, the orbital radius and period of any satellites orbiting the same central body can be compared using $\frac{T_1^{\,2}}{r_1^{\,3}} = \frac{T_2^{\,2}}{r_2^{\,3}}$.

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As there are only three unknowns, we can rearrange this equation to find *r*, *M*, and *T*:

- $r = \sqrt[3]{\frac{GMT^2}{4\pi^2}}$
- $M = \frac{4\pi^2 r^3}{GT^2}$
- $T = \sqrt{\frac{4\pi^2 r^3}{GM}}$

There are some important points to emphasise here.

- A satellite's orbital radius, period, and speed are all independent of its mass.
  - Using the equation $T = \sqrt{\frac{4\pi^2 r^3}{GM}}$, we can see that $T \propto \sqrt{r^3}$. This means that to remain in a stable orbit:
    - if a satellite's period increases, then its orbital radius must also increase
    - if a satellite's orbital radius increases, then its period must also increase
  - Using the equation $v = \sqrt{\frac{GM}{r}}$, we can see that $v \propto \frac{1}{\sqrt{r}}$. This means that to remain in a stable orbit:
    - if a satellite's orbital speed increases then its orbital radius must decrease
    - if a satellite's orbital radius increases then its orbital velocity must decrease

Another way to think of it is that satellites with a smaller radius must travel faster and have shorter periods to remain in orbit.

USEFUL TIP

It is common for exams to ask a question which requires the relationship between orbital period and orbital radius. It can be helpful to copy into your pre-written notes the transformed equations for the radius, mass, period, and orbital speed.

WORKED EXAMPLE 2

Provided is data for Jupiter's moon, Europa:

Orbital period of Europa	3.08×10^5 s
Orbital radius	6.71×10^8 m
Gravitational constant	6.67×10^{-11} N m^2 kg^{-2}

a. Calculate the speed of Europa's orbit.

Step 1

Identify known and unknown variables and write down the formula that relates these variables.

$r = 6.71 \times 10^8$ m, $T = 3.08 \times 10^5$ s, $v = ?$

$v = \frac{2\pi r}{T}$

Step 2

Substitute values into the formula and solve for the speed of Europa's orbit.

$v = \frac{2\pi \times 6.71 \times 10^8}{3.08 \times 10^5}$

$v = 1.369 \times 10^4 = 1.37 \times 10^4$ m s^{-1}

b. Calculate the mass of Jupiter.

Step 1

Identify known and unknown variables and write down the formula that relates these variables.

$r = 6.71 \times 10^8$ m, $G = 6.67 \times 10^{-11}$ N m^2 kg^{-2}, $T = 3.08 \times 10^5$ s, $M = ?$

$4\pi^2 r^3 = GMT^2$

Step 2

Substitute values into the formula and solve for the mass of Jupiter.

$4\pi^2 \times (6.71 \times 10^8)^3 = 6.67 \times 10^{-11} \times M \times (3.08 \times 10^5)^2$

$M = 1.88 \times 10^{27}$ kg

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KEEN TO INVESTIGATE?

4 **How can we utilise different types of orbit**
Search Youtube: Types of orbits UNSW physics

Geostationary orbits

A geostationary orbit is a special case where a satellite remains above the same location on Earth's surface throughout its orbit (Figure 3).[4] In order for this to occur:

- The period of the orbit must equal the period of rotation of the Earth ($T = 24$ hours).
- The satellite must orbit directly above the equator.
- The satellite must orbit in the same direction as Earth's rotation.

If any of these conditions aren't met, the satellite won't stay above the same location as it orbits.

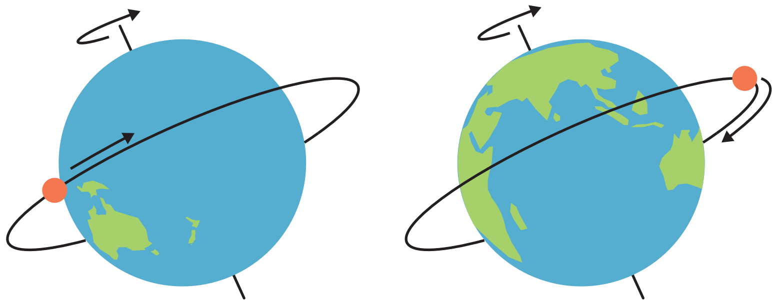

Figure 3 Geostationary satellite orbiting Earth

PROGRESS QUESTIONS

Question 5

A satellite orbiting a star increases its orbital radius. Which of the following gives the change in speed and period required for it to remain in a stable orbit?

	Speed	Period
A.	Increase	Decrease
B.	Decrease	Increase
C.	Increase	Increase
D.	Decrease	Decrease

Question 6

Use the data to calculate the orbital period of Neptune's moon, Triton.

Mass of Neptune	1.02×10^{26} kg
Orbital radius of Triton	3.55×10^{8} m
Gravitational constant	6.67×10^{-11} N m^2 kg^{-2}

A. 2.70×10^{1} s **B.** 2.87×10^{5} s **C.** 5.10×10^{5} s **D.** 2.60×10^{11} s

Question 7

Which of the following is not true about a geostationary satellite orbiting Earth?

A. It can orbit around any axis of Earth.
B. It orbits in the same direction as the Earth's rotation.
C. The orbital period is equal to the rotation of the Earth.
D. It stays above the same point above the Earth's surface.

Theory summary

- For uniform circular orbital motion of a satellite, the force due to gravity provides the centripetal force. It is the only force causing the satellite to remain in orbit.
- There is only one possible period and speed for an orbit at a given orbital radius around a given body.
- Speed, radius, and period of a satellite in orbit are related by $v = \frac{2\pi r}{T}$.
- Speed, mass, and radius of a satellite in orbit are related by $v = \sqrt{\frac{GM}{r}}$.
- Mass, radius, and period of a satellite in orbit are related by $4\pi^2 r^3 = GMT^2$.
  - $r = \sqrt[3]{\frac{GMT^2}{4\pi^2}}$
  - $M = \frac{4\pi^2 r^3}{GT^2}$
  - $T = \sqrt{\frac{4\pi^2 r^3}{GM}}$

KEEN TO INVESTIGATE?

How does the moon affect the tides?
Search YouTube: Mont Saint Michel – tide in time-lapse HD

3C Questions

Mild 🌶 Medium 🌶🌶 Spicy 🌶🌶🌶

Deconstructed exam-style

Use the following information to answer questions 8–10.

CALIPSO is a satellite that observes the air quality on Earth due to clouds and atmospheric aerosols. This satellite orbits at an altitude of 700 km above the surface of the Earth. Assume CALIPSO's orbit is circular. Take $R_E = 6.37 \times 10^6$ m, $m_E = 5.98 \times 10^{24}$, and $G = 6.67 \times 10^{-11}$ N m^2 kg^{-2}.

Question 8 🌶 (1 MARK)

Calculate the orbital radius of CALIPSO.

Question 9 🌶 (1 MARK)

Identify which of the following equations is suitable for calculating the orbital period of CALIPSO.

A. $v = \frac{2\pi r}{T}$

B. $a = \frac{4\pi^2 r}{T^2}$

C. $v = \sqrt{\frac{GM}{r}}$

D. $4\pi^2 r^3 = GMT^2$

Question 10 🌶🌶 (3 MARKS)

Calculate the orbital period of the CALIPSO satellite correct to three significant figures. Show your working.

Adapted from VCAA 2020 exam Short answer Q4b

Exam-style

Question 11 (1 MARK)

A satellite is in "Saturn-stationary" orbit (maintaining a fixed position relative to Saturn's surface). Given that a day on Saturn is 10 hours, 41 minutes and 57 seconds, what is the orbital period of the satellite in seconds?

A. 5.7×10^1 s

B. 3.1×10^3 s

C. 2.5×10^4 s

D. 3.9×10^4 s

Question 12 (2 MARKS)

Mass of Moon	7.35×10^{22} kg
Mass of Earth	5.98×10^{24} kg
Radius of Earth	6.37×10^6 m
Orbital period of the Moon	2.376×10^6 s
Gravitational constant	6.67×10^{-11} N m^2 kg^{-2}

Use the data to calculate the orbital radius of the Moon.

Question 13 (3 MARKS)

Alistair, Zev and Georgina are on a spaceship orbiting the Earth and want to increase the radius of their orbit.

Alistair states that lowering the mass of the spacecraft will increase the orbital radius.

Zev states that lowering the mass of the spacecraft will decrease the orbital radius.

Georgina states that the orbital radius would stay the same.

Evaluate the three statements. Detailed calculations are **not** necessary but you need to support your answer with an appropriate formula.

Adapted from VCAA 2017 exam Short answer Q4c

Question 14 (5 MARKS)

The table provides data for the Earth's orbit around the Sun.

Mass of Sun	1.99×10^{30} kg
Mass of Earth	5.98×10^{24} kg
Period of Earth's orbit	365 days
Gravitational constant	6.67×10^{-11} N m^2 kg^{-2}

a. Calculate the radius of Earth's orbit around the Sun. 3 MARKS

b. What is the orbital speed of Earth around the Sun? 2 MARKS

Question 15 (4 MARKS)

Amalthea is a moon that orbits Jupiter at an orbital radius of 1.81×10^8 m and with a period of 4.32×10^4 s.

a. Assuming that Amalthea follows a circular orbit, calculate the mass of Jupiter. Take $G = 6.67 \times 10^{-11}$ N m^2 kg^{-2}. 2 MARKS

Adapted from VCAA 2021 exam Short answer Q3

b. Calculate the magnitude of the acceleration of Amalthea. 2 MARKS

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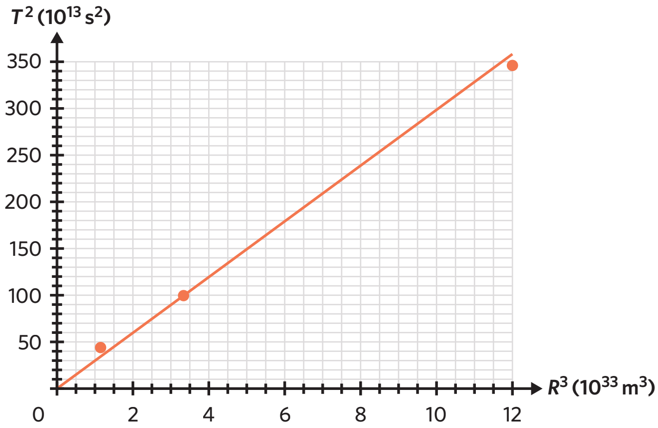
Question 16 (4 MARKS)

Students are measuring the orbital period and orbital radius of planets orbiting the Sun and produce the following graph.



a. *Key science skill*

Show that the gradient of the line is equal to 3.0×10^{-19} s^2 m^{-3}. 1 MARK

FROM LESSON 12D

b. Determine the mass of the Sun. Show your working. 3 MARKS

Adapted from VCAA 2018 exam Short answer Q20

Question 17 (5 MARKS)

Navigation in vehicles or on mobile phones uses a network of global positioning system (GPS) satellites. The GPS consists of 31 satellites orbiting Earth.

One satellite, with a mass of 900 kg, is launched into a circular orbit at an altitude of 2.02×10^4 km.

a. Identify the centripetal force acting on the satellite and describe its direction. 2 MARKS

b. Calculate the period of the satellite to three significant figures. You may use the data from the table in your calculation. Show your working. 3 MARKS

Mass of satellite	900 kg
Mass of Earth	5.98×10^{24} kg
Radius of Earth	6.37×10^6 m
Altitude of satellite above Earth's surface	2.02×10^4 km
Gravitational constant	6.67×10^{-11} N m^2 kg^{-2}

Adapted from VCAA 2019 exam Short answer Q5

Question 18 (3 MARKS)

NASA mission control decides to lower the orbit of its satellite Juno around Jupiter. Will the satellite have to increase, decrease, or maintain the same speed in order to orbit at its new radius? Justify your answer.

Adapted from VCAA 2018 NHT exam Short answer Q1bi

Question 19 (3 MARKS)

Before landing on the Moon, Apollo 11 orbited 121 km above its surface. Take the mass of the moon to be $M = 7.36 \times 10^{22}$ kg, its radius to be $R_M = 1.74 \times 10^6$ m, and take $G = 6.67 \times 10^{-11}$ N m^2 kg^{-2}.

Calculate the period of Apollo 11's orbit.

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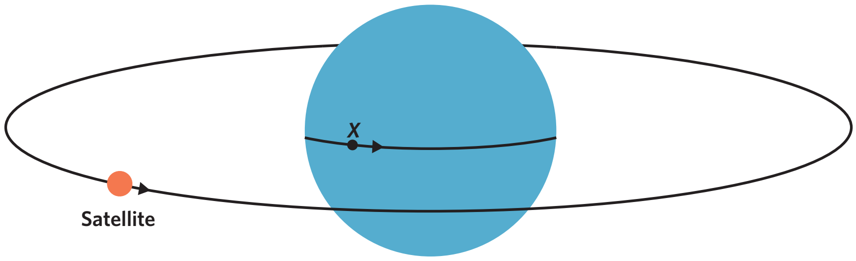
Question 20 (7 MARKS)

Geostationary satellites remain stationary in relation to a fixed point on the equator and have a period of one day when above Earth. The diagram shows an example of a geostationary satellite that is in orbit relative to a fixed point, *X*, on the equator.



a. Explain why geostationary satellites must be vertically above the equator to remain stationary relative to Earth's surface. 2 MARKS

b. A new geostationary satellite has been launched into a circular orbit around Venus. One day on Venus is equal to 2.10×10^7 s. Use $G = 6.67 \times 10^{-11}$ N m^2 kg^{-2}, $M_V = 4.867 \times 10^{24}$ kg and $R_V = 6.05 \times 10^6$ m to show that the altitude of a geostationary satellite must be equal to 1.53×10^9 m. 3 MARKS

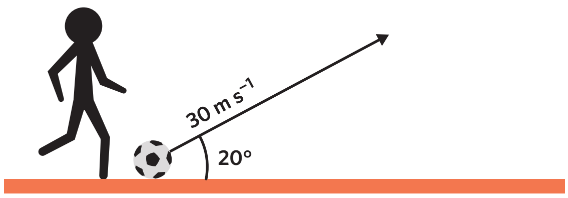
c. Calculate the speed of an orbiting geostationary satellite on Venus. 2 MARKS

Adapted from VCAA 2022 exam Short answer Q2

Previous lessons

Question 21 (3 MARKS)

A stick figure kicks a soccer ball at 30 m s^{-1} at an angle of 20° above the horizontal. Ignore the effects of air resistance in this question.



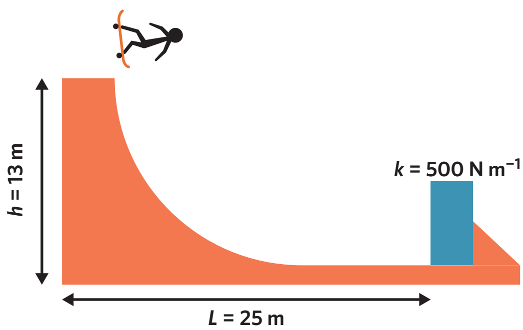
a. Show that the magnitude of the vertical component of the soccer ball's initial velocity is 10 m s^{-1}. 1 MARK

b. Find the maximum height that the soccer ball reaches. 2 MARKS

FROM LESSON 1H

Question 22 (4 MARKS)

A skateboarder with a mass of 67 kg skates down a ramp that is 13 m tall and 25 m long, as shown in the diagram. The skateboarder is brought to rest by a crash mat, which provides a force on the skateboarder as it compresses according to Hooke's law. The mat has a spring constant of 500 N m^{-1}.



a. What is the maximum speed of the skateboarder? 2 MARKS

b. Calculate the maximum compression of the mat. 2 MARKS

FROM LESSON 2D

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Chapter 3 review

Mild 🌶 Medium 🌶🌶 Spicy 🌶🌶🌶

These questions are typical of one hour's worth of questions on the VCE Physics Exam.

Total marks: 50

Section A

All questions in this section are worth one mark.

Unless otherwise indicated, the diagrams in this book are not drawn to scale.

Question 1 🌶

Which of the following statements is false?

A. Gravity is always attractive.

B. All objects with mass attract all other objects with mass.

C. Gravity acts only on objects within a planet's atmosphere.

D. All objects with mass produce their own gravitational field.

Question 2 🌶

Scientists want to reduce the period of a satellite's orbit around a planet. Which of the following statements best describes how this would affect the orbital radius?

A. The orbital radius will need to increase.

B. The orbital radius will need to decrease.

C. The orbital radius will not change since the mass of the planet is constant.

D. The orbital radius could be any value, depending on the speed of the satellite.

Question 3 🌶🌶

Which of the following best describes how reducing the mass of a satellite, while keeping its orbital radius constant, will affect its speed?

A. The speed will increase.

B. The speed will decrease.

C. The speed will not change as the mass of the planet is constant.

D. The speed could be any value, depending on the period of the satellite.

Question 4 🌶🌶

Scientists are measuring the magnitude of the force between two steel balls with masses of 100 g and 1000 g, placed 10 mm apart. Take $G = 6.67 \times 10^{-11}$ N m^2 kg^{-2}.

Which of the following best gives the magnitude of the gravitational force between the two masses?

A. 6.7 N

B. 6.7×10^{-2} N

C. 6.7×10^{-4} N

D. 6.7×10^{-8} N

Adapted from VCAA 2017 exam Multiple choice Q3

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Question 5

A spacecraft is orbiting the planet Mercury at a distance R from the centre of the planet. The spacecraft needs to lower its orbit to a distance $\frac{1}{4}R$ from the centre of Mercury. If the initial gravitational force on the spacecraft was 450 N, what is the magnitude of the force on the spacecraft after lowering its orbit?

A. 2.81×10^2 N

B. 1.13×10^3 N

C. 1.80×10^3 N

D. 7.20×10^3 N

Section B

In questions where more than one mark is available, appropriate working must be shown.

Unless otherwise indicated, the diagrams in this book are not drawn to scale.

Question 6 (5 MARKS)

The Pioneer Venus 1 was sent by NASA to study Venus from orbit. Take $G = 6.67 \times 10^{-11}$ N m^2 kg^{-2}.

Mass of Venus	4.87×10^{24} kg
Radius of Venus	6051.8 km
Mass of Pioneer Venus 1	517 kg
Period of Pioneer Venus 1 orbit	8.64×10^4 s

a. Show that the orbital radius of Pioneer Venus 1 is 3.95×10^7 m. 1 MARK

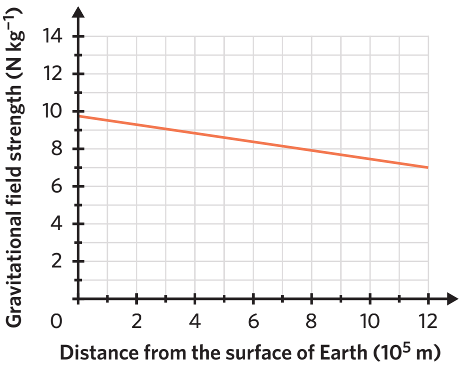
b. Calculate the gravitational force acting upon Pioneer Venus 1. 2 MARKS

c. Calculate the speed of Pioneer Venus 1's orbit. 2 MARKS

Question 7 (6 MARKS)

A Falcon 9 rocket has a mass of 4.49×10^5 kg and will launch into an orbit of 5.00×10^5 m above the Earth's surface. Earth has a mass of 5.98×10^{24} kg and a radius of 6.37×10^6 m.

The graph shows the change in gravitational field strength versus the height above the Earth's surface. Take $G = 6.67 \times 10^{-11}$ N m^2 kg^{-2}.



a. Use the graph to calculate the change in gravitational potential energy of the Falcon 9 as it moves from the Earth's surface to its orbit at an altitude of 5.00×10^5 m. 3 MARKS

b. Calculate the kinetic energy of the Falcon 9 once it has established a stable orbit at an altitude of 5.00×10^5 m above the surface of Earth. 3 MARKS

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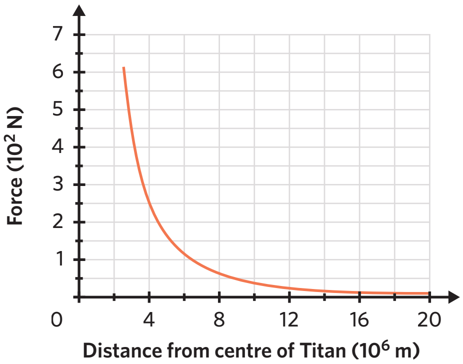
Question 8 (6 MARKS)

Mission Dragonfly is a concept that NASA is pursuing to put a nuclear-powered drone on the surface of Saturn's largest moon, Titan. The table provides information about the Dragonfly drone and Titan. Take $G = 6.67 \times 10^{-11}$ N m^2 kg^{-2}.

Mass of Dragonfly	450 kg
Mass of Titan	1.35×10^{23} kg
Radius of Titan	2.57×10^{6} m
Radius of Titan including atmosphere	4.00×10^{6} m



The graph shows how the gravitational force on Dragonfly changes when it approaches Titan.

a. *Key science skill*

Use the graph to find the acceleration due to gravity that Dragonfly would experience when it is 8.00×10^{6} m from the centre of Titan. 2 MARKS

FROM LESSON 12D

b. Use the graph to estimate the magnitude of the change in kinetic energy as Dragonfly falls from a distance of 12×10^{6} m from the centre of Titan to the top of Titan's atmosphere. 2 MARKS

c. Calculate the gravitational field strength on the surface of Titan. 2 MARKS

Question 9 (5 MARKS)

Astronauts on the International Space Station (ISS) do not feel the effects of Earth's gravity.

Mass of Earth	5.98×10^{24} kg
Mass of ISS	420×10^{3} kg
Height of the ISS orbit above Earth	400 km
Radius of Earth	6.37×10^{6} m

a. Calculate the gravitational field strength of the Earth at the ISS. Take $G = 6.67 \times 10^{-11}$ N m^2 kg^{-2}. 2 MARKS

b. Is the force of Earth's gravity on an astronaut in the ISS zero? Explain why astronauts do not feel gravity on the ISS. 3 MARKS

Adapted from 2018 VCAA Exam Section B Q10b

Question 10 (3 MARKS)

An exoplanet has a radius R_X and the gravitational field strength on its surface is 50 N kg^{-1}. Calculate the magnitude of the force due to the exoplanet's gravity on a rocket, when the rocket is at a distance $10R_X$ from the centre of the exoplanet. The rocket has a mass of 4.0×10^{3} kg.

Question 11 (7 MARKS)

In a geostationary orbit, a satellite will remain over a fixed point on the Earth's equator.

a. What is the period of a geostationary orbit? Give your answer in seconds. 1 MARK

b. Earth has a radius of 6.37×10^{6} m and a mass of 5.98×10^{24} kg. How far above the Earth's surface do geostationary satellites orbit? Take $G = 6.67 \times 10^{-11}$ N m^2 kg^{-2}. 3 MARKS

c. State three conditions for a satellite to remain as a geostationary orbit above the Earth. 3 MARKS

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Question 12 🌶🌶🌶 (2 MARKS)

A spacecraft called New Horizons was sent to orbit Pluto. The spacecraft approached Pluto at speed of 57 936 km h^{-1}. Pluto has a mass of 1.30×10^{22} kg and a radius of 1.19×10^{6} m. Using calculations, explain why New Horizons would not be able to orbit Pluto while travelling at 57 936 km h^{-1}. Take $G = 6.67 \times 10^{-11}$ N m^2 kg^{-2}.

Question 13 (11 MARKS)

Kepler 22 is a star located 990 light-years from Earth. Scientists have collected data from the five planets orbiting Kepler 22. Take $G = 6.67 \times 10^{-11}$ N m^2 kg^{-2}.

Planet	Orbital speed (m s^{-1})	Orbital radius (m)	v^2 (× 10^{14} m^2 s^{-2})	$\frac{1}{r}$ (× 10^{-14} m^{-1})
Kepler 22b	1.06×10^{8}	8×10^{12}	112	12.5
Kepler 22c	8.2×10^{7}	1.4×10^{13}	67	7.1
Kepler 22d	7.2×10^{7}	1.8×10^{13}	52	5.6
Kepler 22e	3.8×10^{7}	6.4×10^{13}	14	1.6
Kepler 22f	2.9×10^{7}	1.07×10^{14}	8.4	0.935

a. Find the orbital period for Kepler 22e. 🌶 2 MARKS

b. *Key science skill*

On a set of axes: 🌶🌶 5 MARKS

- Plot a graph of the data v^2 (vertical axis) versus $\frac{1}{r}$ (horizontal axis)
- Label the axes with units
- Include a scale on each axis
- Draw a line of best fit

FROM LESSON 12D

c. *Key science skill*

Show that the gradient of the line of best fit is equal to 9.3×10^{28} m^3 s^{-2}. 🌶🌶 1 MARK

FROM LESSON 12D

d. Determine the mass of Kepler 22. Show your working. 🌶🌶🌶 3 MARKS

Adapted from VCAA 2018 exam Short answer Q20

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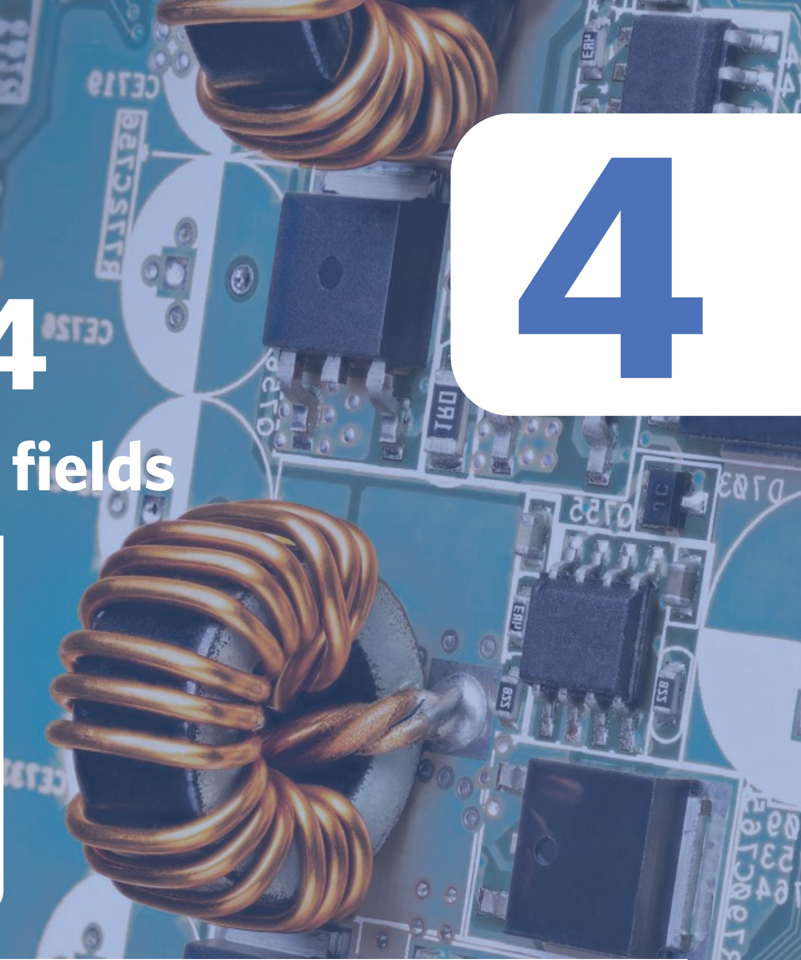

CHAPTER 4

Electric and magnetic fields

LESSONS

STUDY DESIGN DOT POINTS

- describe gravitation, magnetism and electricity using a field model
- investigate and compare theoretically and practically gravitational, magnetic and electric fields, including directions and shapes of fields, attractive and repulsive effects, and the existence of dipoles and monopoles
- investigate and compare theoretically and practically gravitational fields and electrical fields about a point mass or charge (positive or negative) with reference to:
  - the direction of the field
  - the shape of the field
  - the use of the inverse square law to determine the magnitude of the field
  - potential energy changes (qualitative) associated with a point mass or charge moving in the field
- investigate and apply theoretically and practically a field model to magnetic phenomena, including shapes and directions of fields produced by bar magnets, and by current-carrying wires, loops and solenoids
- identify fields as static or changing, and as uniform or non-uniform
- analyse the use of an electric field to accelerate a charge, including:
  - electric field and electric force concepts: $E = k\frac{Q}{r^2}$ and $F = k\frac{q_1q_2}{r^2}$
  - potential energy changes in a uniform electric field: $W = qV$, $E = \frac{V}{d}$
  - the magnitude of the force on a charged particle due to a uniform electric field: $F = qE$
- analyse the use of a magnetic field to change the path of a charged particle, including:
  - the magnitude and direction of the force applied to an electron beam by a magnetic field: $F = qvB$, in cases where the directions of v and B are perpendicular or parallel
  - the radius of the path followed by an electron in a magnetic field: $qvB = \frac{mv^2}{r}$, where $v \ll c$
- describe the interaction of two fields, allowing that electric charges, magnetic poles and current carrying conductors can either attract or repel, whereas masses only attract each other
- investigate and analyse theoretically and practically the force on a current carrying conductor due to an external magnetic field, $F = nIlB$, where the directions of I and B are either perpendicular or parallel to each other
- investigate and analyse theoretically and practically the operation of simple DC motors consisting of one coil, containing a number of loops of wire, which is free to rotate about an axis in a uniform magnetic field and including the use of a split ring commutator
- investigate, qualitatively, the effect of current, external magnetic field and the number of loops of wire on the torque of a simple motor
- model the acceleration of particles in a particle accelerator (including synchrotrons) as uniform circular motion (limited to linear acceleration by a uniform electric field and direction change by a uniform magnetic field).

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4A Electric fields


Image: Tomsickova Tatyana/Shutterstock.com

What's up with this kid's hair?

Negative charges repel each other and are attracted to positive charges. When a person's hair becomes negatively charged, these charges repel each other, causing the hair to stand up. Every object with an electric charge creates an electric field. This lesson will expand our understanding of the field model, introduced in Chapter 3, to include electric fields. We will learn how to draw electric fields and calculate electrical field strength, forces, and potential energy changes in uniform and non-uniform electric fields.

4A 4B 4C 4D

- **3.2.6.1** Electric charge and Coulomb's law
- **3.2.1.2 & 3.2.2.1 & 3.2.3.4 & 3.2.5.1** Electric fields around point charges
- **3.2.2.2 & 3.2.6.2 & 3.2.12.1 & 3.2.16.1** Electric fields between charged parallel plates

ESSENTIAL PRIOR KNOWLEDGE

1A Vector addition

3A Field lines

See questions 43–44.

STUDY DESIGN DOT POINTS

- describe gravitation, magnetism and electricity using a field model
- investigate and compare theoretically and practically gravitational, magnetic and electric fields, including directions and shapes of fields, attractive and repulsive fields, and the existence of dipoles and monopoles
- investigate and compare theoretically and practically gravitational fields and electrical fields about a point mass or charge (positive or negative) with reference to:
  - the direction of the field
  - the shape of the field
  - the use of the inverse square law to determine the magnitude of the field
  - potential energy changes (qualitative) associated with a point mass or charge moving in the field
- identify fields as static or changing, and as uniform or non-uniform
- analyse the use of an electric field to accelerate a charge, including:
  - electric field and electric force concepts: $E = k\frac{Q}{r^2}$ and $F = k\frac{q_1 q_2}{r^2}$
  - potential energy changes in a uniform electric field: $W = qV$, $E = \frac{V}{d}$
  - the magnitude of the force on a charged particle due to a uniform electric field: $F = qE$
- describe the interaction of two fields, allowing that electric charges, magnetic poles and current carrying conductors can either attract or repel, whereas masses only attract each other
- model the acceleration of particles in a particle accelerator (limited to linear acceleration by a uniform electric field and direction change by a uniform magnetic field)

KEY TERMS AND DEFINITIONS

charge a quantifiable property which relates to how strongly an object is affected by an electric field

point charge an electric charge considered to exist as a single point

electric field strength a measure of the electric force that acts per unit of charge at a point in space

static field a field that does not change over time

dipole a field in which field lines point both towards and away from the object(s) generating the field

FORMULAS

- **electric force**
  $F = k\frac{q_1 q_2}{r^2} = qE$
- **electric field strength due to a point charge**
  $E = k\frac{Q}{r^2}$
- **inverse square law for electric fields**
  $E_2 = E_1\left(\frac{r_1}{r_2}\right)^2$
- **electric field strength between charged parallel plates**
  $E = \frac{V}{d}$
- **work in an electric field**
  $W = qEd = qV$
- **energy transformation of a charge moving between charged parallel plates**
  $\frac{1}{2}m(\Delta v)^2 = qV$

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Electric charge and Coulomb's law 3.2.6.1

Electric **charge** is a property of an object that allows it to experience an electric force and create an electric field. We can calculate the magnitude of the electric force between charged particles using Coulomb's law.

How do electric charges exert force on one another?

Just as objects require mass to experience gravitational forces, objects require charge to experience electric forces. We measure charge in coulombs (C), and depending on the object, it can either be positive or negative (Figure 1). The magnitude of the electric force between two **point charges** is given by Coulomb's law:

Figure 1 A representation of **(a)** a positive and **(b)** a negative charge

FORMULA

$$F = k\frac{q_1 q_2}{r^2}$$

F = electric force (N)
k = Coulomb constant (8.99×10^9 N m^2 C^{-2})
q_1 = electric charge of one object (C)
q_2 = electric charge of other object (C)
r = distance between point charges (m)

USEFUL TIP

The most common examples of particles with an electric charge are the electron which has a negative electric charge, and the proton which has a positive electric charge. They both have a charge of magnitude 1.6×10^{-19} C.

- The magnitude of the electric force on each charge is equal, which is consistent with Newton's third law of motion.
- The designation of a charge as q_1 or q_2 does not affect the calculation.

To find the direction of electric force, we consider that like charges repel and opposite charges attract (Figure 2).

- Two positively charged particles repel one another.
- Two negatively charged particles repel one another.
- A positively and negatively charged particle attract one another.

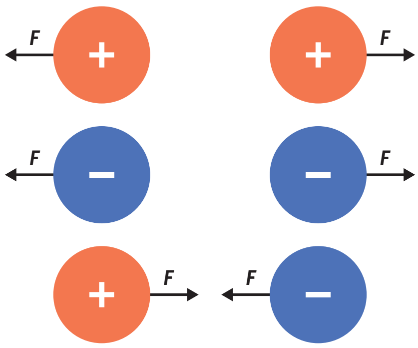

Figure 2 Like charges experience repulsive forces between each other, and opposite charges experience attractive forces between each other.

A charge experiences an electric force due to the presence of an electric field:

FORMULA

$$F = qE$$

F = electric force (N)
q = electric charge (C)
E = electric field strength (N C^{-1} or V m^{-1})

The object with charge, q, is not generating this field but is experiencing the electric force. Combining Coulomb's law and this formula, we can calculate the **electric field strength** due to a charge, Q, using:

FORMULA

$$E = k\frac{Q}{r^2}$$

E = electric field strength around a point charge (N C^{-1} or V m^{-1})
k = Coulomb constant (8.99×10^9 N m^2 C^{-2})
Q = electric charge generating the field (C)
r = distance from the point charge (m)

USEFUL TIP

Electric field strength can be given in two units: N C^{-1} or V m^{-1}. Both of these units are equivalent and can be used interchangeably.

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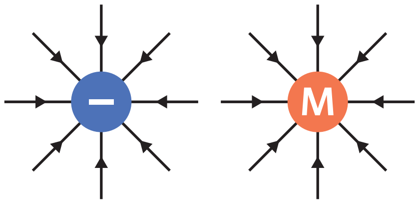


Figure 3 The electric field around a negative charge and the gravitational field around a mass

USEFUL TIP

As electric fields are vector fields, we can find the overall electric field at a point using vector addition.

Electric field strength, $E = k\frac{q}{r^2}$ follows the inverse square law, in the same way gravitational field strength, $g = G\frac{M}{r^2}$, does (Figure 3). The following can be used to relate the electric field strength experienced by a point charge at two different positions in the field.

FORMULA

$$E_2 = E_1\left(\frac{r_1}{r_2}\right)^2$$

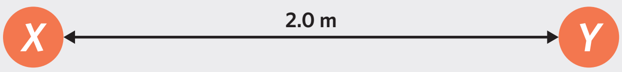
E_2 = electric field strength at position 2 ($N\ C^{-1}$ or $V\ m^{-1}$)
E_1 = electric field strength at position 1 ($N\ C^{-1}$ or $V\ m^{-1}$)
r_1 = distance from centre of charge at position 1 (m)
r_2 = distance from centre of charge at position 2 (m)

The inverse square law similarly applies to electric force.

$$F_2 = F_1\left(\frac{r_1}{r_2}\right)^2$$

WORKED EXAMPLE 1

Particle X has a charge of -4.0×10^{-8} C and particle Y has a charge of 5.0×10^{-8} C. The two particles are separated by a distance of 2.0 m. Take $k = 8.99 \times 10^9\ N\ m^2\ C^{-2}$.



a. Calculate the electric field strength due to particle X at a distance of 2.0 m.

Step 1

Identify known and unknown variables and write down the formula that relates these variables.

Note that as we are calculating the electric field strength due to particle X, Q represents the charge of particle X.

$k = 8.99 \times 10^9\ N\ m^2\ C^{-2}$, $Q = -4.0 \times 10^{-8}$ C, $r = 2.0$ m, $E = ?$

$E = k\frac{Q}{r^2}$

Step 2

Substitute in the values and calculate the electrical field strength.

$E = 8.99 \times 10^9 \times \frac{-4.0 \times 10^{-8}}{2.0^2}$

$E = -90.0 = -90\ N\ C^{-1}$

The electric field strength is $90\ N\ C^{-1}$.

b. Calculate the magnitude of the electric force acting on particle Y.

Step 1

Identify known and unknown variables and write down the formula that relates these variables.

$k = 8.99 \times 10^9$ N m2 C^{-2}, $q_1 = -4.0 \times 10^{-8}$ C, $q_2 = 5.0 \times 10^{-8}$ C, $r = 2.0$ m, $F = ?$

$F = k\frac{q_1 q_2}{r^2}$

OR

$q = 5.0 \times 10^{-8}$ C, $E = 90\ N\ C^{-1}$, $F = ?$

$F = qE$

Continues →

Step 2

Substitute in the values and calculate the electrical force.

$F = 8.99 \times 10^9 \times \dfrac{-4.0 \times 10^{-8} \times 5.0 \times 10^{-8}}{(2.0)^2}$

$F = -4.50 \times 10^{-6} = -4.5 \times 10^{-6}$ N

The electric force on particle Y is 4.5×10^{-6} N.

OR

$F = 5.0 \times 10^{-8} \times 90$

$F = -4.50 \times 10^{-6} = -4.5 \times 10^{-6}$ N

The electric force on particle Y is 4.5×10^{-6} N.

---

c. Compare the electric force acting on particle X and particle Y.

Breakdown	Answer
Compare the differences between the electrical force acting on particle X and particle Y.	The electrical force acting on particle X is to the right, and the electric force acting on particle Y is to the left.
Compare the similarities between the electrical force acting on particle X and particle Y.	The magnitude of the electric force, $F = 4.5 \times 10^{-6}$ N, is the same for both particle X and particle Y.

PROGRESS QUESTIONS

Question 1

The electric field strength due to a charge of 3.0×10^{-17} C at a distance of 3.5 m is

A. 7.7×10^{-26} N C^{-1}.

B. 2.2×10^{-8} N C^{-1}.

C. 7.7×10^{-8} N C^{-1}.

D. 2.2×10^{-1} N C^{-1}.

Question 2

Two electrons ($q_e = 1.6 \times 10^{-19}$ C) are 45 cm apart. The electric force acting on each electron is best described as

A. repulsive, with a magnitude of 1.1×10^{-27} N.

B. attractive, with a magnitude of 1.1×10^{-27} N.

C. repulsive, with a magnitude of 1.1×10^{-31} N.

D. attractive, with a magnitude of 1.1×10^{-31} N.

Electric fields around point charges 3.2.1.2 & 3.2.2.1 & 3.2.3.4 & 3.2.5.1

Electric fields are produced by electric charges, and can be modelled by drawing field line diagrams.

How can we visualise the electric fields around point charges?

Electric field lines are used to visualise the nature of electric fields over a region of space. **Static fields** are created by stationary charged particles and do not change over time. Changing fields are created by moving charges and change as the particle moves.

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USEFUL TIP

When two positive or negative charged particles are placed close together, there may be locations between the charges at which there is no net electric field strength. This is due to the electric field strength of both charged particles being the same magnitude, but opposite in direction at these locations.

The direction of the electric field at any point represents the direction of the electric force a positive charge would experience at that location. Negative electric charges will experience an electric force in the opposite direction to the direction of the electric field at their location.

We follow similar rules for drawing electric field lines as we do for drawing gravitational field lines:

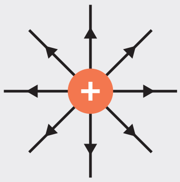
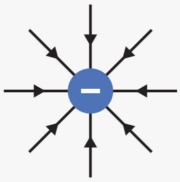
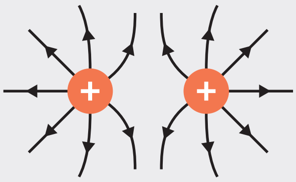
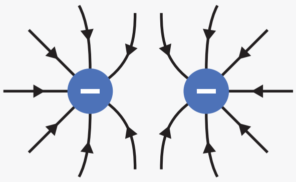
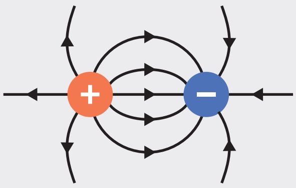
- Field lines always start and end perpendicular to the surface of the charge.
- Field lines point away from positive charges and towards negative charges.
- Field lines must never touch or cross.

Unlike gravitational fields, which we learn in Lesson 3A are only ever monopoles, electric fields can either be monopoles or **dipoles**. To distinguish between whether a field is a monopole or a dipole, we consider the direction of the field lines.

- If the field lines only point towards or away from the source(s) of the field, then the field can be considered a monopole.
- If the field lines point both towards and away from the sources of the field, then the field can be considered a dipole.

In VCE Physics, we will need to know how to draw field lines generated by up to two electric charges. Table 1 shows common examples of electric fields around point charges

Table 1 Electric field lines around point charges

Charge(s)	Electric field diagram	Type of field	Description
A single positive charge		Monopole	• Field lines point radially outwards, away from the positive charge • Field lines are drawn equally spaced around the charge
A single negative charge		Monopole	• Field lines point radially inwards, towards the negative charge • Field lines are drawn equally spaced around the charge
Two positive charges		Monopole	• Field lines point away from the positive charges • Field lines bend away from each other • Field lines do not cross or touch • Charges repel one another
Two negative charges		Monopole	• Each field line points towards one of the negative charges • Field lines bend away from each other • Field lines do not cross or touch • Charges repel one another
One positive and one negative charge		Dipole	• Field lines point away from the positive charge and towards the negative charge • Field lines bend towards each other • Field lines are continuous between the opposite charges, representing the combined effect of each charge's field • Field lines do not cross or touch • Charges attract one another

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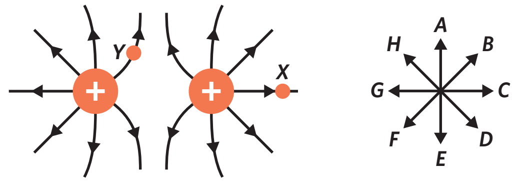
PROGRESS QUESTIONS

Use the following information to answer questions 3 and 4.

Two point charges and their associated electric field are shown. The directions (*A*–*H*) are also shown.



Question 3

What is the direction of the electric field at point *X* (*A*–*H*)?

Question 4

If a negatively charged particle was placed at point *Y*, in which direction would the electric force on it act (*A*–*H*)?

Electric fields between charged parallel plates 3.2.2.2 & 3.2.6.2 & 3.2.12.1 & 3.2.16.1

Charged objects experience a constant electrical force at all locations within a uniform electric field. These fields are often produced by oppositely charged parallel plates.

How can we visualise the electric field between two charged parallel plates?

In a uniform electric field:

- All points in space have the same electric field strength and direction.
- This is shown by field lines being equally spaced and parallel to each other.

When we have two charged parallel plates, one positively and one negatively charged, we can model the electric field in a similar way as if we had two rows of positive and negative charges close together (Figure 4a). This creates a uniform electric field in the region between the two plates. Note the electric field lines at the edge of the charged parallel plates are slightly curved, as there are no charges beyond these points on either side (Figure 4b).

In order to create two parallel plates with opposing charge, we apply a voltage (potential difference) between the two plates using a power source, such as a battery. The electric field strength between the plates can be calculated using:

FORMULA

$$E = \frac{V}{d}$$

E = electric field strength (N C^{-1} or V m^{-1})
V = voltage (potential difference) (V)
d = distance between plates (m)

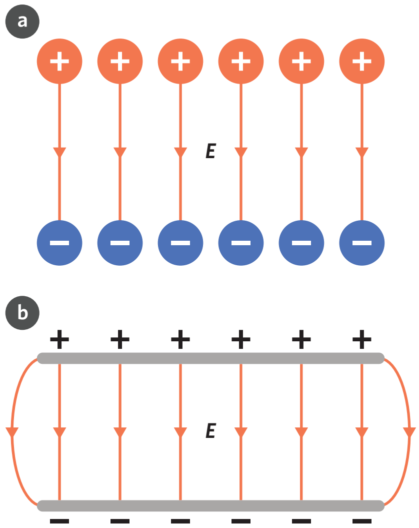


Figure 4 **(a)** The electric field between rows of positive and negative charges and **(b)** the electric field between two charged parallel plates

As the field is uniform, the field strength is the same for all locations between the plates.

How can we accelerate charged particles using charged parallel plates?

USEFUL TIP

d is the distance travelled parallel to the electric field. If a charge moves perpendicular to the direction of an electric field, there is no work associated with its movement.

Recall from Lesson 2A that when a force is applied to an object over a distance, work is being done $W = Fd$. As the electric force on a charged particle can be calculated by $F = qE$, we arrive at the expression:

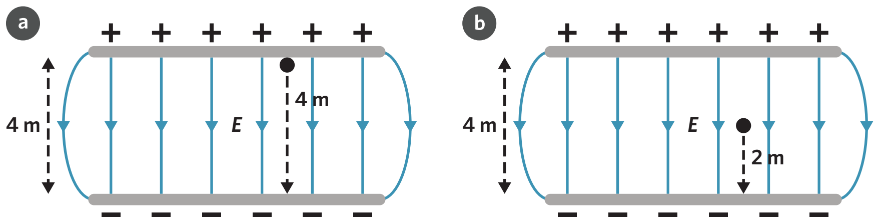
FORMULA

$$W = qEd$$

W = work done by electric field (J)
q = electric charge (C)
E = electric field strength (N C^{-1} or V m^{-1})
d = distance travelled by charged particle parallel to the electric field (m)

By rearranging the formula for electric field strength between two charged plates, we see that $V = Ed$. If a charged particle moves the entire distance between two charge plates we arrive at a simplified expression for work (Figure 5):

$$W = qEd = qV$$



$W = qEd$

$W = qE \times 4$

OR

$W = qV$

$W = qEd$

$W = qE \times 2$

Figure 5 The work done on a charged particle moving **(a)** the entire distance between two charged parallel plates and **(b)** moving a shorter distance between two charged parallel plates

When work is done on an object by a force, the object experiences a change in energy. In the case of a charged object being accelerated from rest through an electric field, as the charge accelerates in the direction of the electric force, electrical potential energy is transformed into kinetic energy. This gives the following relationship:

$$KE_f = W$$

$$\frac{1}{2}mv^2 = qEd$$

If the charged particle travels the whole distance between the two plates, as $V = Ed$, the energy transformation of a particle accelerating from rest can be represented by the following equation:

FORMULA

$$\frac{1}{2}mv^2 = qV$$

m = mass of particle (kg)
v = speed of particle (m s^{-1})
q = charge of particle (C)
V = potential difference (V)

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Scientists use electric fields between two parallel plates to accelerate particles (such as electrons and protons) up to very high speeds. This is often referred to as an electron gun.

Figure 6 shows a simplified version of a particle accelerator, designed to accelerate negatively charged particles.

- A power source creates a potential difference between two plates.
- Once an electron (negatively charged) enters the electric field, it experiences a force to the right, as it is repelled by the negatively charged plate on the left and attracted to the positively charged plate on the right.
- This electric force accelerates the electron to the right.

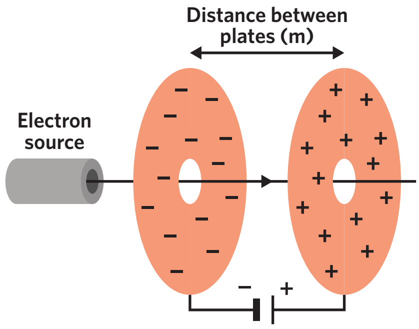
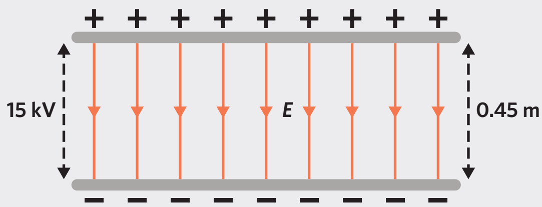


Figure 6 Linear particle accelerator

WORKED EXAMPLE 2

A uniform electric field generated by two electrically charged plates is used to accelerate a stationary proton over a distance of 0.45 m. The potential difference between the two plates is 15 kV. Take $k = 8.99 \times 10^9$ N m^2 C^{-2}.



a. Calculate the electric field strength between the two plates.

Step 1

Identify known and unknown variables and write down the formula that relates these variables.

$V = 15 \times 10^3$ V, $d = 0.45$ m, $E = ?$

$E = \frac{V}{d}$

Step 2

Substitute in the values and solve for the electric field strength.

$E = \frac{15 \times 10^3}{0.45}$

$E = 3.33 \times 10^4 = 3.3 \times 10^4$ V m^{-1}

b. A proton, with mass 1.7×10^{-27} kg and charge 1.6×10^{-19} C, is accelerated between the two plates. Calculate the speed of the proton as it exits the electric field. Ignore relativistic effects.

Step 1

Identify known and unknown variables and write down the formula that relates these variables.

$m = 1.7 \times 10^{-27}$ kg, $q = 1.6 \times 10^{-19}$ C, $V = 15 \times 10^3$ V, $v = ?$

$\frac{1}{2}mv^2 = qV$

Step 2

Substitute in the values and solve for the speed of the proton.

$\frac{1}{2} \times 1.7 \times 10^{-27} \times v^2 = 1.6 \times 10^{-19} \times 15 \times 10^3$

$v = 1.68 \times 10^6 = 1.7 \times 10^6$ m s^{-1}

PROGRESS QUESTIONS

Question 5

A potential difference of 5.0 V is applied to two stationary parallel plates that are 55 cm apart. The electric field between the two plates is best described as

A. uniform and static, with a magnitude of 9.1 V m^{-1}.

B. non-uniform and static, with a magnitude of 9.1 V m^{-1}

C. uniform and static, with a magnitude of 9.1×10^{-2} V m^{-1}.

D. non-uniform and changing, with a magnitude of 9.1×10^{-2} V m^{-1}

Continues →

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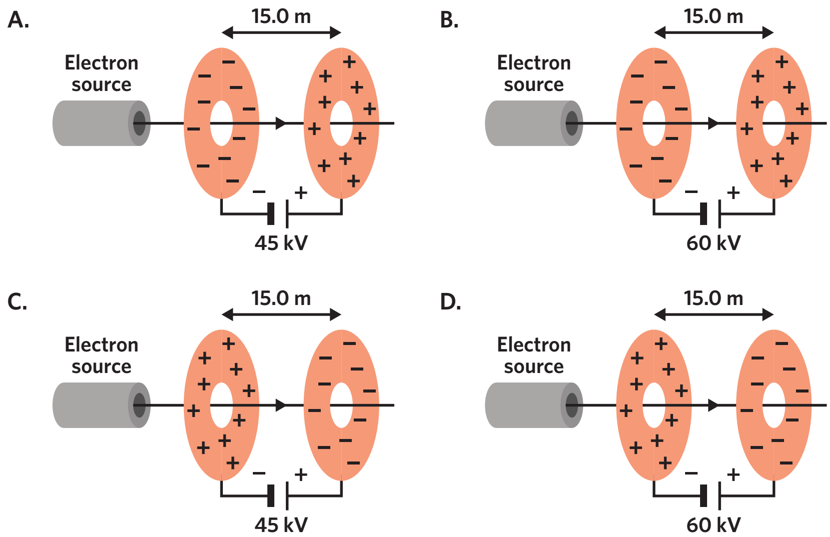
Question 6

Identify which of the following pairs of electric plates will accelerate an electron to the right the quickest.



Theory summary

- Like charges repel and opposite charges attract.
- In electric field diagrams:
  - field lines point away from positive charges and towards negative charges.
  - field lines show the direction of the electric force acting on a positive charge at that point.
  - electric field strength around a point charge follows the inverse square law.
- Charging two parallel plates creates a uniform electric field between the plates.
- When a charged particle moves between the two plates, the work done on the particle can be found using $W = qEd$.
  - If the particle starts from rest and the electrical potential energy of an object is entirely converted into kinetic energy, by the conservation of energy: $\frac{1}{2}mv^2 = qEd$.
  - If a charged particle at rest moves the entire distance between the two plates, as $V = Ed$, the work done on the particle can be simplified to $W = qV$, and the transformation of energy to $\frac{1}{2}mv^2 = qV$.

Table 2 Summary of formulas for electric fields

Type of field	Electric force	Electric field strength
Point charges	$F = k\frac{q_1q_2}{r^2} = qE$	$E = k\frac{Q}{r^2}$
Uniform fields	$F = qE$	$E = \frac{V}{d}$

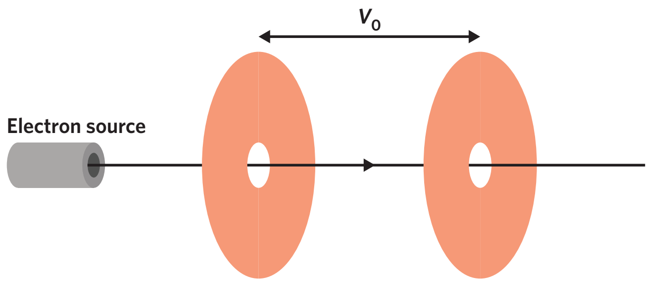
4A Questions

Mild 🌶 Medium 🌶🌶 Spicy 🌶🌶🌶

Deconstructed exam-style

Use the following information to answer questions 7–9.

An electron is accelerated from rest by a potential difference of V_0. It emerges at a speed of 2.0×10^7 m s^{-1}.



Question 7 🌶 (1 MARK)

Identify the mass and the magnitude of the charge of the electron.

Question 8 🌶 (1 MARK)

Identify the relationship between the potential difference applied between the parallel plates, V_0, and the speed of the electron, v.

Question 9 🌶🌶 (3 MARKS)

Calculate the value of the accelerating voltage, V_0, in kV.

Adapted from VCAA 2021 NHT exam Short answer Q2a

Exam-style

Question 10 🌶 (1 MARK)

Students are considering how to make an electric dipole. Which of the following is a valid method?

A. Isolating a single proton.

B. Bringing two electrons close together.

C. It is not possible to create an electric dipole.

D. Bringing a proton and an electron close together.

Question 11 (4 MARKS)

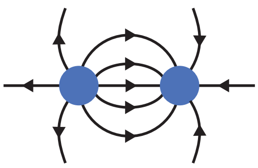
A proton is placed 12 cm to the right of an electron. Both particles have a charge of 1.6×10^{-19} C.

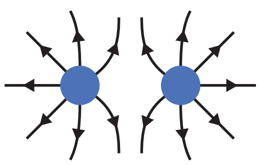
a. Calculate the electric field strength due to the proton at the location of the electron. 🌶 2 MARKS

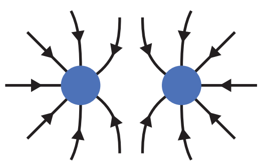
b. Determine the magnitude and direction of the electric force acting on the proton. 🌶🌶 2 MARKS

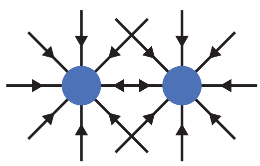
Question 12 🌶 (1 MARK)

Which of the following shows the electric field pattern surrounding two equal magnitude negative charges?

A.


B.


C.


D.


Question 13 (6 MARKS)

The electron gun section of a particle accelerator accelerates electrons between two plates that are 10 cm apart and have a potential difference of 5000 V between them.

a. Calculate the electric field strength between the plates. Include an appropriate unit. 2 MARKS

b. Calculate the magnitude of the force on an electron between the plates. 2 MARKS

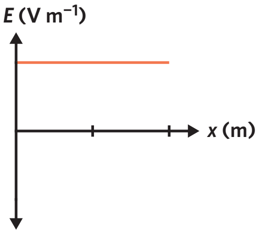
c. Calculate the speed of the electrons as they exit the electron gun. Ignore any relativistic effects. Assume that the initial speed of the electrons is zero. 2 MARKS

Adapted from VCAA 2018 NHT exam Short answer Q2

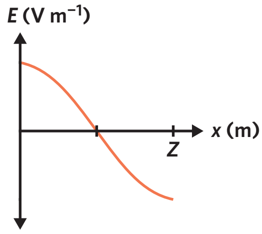
Question 14 (1 MARK)

Which one of the following graphs best shows the electric field strength, E, versus the position, x, between two charged parallel plates?

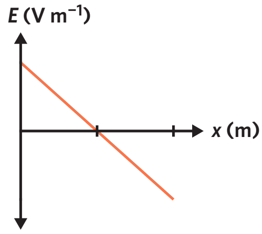
A.



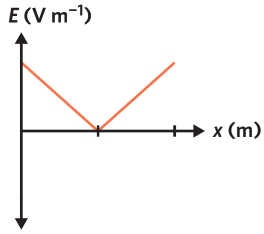
B.



C.



D.



Adapted from VCAA 2021 exam Multiple choice Q3

Question 15 (1 MARK)

Three charges are arranged in a line as shown.

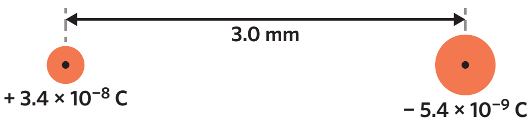
Draw an arrow at point G to show the direction of the electric field at that point.

Adapted from VCAA 2017 exam Short answer Q1

Question 16 (5 MARKS)

A metal sphere has a charge of $+3.4 \times 10^{-8}$ C. A larger sphere with a charge of -5.4×10^{-9} C is placed 3.0 mm to the right of the first sphere.

In calculations, treat both spheres as point charges.



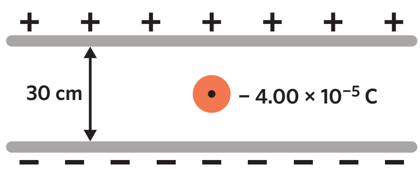
a. What is the direction of the electric field due to the smaller sphere at the point where the larger sphere is located? 1 MARK

b. What is the magnitude and direction of the force on the larger sphere? 2 MARKS

c. Using your answer from part **b**, determine the magnitude of the force on the larger sphere if it were moved three times further away. 2 MARKS

Question 17 (5 MARKS)

An experiment is set up to calculate the mass of a charged sphere. In this experiment, an electrical force is used to balance out the gravitational force on the sphere. Two electrically charged plates are placed 30 cm vertically apart with a potential difference of 1.67×10^3 V between them. The sphere has a charge of -4.00×10^{-5} C. The charged sphere is placed between the two plates and remains stationary.



a. Draw the electric field between the two charged parallel plates. 2 MARKS

b. Show that the electric field strength between the two plates is 5.6×10^3 N C^{-1}. 1 MARK

Adapted from VCAA 2016 exam Detailed Study 4 Q2

c. Find the mass of the sphere. 2 MARKS

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Question 18 (5 MARKS)

In a particle accelerator, electrons initially travelling at 1.2×10^6 m s^{-1} are accelerated from rest by a uniform field of 2.0×10^3 V m^{-1} up to a speed of 6.3×10^6 m s^{-1}. Take the charge of an electron to be -1.6×10^{-19} C and its mass to be 9.1×10^{-31} kg.

a. What is the distance, in cm, over which the electrons are accelerated? Ignore relativistic effects. 3 MARKS

b. Explain how the electric force acting on the electron changes as it is accelerated. 2 MARKS

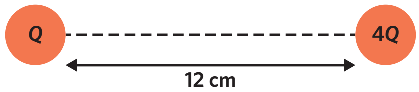
Adapted from 2016 VCAA Exam Section A Q2

Question 19 (1 MARK)

Key science skill

Two point charges, Q and $4Q$, are placed 12 cm apart, as shown in the diagram below.

On the straight line between the charges Q and $4Q$, the electric field is



A. non-zero everywhere.

B. zero at a point 2.4 cm from Q.

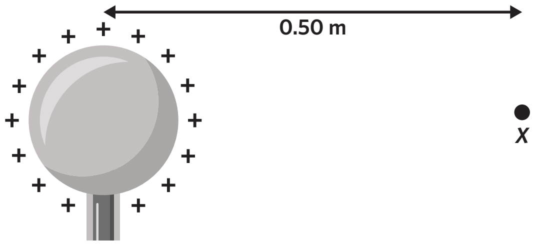
C. zero at a point 3 cm from Q.

D. zero at a point 4 cm from Q.

Adapted from VCAA 2022 exam Multiple choice Q4

Question 20 (6 MARKS)

A common piece of equipment used to demonstrate electric fields is the Van der Graaff generator. The diagram shows a Van der Graaff generator with an electric field strength of 4.4×10^6 N C^{-1} at position X. The charge on the Van de Graaff generator can be considered a point charge.



a. Calculate the number of protons positioned at the same point as the Van de Graaf generator that would give the same equivalent electric field strength at position X as the generator itself. 3 MARKS

b. ***Key science skill***

Van der Graaff generators are capable of generating sparks of 50 000 – 150 000 V but with a very small current of a few microamperes. The severity of an electric shock is determined by the size of the current. One common classroom demonstration involves multiple students holding hands before the first student touches the Van de Graaf generator. This gives all the students holding hands a small shock. Evaluate whether this demonstration is safe to use in a classroom. 3 MARKS

FROM LESSON 12A

Previous lessons

Question 21 (3 MARKS)

Two cars travelling towards one another collide. Compare the impulse exerted on each car during the collision.

FROM LESSON 1I

Question 22 (1 MARK)

The acceleration of a vertical spring-mass oscillating system is zero at the point at which

A. the spring force is a maximum.

B. the gravitational force is a maximum.

C. the net force acting on the mass is a maximum.

D. the spring force is equal to the gravitational force.

FROM LESSON 2E

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4B Magnetic fields

STUDY DESIGN DOT POINTS

- describe gravitation, magnetism and electricity using a field model
- investigate and compare theoretically and practically gravitational, magnetic and electric fields, including directions and shapes of fields, attractive and repulsive effects, and the existence of dipoles and monopoles
- investigate and apply theoretically and practically a field model to magnetic phenomena, including shapes and directions of fields produced by bar magnets, and by current-carrying wires, loops and solenoids
- identify fields as static or changing, and as uniform or non-uniform
- describe the interaction of two fields, allowing that electric charges, magnetic poles and current carrying conductors can either attract or repel whereas masses only attract each other

4A 4B 4C 4D

3.2.1.3 & 3.2.2.3 & 3.2.5.2 Magnetic fields

3.2.2.4 & 3.2.12.2 & 3.2.4.1 Magnetic field patterns

ESSENTIAL PRIOR KNOWLEDGE

1B Vector addition

3A Field lines

See questions 45–46.

KEEN TO INVESTIGATE?

1 **Which materials can behave as magnets?**
Search YouTube: How do magnets work

KEEN TO INVESTIGATE?

2 **How are permanent magnets created?**
Search YouTube: Magnets | how it's made

How does a compass work?

A compass has a small magnetised needle inside the dial, which aligns itself with the magnetic field at the position it is located. This lesson introduces magnetic fields, how they form, and their direction around current-carrying wires and coils. The presence of magnetic fields around current-carrying wires demonstrates a relationship between electricity and magnetism, which will be explored in depth in future lessons.

KEY TERMS AND DEFINITIONS

magnetic field a vector field that arises from the movement of charge

permanent magnet an object with material properties that cause it to produce a persistent magnetic field

electromagnet a magnet created by an electric current

bar magnet a permanent magnet in the shape of a bar

solenoid an electromagnet made from coils of wire

Magnetic fields 3.2.1.3 & 3.2.2.3 & 3.2.5.2

A **magnetic field** is a field, just like electric and gravitational fields, that arises from the movement of charge. These fields can be static or changing.

What is magnetism?

As a result of the movement of electric charges, certain materials can behave as magnets.[1] There are two main types of magnets we will look at: **permanent magnets** and **electromagnets**.

Figure 1a shows a **bar magnet**, the most common type of permanent magnet; while Figure 1b shows a **solenoid,** a common type of electromagnet.

The constant movement of charges within a material creates a magnetic field. To create a permanent magnet, the movement of the charges align so that their individual magnetic fields add up to create an overall stronger magnetic field.[2] Electromagnets are created by moving charged particles in the form of an electric current.

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In VCE Physics, we will consider magnets which always have two poles: a north pole (N) and a south pole (S). Similar to electric fields, where like charges repel and opposite charges attract; in magnetic fields, like poles repel and opposite poles attract.

Recall, a static field is a field that does not change over time, while a changing field does change over time. Table 1 shows how to classify magnetic fields as static or changing.

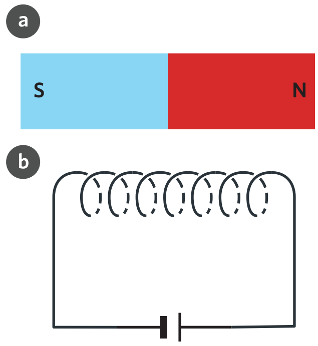


Figure 1 **(a)** Representations of a permanent bar magnet and **(b)** a solenoid

Table 1 Identifying magnetic fields as static or changing

	Static	Changing
Permanent magnet	If the magnet is stationary	If the magnet is in motion
Electromagnet	If the current in constant and the electromagnet is stationary	If the current is changing or the electromagnet is in motion

Conventions for representing vectors

When drawing vectors in three dimensions, including field lines, specific conventions must be followed. Since a page has only two dimensions, we define the extra directions of 'into the page' and 'out of the page' to form our third dimension.

We can determine whether a magnetic field is acting 'into the page' or 'out of the page' by considering the movement of an arrow (Figure 2).

- If you were to shoot an arrow into the page, moving away from you, you would see the feathers of the arrow. This is represented by a cross.
- If an arrow were to be shot out of the page, moving towards you, you would see the point of the arrow. This is represented by a dot.

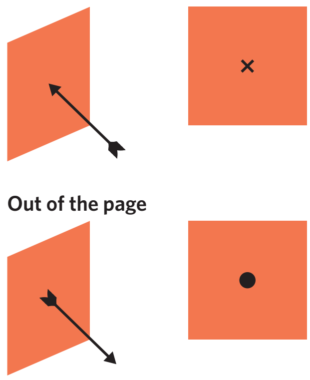


Figure 2 An arrow moving into and out of the page

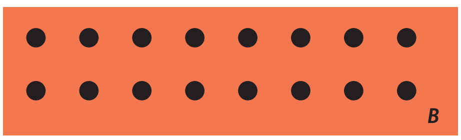
Table 2 shows the drawing convention for vectors and field lines into and out of the page.

Table 2 Drawing conventions for vectors and field lines into and out of the page.

Static	Changing	Drawing convention
Into the page	Moving away from you	✕
Out of the page	Moving towards you	●

PROGRESS QUESTIONS

Question 1



The direction of the magnetic field shown is

A. to the left.

B. to the right.

C. into the page.

D. out of the page.

Continues →

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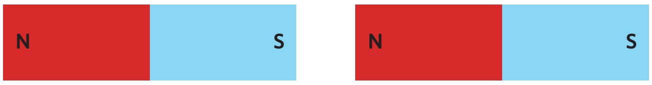
Question 2



Two bar magnets are placed close together, as shown.
These bar magnets will

A. repel one another.

B. attract one another.

C. merge to form a magnetic monopole.

D. have no interaction with one another.

Magnetic field patterns 3.2.2.4 & 3.2.12.2 & 3.2.4.1

Magnetic field patterns are represented by field lines which run in loops from north to south poles.

USEFUL TIP

The field lines form complete loops when they run back through the magnet itself, however we do not draw these internal lines in VCE Physics.

How can we find the direction of a magnetic field around a permanent magnet?

The magnetic field lines around a permanent magnet

- will run from the north pole (N) to the south pole (S) of the magnet.
- are closer together where the field is stronger.
- never touch or cross.

The north and south poles simply represent the ends of the magnet where the field lines exit and enter. The most common type of permanent magnets in VCE Physics are bar magnets. The magnetic field around a bar magnet is shown in Figure 3.

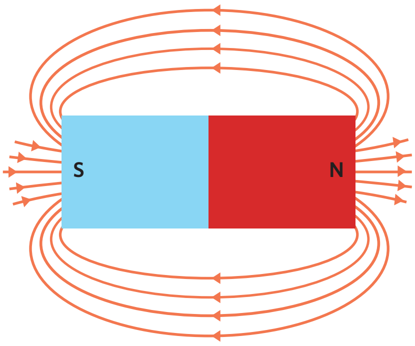


Figure 3 The magnetic field around a bar magnet

The Earth is essentially a very large electromagnet with magnetic poles that are the opposite of their geographic names.[3] A compass is a magnet that aligns itself with the magnetic field lines of Earth, and since magnetic field lines around the Earth run from the north pole to south pole, a compass actually points to the Earth's magnetic south pole (Figure 4). We call this the geographic north pole due to historical reasons.[4]

KEEN TO INVESTIGATE?

3 **Why are the magnetic and geographical poles of the Earth opposite to one another?**
Search: Flipping of magnetic poles

4 **How does a compass work?**
Search: The history of the compass

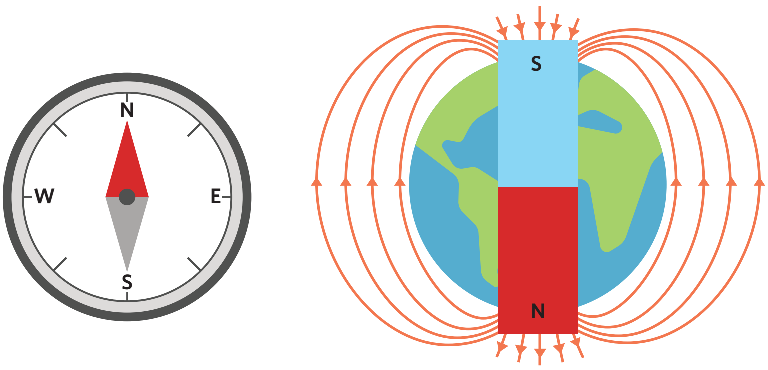


Figure 4 A compass will orient its north needle towards Earth's geographic North Pole.

In VCE Physics, we need to draw field lines generated by up to two bar magnets. Table 3 shows common examples of magnetic field patterns between bar magnets.

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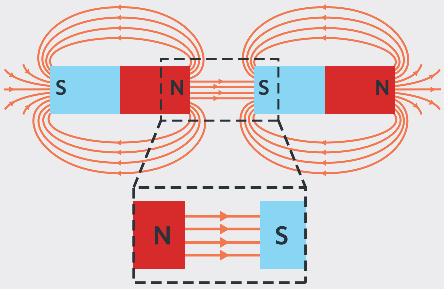
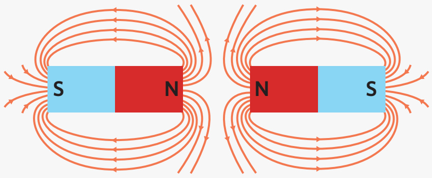
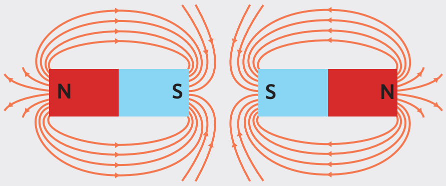
Table 3 Magnetic field patterns around bar magnets

Magnet orientation	Magnetic field diagram	Type of field[5]	Description
Opposite poles facing each other		Dipole	• Field lines run from the north pole of one magnet to the south pole of the other. • The field in the small region between opposite poles can be approximated as uniform, with the field lines between the poles drawn parallel.
Two north poles facing each other		Dipole	• Field lines diverge between like poles, creating a point between the two magnets where no magnetic force acts. • The direction of the field lines is from north to south.
Two south poles facing each other		Dipole	• Field lines diverge between like poles, creating a point between the two magnets where no magnetic force acts. • The direction of the field lines is from north to south.

Other examples of permanent magnets that may be encountered are horseshoe or circular magnets. In all cases, magnetic field lines are directed from the north pole to south pole.

KEEN TO INVESTIGATE?

[5] **Can a magnetic monopole exist?**
Search: Creation and measurement of magnetic monopole

PROGRESS QUESTIONS

Question 3

Which of the following correctly describes the directions of the magnetic field lines around a bar magnet?

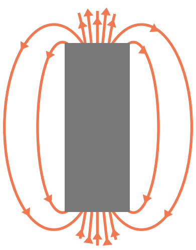
A. radially towards the magnet

B. radially away from the magnet

C. directed from the south pole to the north pole

D. directed from the north pole to the south pole

Question 4



The magnetic field produced by a bar magnet is shown. The magnet has

A. two north poles

B. two south poles

C. a north pole on the top, and a south pole on the bottom

D. a south pole on the top, and a north pole on the bottom

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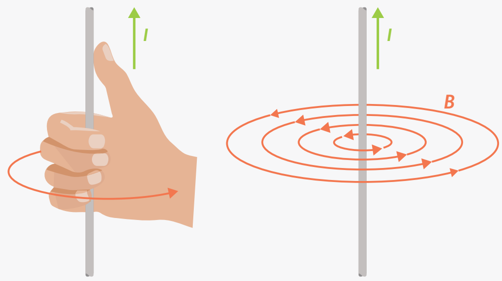
How can we find the direction of a magnetic field around a current-carrying wire?

A current-carrying wire creates a circular magnetic field around it. The direction of the circular magnetic field can be determined using the right-hand grip rule, shown in Table 4.

Table 4 Applying the right-hand grip rule to a current-carrying wire

Application	To find the direction of the magnetic field around a current carrying wire
Thumb	Points in direction of current
Curled grip	Direction of field lines
Example	

A current-carrying loop also creates a magnetic field. For a square loop, analysing the field around each edge of the loop using the right-hand grip rule (Figure 5a) helps us find the combined field from each individual side of the loop (Figure 5b). The same method can be applied to different sections of a circular loop of wire.

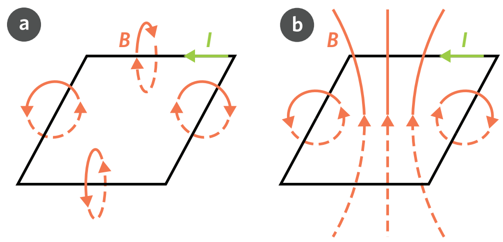
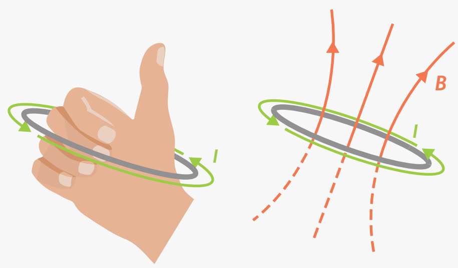


Figure 5 **(a)** The circular magnetic field around each side of a current-carrying square loop add (using vector addition) to create **(b)** a stronger resultant magnetic field in a single direction through the middle of the loop.

Alternatively, to determine the direction of the magnetic field through the middle of a current-carrying loop, we can use the right-hand coil rule shown in Table 5.

Table 5 Applying the right-hand coil rule to a current-carrying loop

Application	To find the direction of the magnetic field through a current carrying loop
Thumb	Points in direction of magnetic field through the loop
Curled grip	Direction of current around the loop
Example	

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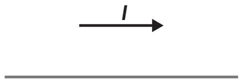
PROGRESS QUESTIONS

Question 5

Which rule can be used to find the magnetic field produced by a current-carrying wire?

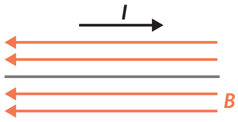
A. left-hand grip rule **B.** left-hand palm rule **C.** right-hand grip rule **D.** right-hand palm rule

Question 6

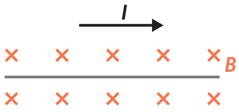


Which of the following correctly shows the magnetic field around the current-carrying wire shown?

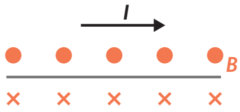
A.



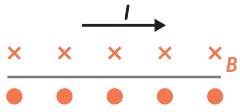
B.



C.



D.



How can we find the direction of a magnetic field associated with a solenoid?

One kind of common electromagnet made from a current-carrying wire is a solenoid:

- A solenoid is created by wrapping a piece of wire around a circular bar continuously to create a coil. It can be thought of as many connected loops of wire.
- The magnetic field of a solenoid is the sum of the fields created by each loop within the coil.
- This results in a strong field along the length of the solenoid, and a weaker magnetic field outside the radius of the solenoid.

The direction of current in a solenoid can be determined by visually inspecting how the solenoid curls and the orientation of the power supply. Current is always directed out from the positive (or longer side) of the power supply and into the negative (or shorter side) of the power supply (Figure 6).

- In Figure 6a, current is directed out of the longer side of the battery. Current runs around the solenoid clockwise when viewed from the left.
- In Figure 6b, current is directed out of the longer side of the battery. Current runs around the solenoid anticlockwise when viewed from the left.

To determine the direction of the magnetic field created by the solenoid (inside the solenoid), we can use the right-hand coil rule shown in Table 6.

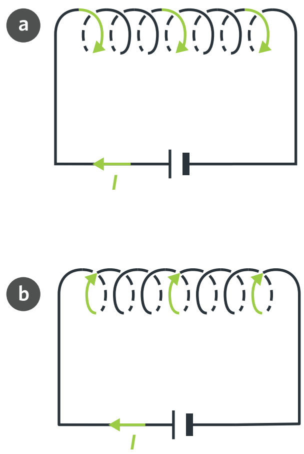


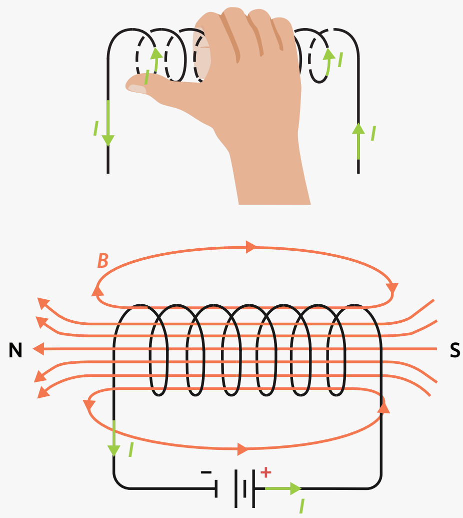
Figure 6 **(a)** The direction of the coils in the solenoid causes the direction of the current around the solenoid to be clockwise when viewed from the left and **(b)** anticlockwise when viewed from the left.

Table 6 Applying the right-hand coil rule to a solenoid

Application	To find the direction of the magnetic field through a solenoid
Thumb	Points in direction of magnetic field through the solenoid
Curled grip	Direction of current around each loop • current runs out of the + (longer line of the battery) and towards the − (shorter line of the battery)

Continues →

Table 6 Continued

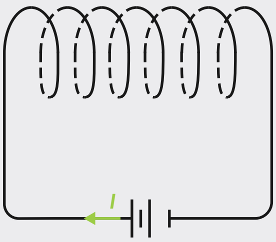
Example	

USEFUL TIP

We can model the solenoid shown in Table 6 as a bar magnet with a north pole on the left, as field lines point away from this side, and south pole on the right, as field lines point towards this side. This can be useful to determine whether solenoids and other types of magnets will attract or repel one another.

WORKED EXAMPLE 1

A solenoid is connected to a power source as shown.

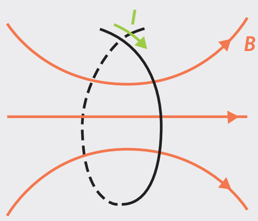


a. Draw the current and direction of the magnetic field around a single turn of the solenoid.

Breakdown

I have drawn the current running clockwise, when viewed from the left.

I have drawn a magnetic field directed towards the right through the loop of wire.

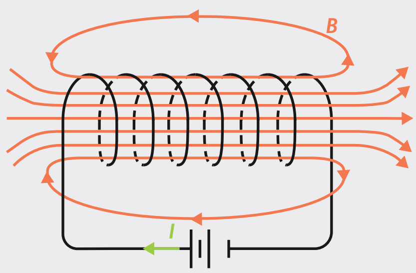


b. Draw the magnetic field around the whole solenoid.

Breakdown

I have drawn magnetic field lines directed towards the right through the solenoid.

I have drawn magnetic field lines looping from the right hand side of the solenoid back to the left, on the outside of the solenoid.



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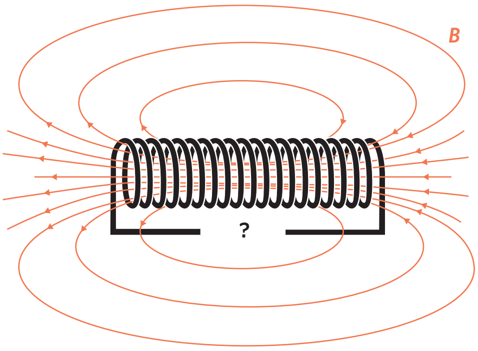
PROGRESS QUESTIONS

Question 7

Which rule can be used to find the magnetic field produced by a solenoid?

A. left-hand coil rule **B.** left-hand grip rule **C.** right-hand coil rule **D.** right-hand palm rule

Question 8



A solenoid produces a magnetic field as shown. The correct representation of the battery must be

A. 

B. 

C. 

D. 

Theory summary

- Magnetic fields are created by permanent magnets or electromagnets as a result of the movement of charge.
- Like poles repel and opposite poles attract.
- Magnetic fields can be static or changing.
- The direction of the current through the wires of a solenoid determines the direction of the magnetic field. The way that a solenoid is coiled and the orientation of the power source must be considered when determining field direction.

Table 7 Summary of determining magnetic field patterns

Source of magnetic field	Magnetic field direction
Permanent magnet	Runs from north to south
Current-carrying wire	Found using the right-hand grip rule
Current-carrying loop	Found using the right-hand coil rule
Solenoid	Found using the right-hand coil rule

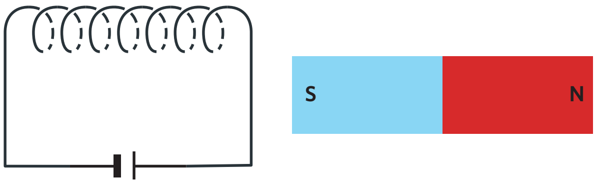
4B Questions

Mild 🌶 Medium 🌶🌶 Spicy 🌶🌶🌶

Deconstructed exam-style

Use the following information to answer questions 9–12.

A bar magnet is placed close to a solenoid as shown.



Question 9 🌶 (1 MARK)

Describe the conditions in which two magnets will attract each other.

Question 10 🌶 (1 MARK)

The bar magnet and the solenoid will attract each other if

A. the magnetic field created by the solenoid is pointing to the left at the position of the bar magnet.

B. the magnetic field created by the solenoid is pointing to the right at the position of the bar magnet.

C. the magnetic field created by the solenoid is pointing into the page at the position of the bar magnet.

D. the magnetic field created by the solenoid is pointing out of the page at the position of the bar magnet.

Question 11 🌶 (1 MARK)

State the direction of the magnetic field through the solenoid.

Question 12 🌶🌶 (3 MARKS)

Determine the direction of the magnetic field through the solenoid and explain whether the bar magnet and the solenoid will attract or repel each other.

Exam-style

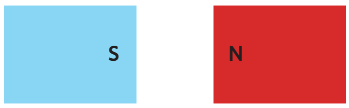
Question 13 (12 MARKS)

Four magnetic fields are being analysed.

a. **i.** Draw the magnetic field in the space between these two bar magnets. Use four field lines. 🌶 2 MARKS

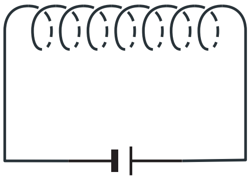
ii. Is the magnetic field between these magnets uniform or non-uniform? 🌶 1 MARK

b. **i.** Draw the magnetic field in the space between these bar magnets. Use five field lines. 🌶 2 MARKS



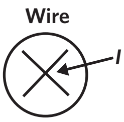
ii. The magnet on the right is moving away from the other magnet. Is the magnetic field around these magnets static or changing? 🌶 1 MARK

c. **i.** Draw the magnetic field through and around this solenoid. Use five field lines. 🌶🌶 — 2 MARKS



ii. State whether the field surrounding the solenoid is uniform or non-uniform. 🌶 — 1 MARK

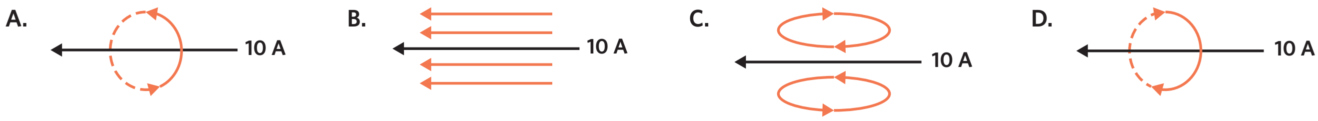
d. **i.** Draw the magnetic field around the wire shown, carrying current into the page. Use four field lines. 🌶🌶 — 2 MARKS



ii. The current through the wire varies with time. State whether the field is static or changing. 🌶 — 1 MARK

Question 14 🌶 (1 MARK)

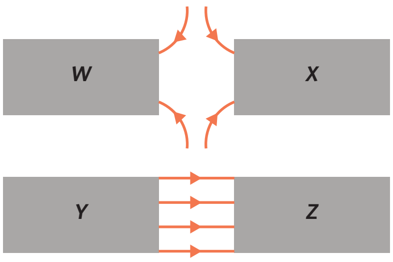
A wire carries a 10 A current to the left. Which of the following diagrams shows the magnetic field produced by the current?



Adapted from VCAA 2018 exam Multiple choice Q3

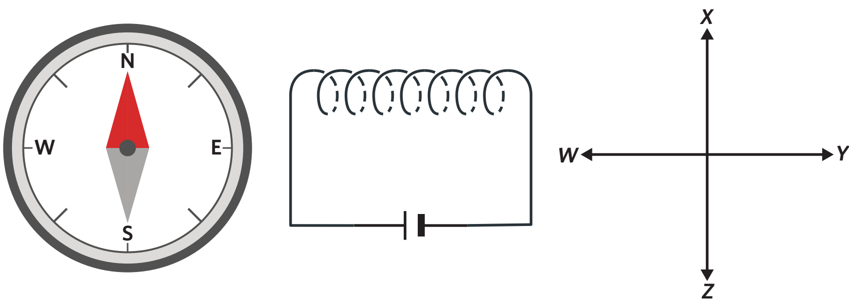
Question 15 🌶🌶 (2 MARKS)

A student has drawn field lines between the poles of two bar magnets in two different orientations. Determine the pole type (north or south) of poles *W*, *X*, *Y* and *Z*.



Question 16 🌶🌶 (2 MARKS)

Current runs through a solenoid from a battery. A small compass, which orients so that its north pole points in the direction of field lines around it, is next to the solenoid. Determine the direction (*W*, *X*, *Y*, or *Z*) that the north pole of the compass would point when the solenoid is turned on. Justify your answer.



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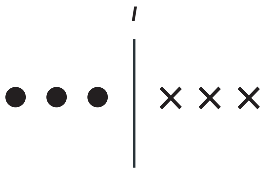
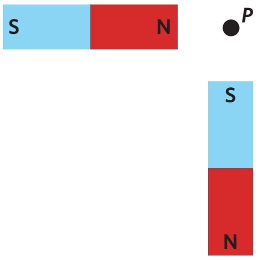
Question 17 (1 MARK)

A current-carrying wire is creating a magnetic field. Determine the direction of the current *I*.



Question 18 (2 MARKS)

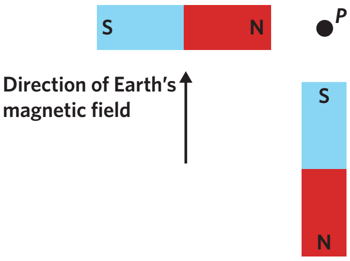
Two identical bar magnets of the same strength are arranged at right angles and are equidistant from point *P*, as shown.



a. At point *P* on the diagram, draw an arrow indicating the direction of the combined magnetic field of the bar magnets. 1 MARK

Adapted from VCAA 2011 Exam 2 Area of Study 1 Section A Q1

b. The bar magnets are replaced by two weaker magnets. The two new magnets are identical to each other. They are arranged at right angles and are equidistant from point *P*. The magnitude of the magnetic field of a single bar magnet at point *P* is the same as the magnitude of the magnetic field of Earth at point *P*. The direction of the Earth's magnetic field is shown.

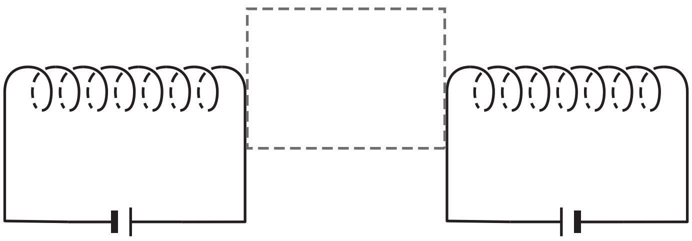


At point P on the diagram, draw an arrow indicating the direction of the combined magnetic field of the bar magnets and the Earth. 1 MARK

Adapted from VCAA 2011 Exam 2 Area of Study 1 Section A Q2

Question 19 (2 MARKS)

Two solenoids are brought close together. In the dashed area, use four field lines to show the shape of the magnetic field between the solenoids.



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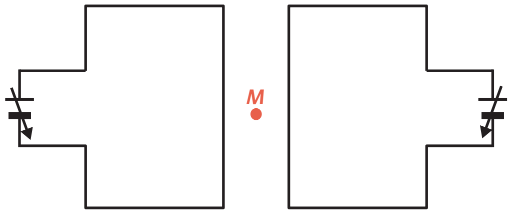
Question 20 (5 MARKS)

A student has two identical loops of wire, oriented on their desk as shown. Connected to each wire is a variable voltage source – one which can create current to be directed either way around the loops. The point M is directly between the two loops. The student uses a magnetometer to measure the strength of the magnetic field at point M.



a. *Key science skill*

The student turns on both variable voltage sources so that the currents flow in opposite directions around the loops. Use the vector field model of magnetic fields to explain why there is no detected change to the strength of the magnetic field at point M. 3 MARKS

FROM LESSON 12A

b. *Key science skill*

The student now replaces the variable voltage sources with two standard DC power supplies. Draw the correct experimental set up, including the orientation of the power supplies, so that the resultant magnetic field at point M due to the current-carrying loops is directed out of the page. 2 MARKS

FROM LESSON 12A

Previous lessons

Question 21 (2 MARKS)

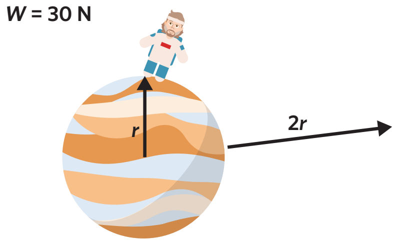
A tennis ball, of mass 50 g, is bounced on the ground. Just before it hits the ground it is travelling at 14 m s^{-1} and it bounces up at 13 m s^{-1}. If it is in contact with the ground for 0.30 s, calculate the magnitude of the impulse exerted on the ball.

FROM LESSON 1I

Question 22 (2 MARKS)

Astronaught measures their weight at the surface of a nearby planet to be 30 N. They now move to an altitude that is double the radius of the planet. Determine the weight of Astronaught at this new position.

FROM LESSON 3A



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4C Magnetic forces on charged particles

STUDY DESIGN DOT POINTS

- analyse the use of a magnetic field to change the path of a charged particle, including:
  - the magnitude and direction of the force applied to an electron beam by a magnetic field: $F = qvB$, in cases where the directions of v and B are perpendicular or parallel
  - the radius of the path followed by an electron in a magnetic field $qvB = \frac{mv^2}{r}$, where $v << c$
- investigate and analyse theoretically and practically the force on a current carrying conductor due to an external magnetic field, $F = nBIL$, where the directions of I and B are either perpendicular or parallel to each other

4A 4B 4C 4D

3.2.7.1 Magnetic forces on charged particles

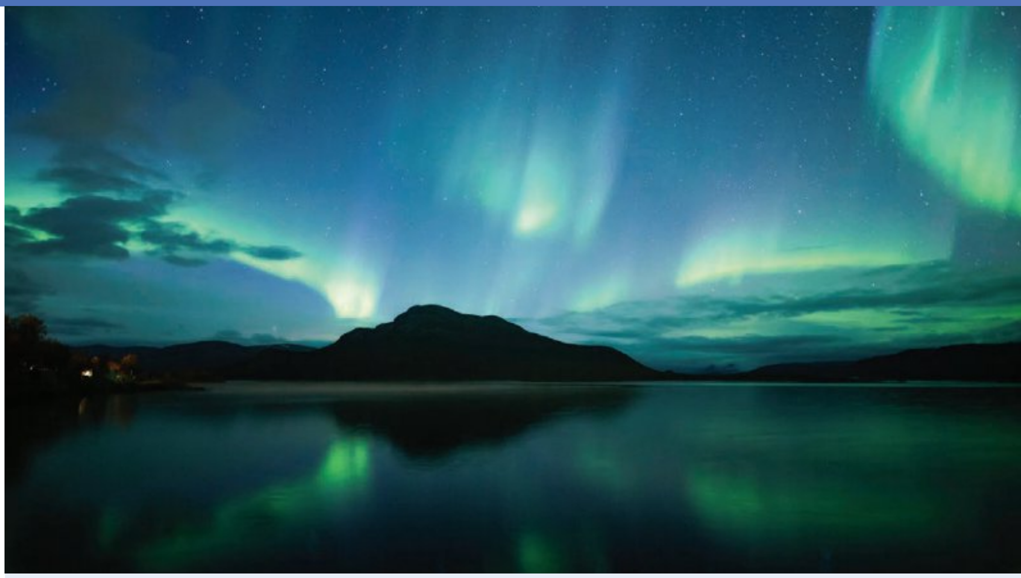
3.2.7.2 & 3.2.13.2 Circular motion in magnetic fields

3.2.13.1 Magnetic forces on current-carrying wires

ESSENTIAL PRIOR KNOWLEDGE

4B Vector field conventions

See question 47.



How are the southern lights formed?

Aurora australis (the scientific name for the phenomena which causes the southern lights) occurs when charged particles interact with the Earth's magnetic field. This lesson will investigate the forces on charged particles and current-carrying wires caused by magnetic fields. The interaction between charges and magnetic fields is further evidence that electric fields and magnetic fields are two versions of the same thing, known as 'electromagnetism'.

KEY TERMS AND DEFINITIONS

conventional current current that is modelled as positive charges that flow from the positive to the negative terminal of a cell

FORMULAS

- **magnetic force on a charged particle**
  $F = qvB$
- **magnetic force on a current-carrying wire**
  $F = nBIL$
- **radius of a charged particle in a magnetic field**
  $r = \frac{mv}{qB}$

Magnetic forces on charged particles 3.2.7.1

A charged particle will experience a magnetic force when it is moving through a magnetic field at an angle to its field lines. The direction of the force is determined by using the right-hand palm rule.

How can we find the magnetic force acting on a charged particle?

When moving through a magnetic field, a charged particle will experience a force which depends on the angle between its direction of motion and the magnetic field lines.[1] In VCE Physics, we only consider the motion of charged particles perpendicular or parallel to the magnetic field.

KEEN TO INVESTIGATE?

[1] **How are the northern lights formed?**
Search: How does the aurora borealis work?

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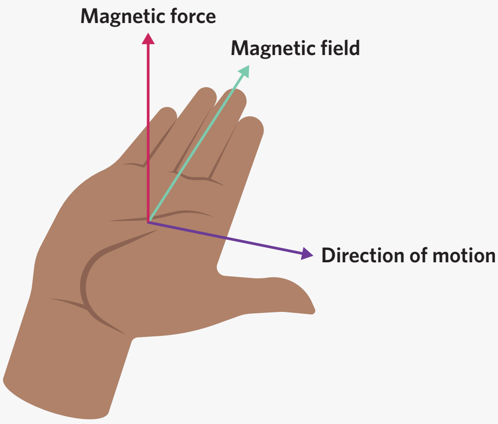
- The magnetic force is a maximum when the direction of motion of a charged particle is perpendicular to the magnetic field lines (Figure 1a and 1b).
- There is no magnetic force acting on a charged particle when its direction of motion is parallel to the magnetic field lines or if the particle is stationary (Figure 1c).

The direction of the magnetic force on a charged particle is perpendicular to both its direction of motion and the direction of the magnetic field. Table 1 shows how to find the direction of the magnetic force on a positively charged particle, determined by the right-hand palm rule (also known as the right-hand slap rule).

Table 1 Applying the right-hand palm rule to a charged particle

Application	To determine the direction of magnetic force on a charged particle
Thumb	Points in direction of motion
Fingers	Direction of magnetic field
Palm	Direction of magnetic force on a positively charged particle
Example	

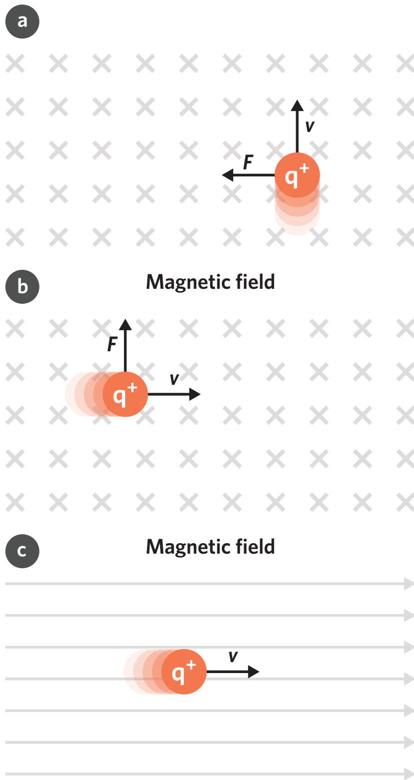


Figure 1 A charged particle **(a)** & **(b)** will experience a force when moving perpendicular to a magnetic field, and **(c)** will not experience a force when moving parallel to a magnetic field.

STRATEGY

To determine the direction of the magnetic force on a negatively charged particle we can

- point the thumb opposite to the direction of motion of the particle (Figure 2b)

OR

- consider the force on a negatively charged particle to be out the back of the hand, with the thumb in the direction of motion of the particle.

This is because the magnetic force on a negatively charged particle is in the opposite direction to the force on a positively charged particle.

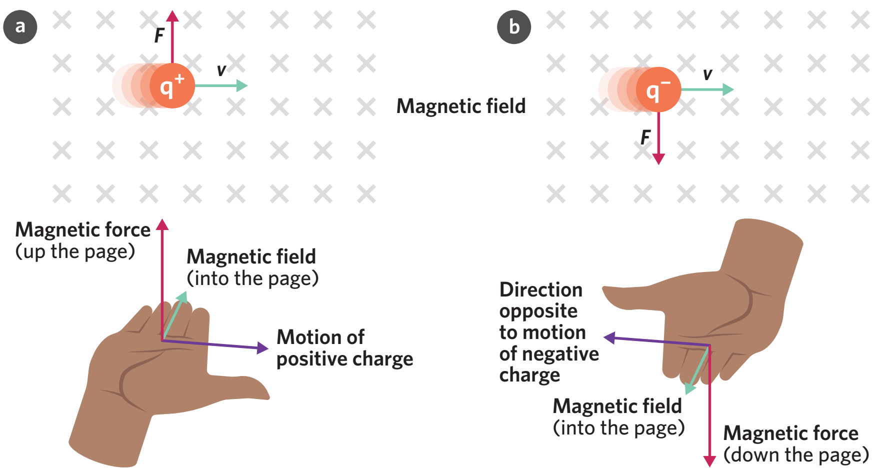


Figure 2 **(a)** Determining the direction of the magnetic force on a positively charged and **(b)** negatively charged particle.

USEFUL TIP

Before completing any magnetic force calculations, check that the direction of motion of the charge is perpendicular to the magnetic field to ensure that the magnetic force is present.

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4C THEORY

The magnitude of the magnetic force on a charged particle moving perpendicular to a magnetic field can be calculated using:

USEFUL TIP

Equations involving magnetic fields use the variable B to represent magnetic field strength, measured in tesla (T). It is common for magnetic field strength to be far smaller than 1 T.

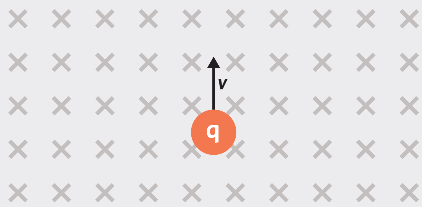
FORMULA

$$F = qvB$$

F = magnetic force (N)
q = electric charge of particle (C)
v = speed of particle ($m\ s^{-1}$)
B = magnetic field strength (T)

WORKED EXAMPLE 1

A charged particle is moving up the page through a magnetic field of strength $B = 0.50$ T at $v = 20\ m\ s^{-1}$. The magnetic field direction is into the page.



a. If the charged particle is a proton, calculate the magnitude of the magnetic force acting on it.

Step 1

Identify known and unknown variables and write down the formula that relates these variables.

Note that as the proton is moving perpendicular to a magnetic field, a magnetic force will be present.

$q = 1.6 \times 10^{-19}$ C, $v = 20\ m\ s^{-1}$, $B = 0.50$ T, $F = ?$

$F = qvB$

Step 1

Substitute values into the formula and solve for the magnetic force acting on the proton.

$F = 1.6 \times 10^{-19} \times 20 \times 0.50$

$F = 1.6 \times 10^{-18}$ N

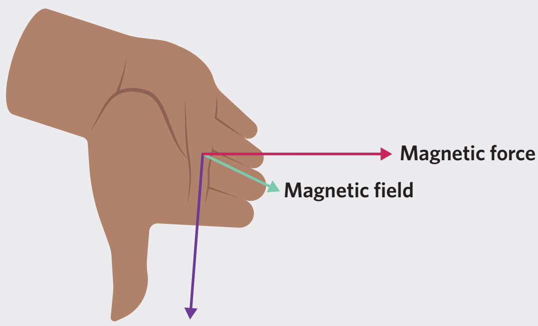
b. If the charged particle is an electron, determine the direction of the magnetic force acting on it.

Breakdown

Use the right-hand palm rule to determine the direction of the magnetic force acting on the electron.

Answer

Using the right-hand palm rule, the direction of the magnetic force acting on the charged particle is to the right.



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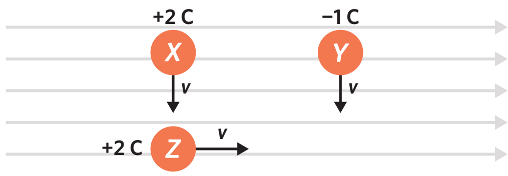
PROGRESS QUESTIONS

Use the following information to answer questions 1–3.

Three charged particles, *X*, *Y*, and *Z*, are moving inside a magnetic field with directions shown in the diagram. The magnetic field strength is 0.60 T, and all particles are moving at 1.4×10^5 m s^{-1}.



Question 1

What is the direction of the magnetic force exerted on particle *X*?

A. to the left

B. up the page

C. out of the page

D. There is no magnetic force exerted on particle *X*.

Question 2

What is the magnitude of the magnetic force exerted on particle *Y*?

A. 0 N

B. 1.4×10^4 N

C. 8.4×10^4 N

D. 1.7×10^4 N

Question 3

What is the magnitude of the magnetic force exerted on particle *Z*?

A. 0 N

B. 1.4×10^5 N

C. 8.4×10^5 N

D. 1.7×10^6 N

Circular motion in magnetic fields 3.2.7.2 & 3.2.13.2

Charged particles moving perpendicular to a magnetic field may travel in uniform circular motion. The magnetic force on a charged particle can act as the centripetal force.

How do charged particles undergo circular motion in a magnetic field?

From Lesson 1E, recall that an object undergoes uniform circular motion if the net force acting on it is:

- of constant magnitude
- directed perpendicular to an object's velocity.

When a charged particle is moving through a uniform magnetic field perpendicular to its field lines, the magnetic force:

- is of constant magnitude
- always acts perpendicular to the motion of the particle.

As a result, in the absence of any other forces, a charged particle moving perpendicular to a magnetic field will undergo uniform circular motion. Since the direction of force will be opposite for positive and negative charges, the direction of the circular motion will be opposite for positive and negative charges (Figure 3).

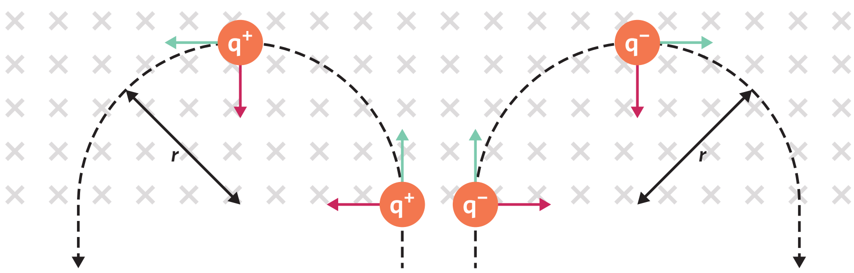


Figure 3 Charged particles with opposite charges will experience rotation in the opposite directions.

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During uniform circular motion in a magnetic field, the force on a charged particle, $F = qvB$, is equal to the centripetal force $F = \frac{mv^2}{r}$. By equating these two formulas ($qvB = \frac{mv^2}{r}$) and rearranging, the radius of the circular motion of a charged particle in a magnetic field can be calculated using:

USEFUL TIP

The formula for the radius of the path followed by a charged particle in a magnetic field assumes the speed of the charged particle is much less than the speed of light, so that no relativistic effects are present (relativistic effects are explored in Chapter 11).

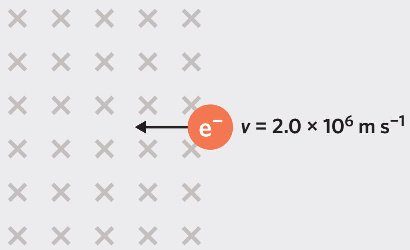
FORMULA

$$r = \frac{mv}{qB}$$

r = radius of circular path (m)
m = mass of particle (kg)
v = speed of particle (m s^{-1})
q = electric charge of particle (C)
B = magnetic field strength (T)

WORKED EXAMPLE 2

An electron enters a uniform magnetic field with field strength $B = 2.0 \times 10^{-3}$ T. The electron moves perpendicular to the magnetic field and turns through one quarter of a circle. The initial speed of the electron is 2.0×10^6 m s^{-1}.

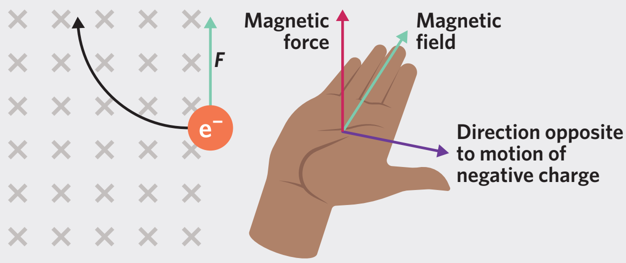


a. Draw the direction of the magnetic force acting on the electron at the position shown and the path of the electron through the magnetic field.

Breakdown

Use the right-hand palm rule to determine that the direction of the magnetic force acting on the electron is up the page.

Answer



b. Calculate the radius of the electron's circular path.

Step 1

Identify known and unknown variables and write down the formula that relates these variables.

Note that as the electron is moving perpendicular to a magnetic field, a magnetic force will be present.

$m = 9.1 \times 10^{-31}$ kg, $v = 2.0 \times 10^6$ m s^{-1}, $q = 1.6 \times 10^{-19}$ C, $B = 2.0 \times 10^{-3}$ T, $r = ?$

$$r = \frac{mv}{qB}$$

Step 2

Substitute values into the formula and solve for the radius of the electron's circular path.

$$r = \frac{9.1 \times 10^{-31} \times 2.0 \times 10^6}{1.6 \times 10^{-19} \times 2.0 \times 10^{-3}}$$

$$r = 5.69 \times 10^{-3} = 5.7 \times 10^{-3} \text{ m}$$

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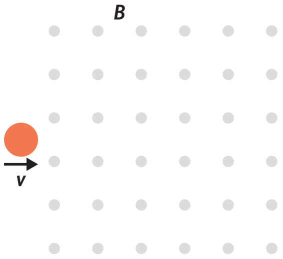
PROGRESS QUESTIONS

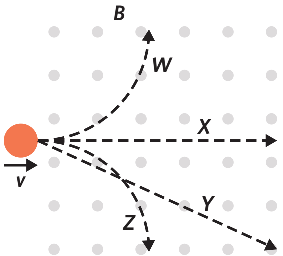
Use the following information to answer questions 4 and 5.

A proton travelling at 1.5×10^6 m s^{-1} enters a uniform magnetic field as shown.



Question 4

Which of the following correctly shows the path of the proton?



A. *W* **B.** *X* **C.** *Y* **D.** *Z*

Question 5

If the radius of the circular path the proton travels is 35 cm, what is the value of the magnetic field strength? Take mass of a proton to be 1.67×10^{-27} kg.

A. 2.4×10^{-7} T **B.** 2.4×10^{-5} T **C.** 4.5×10^{-4} T **D.** 4.5×10^{-2} T

Magnetic forces on current-carrying wires 3.2.13.1

Current-carrying wires experience magnetic forces when the current is at an angle to an external magnetic field. The magnitude of the force is dependent on this angle, the current, the number of wires, the length of the wires within a magnetic field, and the magnetic field strength. The direction of the force is determined using the right-hand palm rule.

How can we find the magnetic force acting on a current-carrying wire?

Electric current can be modelled as the movement of many charged particles in the same direction. Since a charged particle moving perpendicular to a magnetic field experiences a magnetic force, the moving charged particles inside a current-carrying wire also experience a magnetic force. Because the charged particles must remain inside the wire, we can model the overall magnetic force on the current-carrying wire (Figure 4).

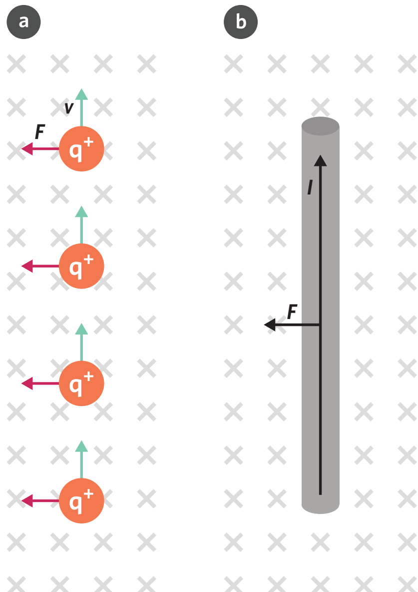


Figure 4 **(a)** The magnetic forces on a flow of positive charges and **(b)** the magnetic force on a current-carrying wire

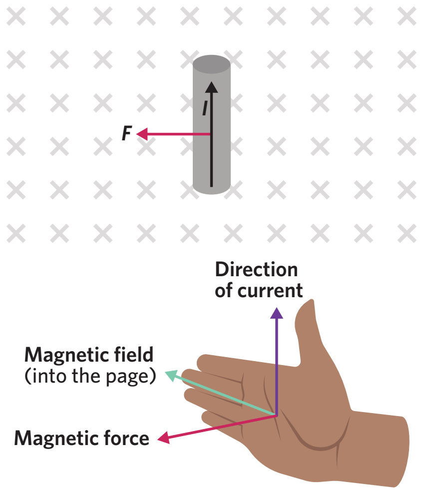


Figure 5 How to use the right-hand palm rule to determine the force on a current-carrying wire.

In an electric circuit, **conventional current** flows from the positive terminal to the negative terminal of a power source. This means that we can use the right-hand palm rule, with the thumb representing conventional current direction, to determine the direction of the magnetic force on a current-carrying wire (Figure 5).

In VCE Physics only current flowing perpendicular or parallel to a magnetic field is considered. If the direction of the current is parallel to the magnetic field, there is no magnetic force acting on the wire.

The magnitude of the magnetic force on a current-carrying wire perpendicular to a magnetic field is given by:

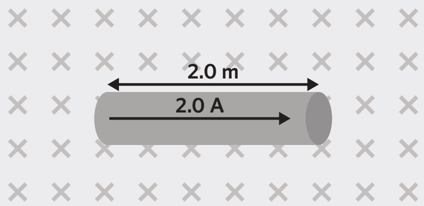
FORMULA

$$F = nBIL$$

F = magnitude of magnetic force (N)
n = number of wires (no units)
I = current perpendicular to magnetic field (A)
L = length of wire within magnetic field (m)
B = magnetic field strength (T)

WORKED EXAMPLE 3

A bundle of 10 wires, each carrying 2.0 A, is placed in a perpendicular magnetic field of strength 0.050 T. A 2.0 m length of the bundle lies within the magnetic field, as shown. Determine the magnitude and direction of the magnetic force acting on the current-carrying bundle.



Step 1

Identify known and unknown variables and write down the formula that relates these variables.

$n = 10$, $B = 0.050$ T, $I = 2.0$ A, $L = 2.0$ m, $F = ?$

$F = nBIL$

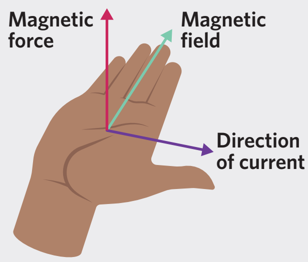
Step 2

Substitute values into the formula and solve for the magnitude of the force on the current-carrying bundle.

$F = 10 \times 0.050 \times 2.0 \times 2.0$

$F = 2.00 = 2.0$ N

Using the right-hand palm rule, the direction of the force on the current carrying wire is up the page.



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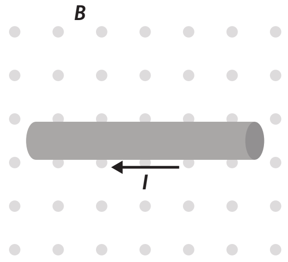
PROGRESS QUESTIONS

Use the following information to answer questions 6 and 7.

A 20 cm wire carrying 3.0 A is placed in a magnetic field of strength 1.5 T, as shown.



Question 6

What is the magnitude of the magnetic force acting on the current-carrying wire?

A. 0 N **B.** 0.45 N **C.** 0.90 N **D.** 9.0 N

Question 7

What is the direction of the magnetic force on the current-carrying wire?

A. to the right **B.** up the page **C.** into the page **D.** down the page

Theory summary

- A magnetic force will be experienced by a charged particle when it is moving at an angle to a magnetic field.
  - The magnitude of the magnetic force is found using $F = qvB$, for motion which is perpendicular to the magnetic field.
  - There is no magnetic force if the direction of motion is parallel to a magnetic field.
- The direction of the magnetic force is perpendicular to both the direction of motion of the charged particle and the magnetic field.
  - The direction of the force is determined using the right-hand palm rule.
  - For negative charges, point the thumb in the opposite direction to the motion.
- A charged particle which moves perpendicular to a uniform magnetic field will follow a circular path with radius $r = \frac{mv}{qB}$.
- A magnetic force is experienced by a current-carrying wire in a magnetic field when the current flows at an angle to the field.
  - The magnitude of the magnetic force is found using $F = nBIL$, for current which is perpendicular to the magnetic field.
  - There is no magnetic force if the current is parallel to the magnetic field.
- The direction of the magnetic force on a current-carrying wire is determined by the right-hand palm rule, where the thumb represents the direction of conventional current (the direction positive charges would flow).

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4C QUESTIONS

4C Questions

Mild 🌶 Medium 🌶🌶 Spicy 🌶🌶🌶

Deconstructed exam-style

Use the following information to answer questions 8–10.

A charged particle is moving through a uniform magnetic field at a constant speed, with its direction of motion perpendicular to the direction of the magnetic field.

Question 8 🌶 (1 MARK)

Describe how the magnitude of the magnetic force acting on the charged particle changes when it is within the magnetic field.

Question 9 🌶 (1 MARK)

Describe how the direction of the magnetic force on the charged particle changes when it is within the magnetic field.

Question 10 🌶🌶 (2 MARKS)

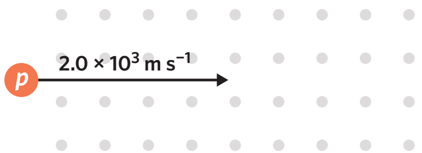
Explain why the path of the charged particle in the magnetic field follows a circular path.

Adapted from VCAA 2021 NHT exam Short answer Q2b

Exam-style

Question 11 (4 MARKS)

A proton is moving to the right at 2.0×10^3 m s^{-1} and enters a uniform magnetic field of $B = 0.030$ T, as shown. The charge of a proton is $+1.6 \times 10^{-19}$ C.



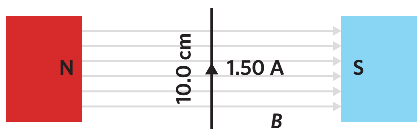
a. Determine the magnitude of the magnetic force experienced by the proton, at the position shown. 🌶 2 MARKS

b. Determine the direction of the magnetic force experienced by the proton, at the position shown. 🌶 1 MARK

c. Determine the direction of the magnetic force if the proton was replaced by an electron with the same velocity, at the position shown. 🌶 1 MARK

Use the following information to answer questions 12 and 13.

A current-carrying wire runs between the opposite poles of two bar magnets. The length of wire within the magnetic field is 10.0 cm, and it carries a current of 1.50 A up the page. The magnetic field strength is 0.400 T.



Question 12 🌶 (2 MARKS)

Determine the magnitude of the force on the current-carrying wire.

Adapted from VCAA 2021 NHT exam Multiple choice Q1

Question 13 🌶 (1 MARK)

What is the direction of the force on the current-carrying wire?

A. to the left **B.** up the page **C.** into the page **D.** down the page

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Question 14 (5 MARKS)

A group of students are investigating the motion of an electron moving perpendicular to a magnetic field. They calculate that the electron experiences a magnetic force of 2.00×10^{-11} N when inside a magnetic field of strength 3.00 T. Ignore relativistic effects

a. Show that the speed of the electron within the magnetic field is 4.2×10^7m s^{-1}. 1 MARK

b. Calculate the radius of the path of this electron. Show your working. 2 MARKS

Adapted from VCAA 2018 exam Short answer Q1c

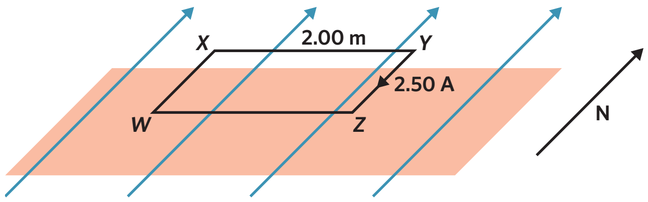
c. *Key science skill*

The students now increase the strength of the magnetic field. Predict how the radius of the electron's path in the magnetic field changes. Justify your answer. 2 MARKS

FROM LESSON 12A

Question 15 (8 MARKS)

2.50 A of current is flowing around the 10 turn current-carrying loop *WXYZ*. Each side of the loop is 2.00 m long. The loop is within the Earth's magnetic field at a point where the magnetic field lines are parallel to the Earth's surface and point geographically north. The field strength at this point is 6.50×10^{-6} T.



a. Which side(s) of the loop experience a magnetic force? Explain your answer. 2 MARKS

b. Determine the magnitude of the force exerted on each of the side(s) of the loop experiencing a magnetic force. 2 MARKS

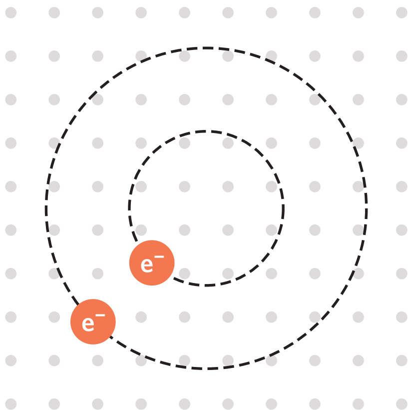
Adapted from VCAA 2017 exam Short answer Q3a

c. Determine the direction of the force exerted on each of the side(s) of the loop experiencing a magnetic force. 2 MARKS

d. What is the net force acting on the loop of wire? Justify your answer. 2 MARKS

Use the following formation to answer questions 16–18.

Two electrons are undergoing circular motion within a magnetic field of strength 4.0 mT.



Question 16 (1 MARK)

What is the direction of the electrons' motion around the circular path shown?

A. clockwise

B. anticlockwise

C. The electrons can move clockwise or anticlockwise.

D. There is not enough information to determine the direction of the electron's motion.

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Question 17 🌶🌶 (2 MARKS)

Determine which electron (the inner or outer) would experience a greater magnetic force.

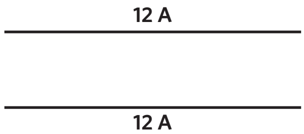
Question 18 🌶🌶 (3 MARKS)

The inner electron is travelling at 2.3×10^4 m s^{-1}. Calculate the diameter of the circular path it is travelling in.

Adapted from VCAA 2021 NHT exam Short answer Q2c

Question 19 (6 MARKS)

Two current-carrying wires are placed close to each other. They each carry a current of 12 A.



a. Explain whether the wires are attracted or repelled from each other when they carry a current to the right. 🌶🌶🌶 3 MARKS

b. Explain whether the wires are attracted or repelled from each other when the upper wire carries current to the right, and the lower wire carries current to the left. 🌶🌶 3 MARKS

Question 20 (8 MARKS)

Lucia is conducting an experiment where she uses a magnetic field to accelerate an unknown charge in a circular path. Accelerating at 6.25×10^{10} m s^{-2}, the charge's path has a radius of 1.0 m. The strength of the magnetic field is 1.42×10^{-6} T. Ignore relativistic effects. When a charge undergoes circular motion, its acceleration can be found using $a = \frac{v^2}{r} = \frac{F_B}{m}$.

a. Determine whether the charge is an electron or a proton. 🌶🌶🌶 4 MARKS

Adapted from 2015 VCAA Exam Section B Detailed study 4 Q5

b. ***Key science skill***

Lucia changes the experiment so that she now accelerates an alpha particle, which has four times the mass of a proton and twice the charge. If she keeps the magnetic field strength and the acceleration of the particle the same, predict the change in the radius of the particle's path. Justify your answer. 🌶🌶🌶 4 MARKS

Previous lessons

Question 21 🌶 (1 MARK)

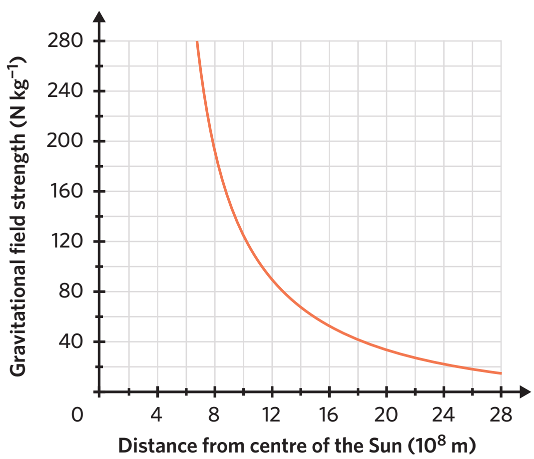
A 2.5 kg ball is thrown at 13 km h^{-1} upwards. What is the kinetic energy of the ball as it is thrown?

FROM LESSON 2A

Question 22 🌶🌶 (3 MARKS)

Using the graph, estimate the change in gravitational potential energy of a 200 kg asteroid when moving from 14×10^8 m to 26×10^8 m from the centre of the Sun.

FROM LESSON 3B



4D DC motors

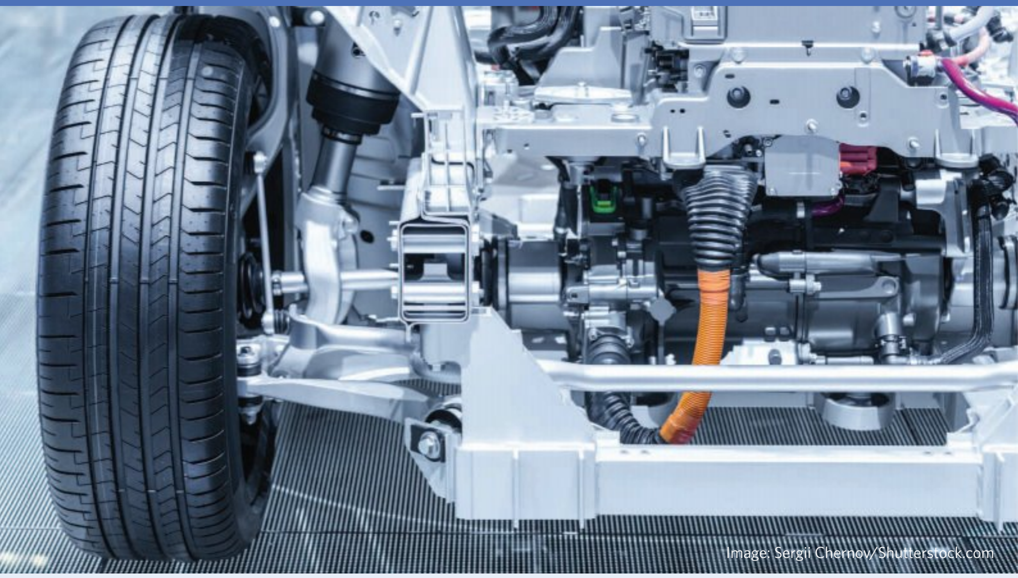


Image: Sergii Chernov/Shutterstock.com

Why are electric cars so much heavier than petrol cars?

Electric vehicles use large DC motors to convert electrical potential energy into kinetic energy, which allows the car to accelerate. In order to provide enough energy to power their large motor, they need a large and heavy battery. However, despite this increase in mass, electric cars can accelerate faster and deliver power quicker than petrol cars. DC motors can be seen in many applications across different industries and within household appliances. This lesson will build upon previous lessons from this chapter to explore the operation and principles behind DC motors.

STUDY DESIGN DOT POINTS

- investigate and analyse theoretically and practically the operation of simple DC motors consisting of one coil, containing a number of loops of wire, which is free to rotate about an axis in a uniform magnetic field and including the use of a split ring commutator
- investigate, qualitatively, the effect of current, external magnetic field and the number of loops of wire on the torque of a simple motor

4A 4B 4C **4D**

3.2.14.1 & 3.2.15.1 DC motor operation

3.2.14.2 Split ring commutators in DC motors

ESSENTIAL PRIOR KNOWLEDGE

4C Magnitude of magnetic force on a current-carrying wire

4C Direction of magnetic force on a current-carrying wire

See questions 48–49.

KEY TERMS AND DEFINITIONS

direct current (DC) electricity with a constant direction of current

split ring commutator a component used to reverse the electrical connection between a stationary external circuit and a rotating coil every half rotation

torque the turning effect due to a force acting at a perpendicular distance from an object's axis of rotation (vector)

slip rings a component used to maintain a constant electrical connection between a stationary external circuit and a rotating coil

FORMULAS

- **magnetic force on a current carrying wire**
  $F = nBIL$

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DC motor operation 3.2.14.1 & 3.2.15.1

Direct current (DC) motors convert electrical potential energy into kinetic energy using the magnetic force that acts on a current-carrying wire within a magnetic field.

What is a DC motor?

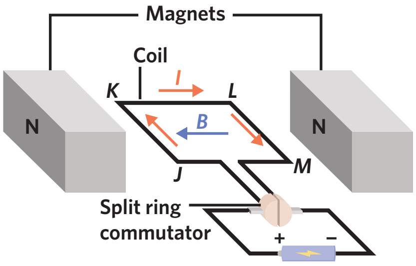

Figure 1 A simple DC motor

A simple DC motor (Figure 1) consists of:

- a constant DC voltage supply – used to produce DC electricity. DC runs out of the positive terminal of the battery and into the negative terminal.
- a coil of current-carrying wire (also called the armature) – made of one or more windings free to rotate. Each coil or winding is called a 'turn' of wire.
- a **split ring commutator** – used to transmit the direct current to the coil in a way that allows continuous rotation.
- a magnetic field – produced by either permanent magnets or electromagnets.
- brushes – used to maintain electrical contact between the turning parts of the motor and the stationary power supply.

When an electrical current flows through the coil of wire, the sides perpendicular to the magnetic field (JK and LM) experience a force with:

- a magnitude found using $F = nILB$, and
- a direction found by applying the right-hand palm rule to each side.

Using the right-hand palm rule on sides JK and LM we get:

- an upwards force on side JK, and
- a downwards force on side LM (Figure 2a).

As the forces acting on opposite sides are in opposite directions, it creates a **torque** about the axis of rotation, causing the coil to spin. As the direction of the current in sides JK and LM is always perpendicular to the magnetic field, the magnitude of the magnetic force acting on those sides remains constant throughout the coils rotation, when present (Figure 2b).

A torque is only present if this force acts at a perpendicular distance from an axis of rotation or pivot point. Changing the torque acting on a DC motor will be discussed in more detail later in this lesson.

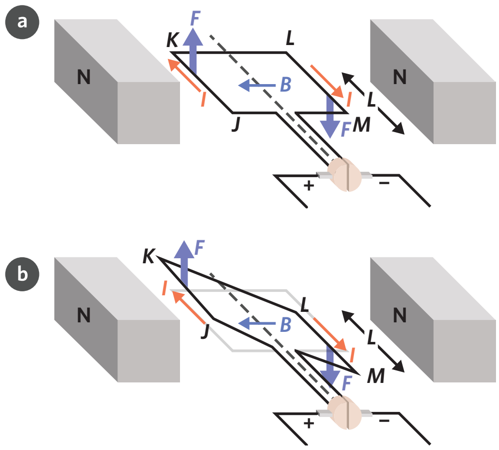

Figure 2 Forces acting on sides JK and LM rotate the coil

The magnetic forces on sides JM and KL of the coil in Figure 2 do not contribute to the torque of the motor. This is because when the loop is horizontal, sides JM and KL are parallel to the magnetic field and there is no magnetic force acting on them; even as the loop rotates, any magnetic force acting on sides JM and KL is not perpendicular to the axis of rotation. As a result, the forces on these sides can be ignored when analysing the rotation of the coil.

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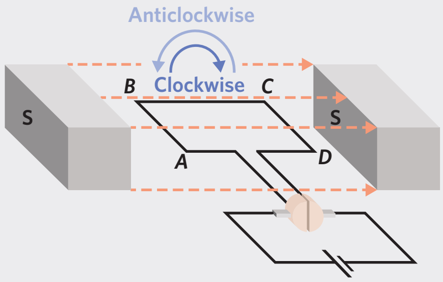
WORKED EXAMPLE 1

A simple DC motor is constructed using 150 turns of wire in a square shape with 7.5 cm side lengths. Permanent magnets produce a magnetic field with a strength of 2.5×10^{-2} T. A current of 2.0 A flows through the coil.



a. Determine the magnitude and direction of the magnetic force on side *AB*.

Step 1

Identify known and unknown variables and write down the formula that relates these variables.

Note that the length is given in cm and must be converted into m to correctly calculate the magnitude of the magnetic force.

$n = 150, B = 2.5 \times 10^{-2}$ T, $I = 2.0$ A, $L = \frac{7.5}{100} = 0.075$ m, $F = ?$

$F = nBIL$

Step 2

Substitute values into the formula and solve for the magnitude of the magnetic force on side *AB*.

Note that the right hand palm rule (introduced in Lesson 4C) is used to find the direction of a magnetic force on a current-carrying wire.

$F = 150 \times 2.5 \times 10^{-2} \times 2.0 \times 0.075$

$F = 0.563 = 0.56$ N

By the right-hand palm rule, the direction of the magnetic force on side *AB* is down.

b. Determine the direction of rotation of the coil (clockwise or anticlockwise) as viewed from the split ring commutator.

Breakdown

Use the right-hand palm rule to determine the direction of the magnetic force acting on sides *AB* and *CD*.

Using the right-hand palm rule, the direction of the magnetic force acting on side *AB* is down and the direction of the magnetic force acting on side *CD* is up.

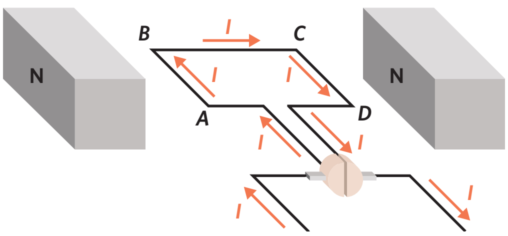
Determine the turning effect created by the magnetic force acting on sides *AB* and *CD*.

This causes an anticlockwise rotation of the coil when viewed from the split ring commutator.

PROGRESS QUESTIONS

Use the following information to answer questions 1–4.

The diagram shows a DC motor with a single turn of wire within a magnetic field.



Question 1

For the first quarter rotation of the coil, the magnetic force on side *AB*

A. will always act upwards.

B. will always act downwards.

C. will always act perpendicular to the plane of the coil.

D. will switch between acting upwards and downwards.

Continues →

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4D THEORY

Question 2

When rotating from the horizontal position shown to just before the vertical position, the magnitude of the magnetic force on side *AB*

A. increases.

B. decreases.

C. remains constant.

D. is zero as it is parallel to the magnetic field.

Question 3

During the rotation of the coil

A. the force on side *AB* is always zero.

B. the force on side *BC* is always zero.

C. the force on side *AB* does not contribute to the rotation of the loop.

D. the force on side *BC* does not contribute to the rotation of the loop.

Question 4

As viewed from the split ring commutator, in which direction will the coil rotate?

A. clockwise

B. anticlockwise

C. The coil will not rotate.

D. The coil will oscillate about the vertical position.

How can we vary the torque of a DC motor?

Recall from Lesson 4C that the magnitude of the magnetic force acting on a current-carrying wire is found using $F = nBIL$, when the direction of current is perpendicular to the direction of the magnetic field.

As the torque created by the magnetic force is proportional to this force, we can increase the torque on a DC motor by:

- increasing the number of turns of wire (n)
- increasing the magnetic field strength (B)
- increasing the current in the loop of wire (I)
- increasing the length of the sides of the DC motor (L).[1]

A DC motor with increased torque will rotate at a quicker rate (Figure 3).

KEEN TO INVESTIGATE?

[1] **What is torque?**
Search YouTube: Torque basics explained

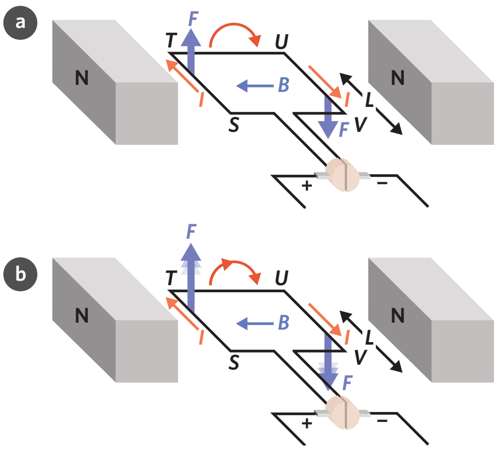

Figure 3 The loop with a greater force on each side will rotate at a quicker rate.

USEFUL TIP

The best position to begin a DC motor from is the horizontal position (Figure 3a), as this is the point at which the sides *ST* and *UV* are the furthest perpendicular distance away from the axis of rotation and therefore the torque on the coil is at a maximum. A DC motor cannot begin in the vertical position, as there is no current in the coil at this orientation due to the split ring commutator.

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PROGRESS QUESTIONS

Use the following information to answer questions 5 and 6.

A DC motor is created using 10 turns of a square loop of wire, with 10 cm sides. 3.0 A of current runs in the loop which is in a magnetic field of strength 40 mT.

Question 5

What is the magnitude of the force acting on a side perpendicular to the magnetic field?

A. 0 N **B.** 0.12 N **C.** 1.2 N **D.** 4.0 N

Question 6

The square loop is replaced by a loop the same size, with 20 turns of wire. The loop will now rotate

A. at a slower rate.
B. at a quicker rate.
C. at the same speed as before.
D. the loop will no longer rotate.

Split ring commutators in DC motors 3.2.14.2

A split ring commutator acts to reverse the direction of the current within the coil every half rotation. This reverses the direction of the force on each side of the coil so that the direction of rotation is constant.

What is the purpose of a split ring commutator in a DC motor?

A split ring commutator connects the coil of a DC motor to an external circuit via the brushes:

- Each half of the split ring commutator is attached to ends of the rotating coils in the DC motor (Figure 4).
- The brushes are used to maintain electrical contact between the rotating commutator and the external circuit.
- When the coil is not in the vertical position, each half of the split ring commutator is in contact with one of the brushes. This allows current to flow from the positive terminal, through the rotating coils and back to the negative terminal of the battery.

As the split ring commutator rotates past the vertical position:

- It loses contact with one brush and gains contact with the other.
- This engages that end of the wire to the opposite side of the external circuit, reversing the direction of the current in the coil.
- This produces a force in the opposite direction on each side.

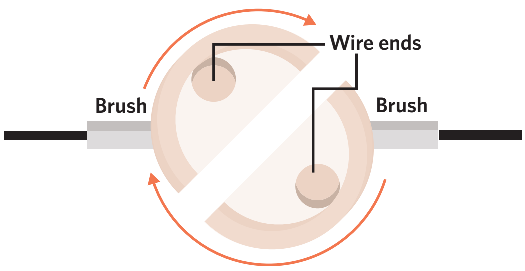

Figure 4 The structure of a split ring commutator

USEFUL TIP

When the brushes are in contact with each side of the split ring commutator, a complete circuit is formed and so current is able to run through the circuit.

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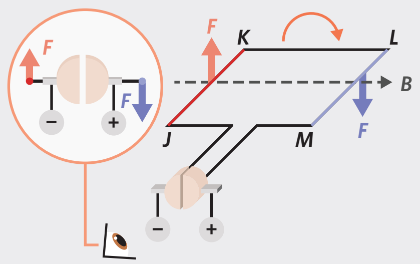
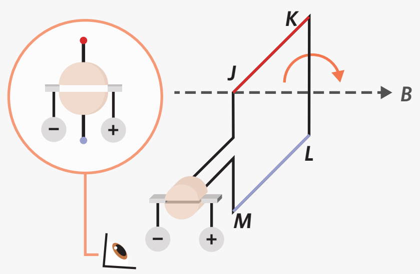
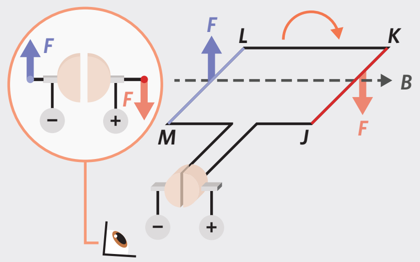
Table 1 shows how a split ring commutator changes the connection between the coil of wire and the external circuit.

Table 1 How the magnetic force on each side of the loop changes as the coil rotates

Position of loop	Diagram	Side *JK* (red)	Side *LM* (purple)	Rotation of loop
Initial position		• current runs from *K* to *J* • direction of magnetic force is up	• current runs from *M* to *L* • direction of magnetic force is down	loop rotates clockwise
After a quarter of a rotation		• no current runs through the loop • there is no magnetic force present	• no current runs through the loop • there is no magnetic force present	loop continues to rotate clockwise due to its motion
After half of a rotation		• current now runs from *J* to *K* • direction of magnetic force is down	• current now runs from *L* to *M* • direction of magnetic force is up	loop continues to rotate clockwise

KEEN TO INVESTIGATE?

[2] **How do slip rings work?**
Search Youtube: Introduction to slip rings

Slip rings should not be confused with split ring commutators. Slip rings consist of two adjacent rings (Figure 5). They maintain a constant electrical connection between the external circuit and the rotating coil of wire at all times.[2]

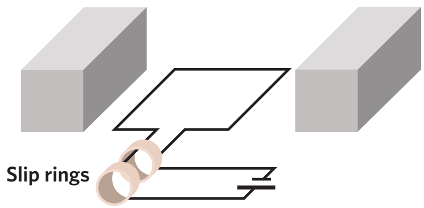


Figure 5 The structure of slip rings

Slip rings do not reverse the current in the coil like a split ring commutator. This means that if they are used in a DC motor then the direction of the force acting on the sides perpendicular to the magnetic field will not change and as a result the coil will oscillate about the vertical position (Figure 6).

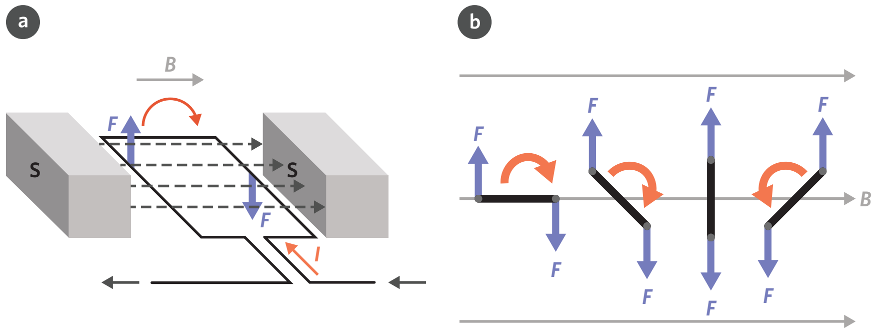


Figure 6 When slip rings are used, the loop is not able to rotate continuously in the same direction.

USEFUL TIP

The appropriate use of slip rings in the context of alternators (AC generators) will be explained in Lesson 5C, but it is important to understand that a DC motor cannot function properly with slip rings.

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PROGRESS QUESTIONS

Question 7

Which of the following best describes the purpose of a split ring commutator in a DC motor?

A. To reverse the direction of the current in the coil every half rotation.

B. To reverse the direction of the current in the coil every quarter rotation.

C. To maintain a constant connection between the coil and the external circuit.

D. To ensure that the force on each side is always in the same direction as the loop rotates.

Question 8

What is the effect of replacing the split ring commutator in a DC motor with slip rings? Assume a horizontal magnetic field.

A. The coil will not be able to rotate from any position.

B. Slip rings have no effect on the operation of a DC motor.

C. The coil will oscillate around the vertical position before coming to rest.

D. The coil will oscillate around the horizontal position before coming to rest.

Theory summary

- A DC motor converts electrical potential energy into kinetic energy.
- DC motors use current running through a coil of wire within a magnetic field to produce a turning effect (torque) acting on the coil.
  - The magnitude of the force on each side of the coil which is perpendicular to the magnetic field can be calculated from $F = nILB$.
  - The direction of the force is found using the right-hand palm rule on each side.
  - The torque acting on the coil is proportional to the magnetic force acting on each side of the loop.
- DC motors use split ring commutators to
  - reverse the direction of the current in the coil every half rotation.
  - cause the direction of the force acting on the wires in the coil to reverse every half rotation.
  - allow the motor to rotate in a constant direction.
- A DC motor will not be able to complete full rotations if slip rings are used instead of a split ring commutator. The motor will oscillate and then get stuck in the vertical position (assuming a horizontal magnetic field).

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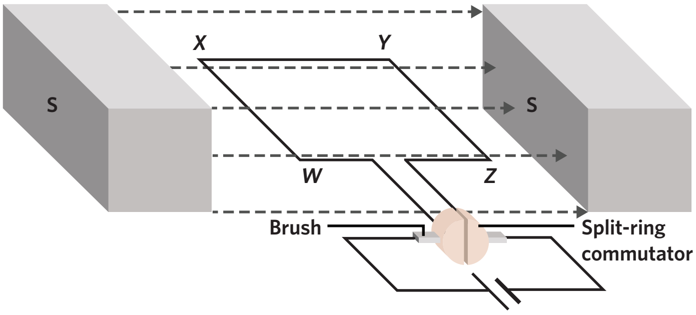
4D Questions

Mild 🌶 Medium 🌶🌶 Spicy 🌶🌶🌶

Deconstructed exam-style

Use the following information to answer questions 9-11.

A DC motor is constructed as shown.



Question 9 🌶 (1 MARK)

Identify which direction the current runs in the loop of wire on side *WX*.

Question 10 🌶 (1 MARK)

Determine the direction of the magnetic force on side *WX*.

Question 11 🌶🌶 (2 MARKS)

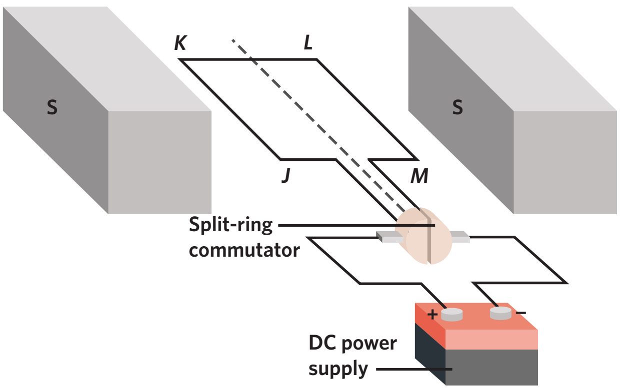
Determine whether the DC motor rotates clockwise or anticlockwise, when viewed from the battery.

Adapted from VCAA 2014 exam Short answer Q17c

Exam-style

Question 12 (4 MARKS)

The diagram shows a simple DC motor. It consists of two magnets, a single DC power supply, a split-ring commutator and a rectangular coil of wire consisting of 10 loops. The current in each loop is 1.5 A. The length of the side *JK* is 12 cm and the length of the side *KL* is 6.0 cm. The strength of the uniform magnetic field is 0.50 T.



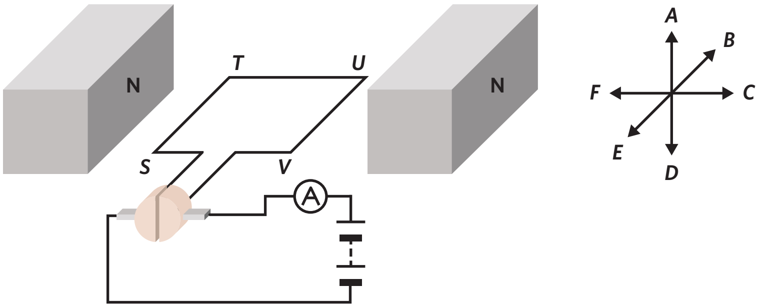
a. Determine the magnitude of the force acting on the side *JK*. 🌶 2 MARKS

b. What is the size of the force acting on the side *KL* in the orientation shown in the diagram? Justify your answer. 🌶 2 MARKS

Adapted from VCAA 2017 exam Short answer Q3

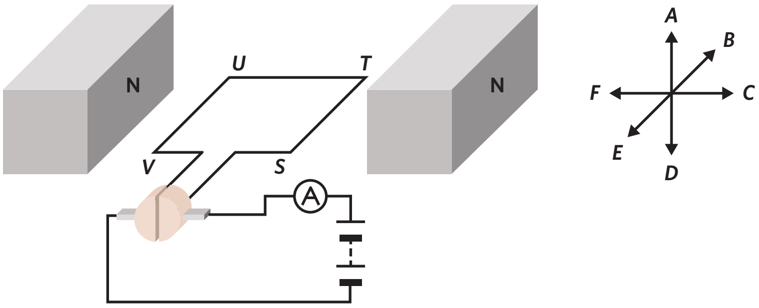
Question 13 (4 MARKS)

A DC motor is constructed with 80 square loops of wire with a side length of 10 cm and a split ring commutator. The motor's coil sits within a uniform magnetic field of 2.0×10^{-3} T and has a current of 2.5 A.



a. What is the direction (*A*–*F*) of the force on side *UV*, when the loop is in the horizontal position shown? 1 MARK

b. After the loop has undergone half a rotation, the loop is oriented as shown. What is the direction (*A*–*F*) of the force on side *UV* in the new orientation shown? 1 MARK

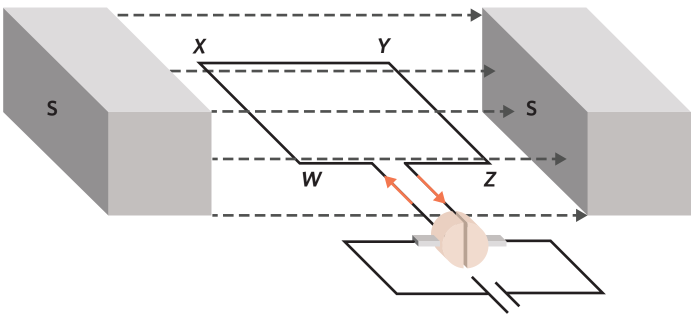


c. Explain the operation and purpose of the split ring commutator in a DC motor. 2 MARKS

Adapted from VCAA 2021 NHT exam Short answer Q4b

Use the following formation to answer questions 14 and 15.

Students create a simple DC motor, which is shown in the diagram.



Question 14 (1 MARK)

Which option describes all the positions during the rotation of the coil when the magnitude of the magnetic force on side *XY* is zero?

A. At only the position shown.

B. Only in the vertical position.

C. Any position for which *XY* is horizontal.

D. Any position for which *XY* is horizontal or vertical.

Adapted from 2016 VCAA Exam Section B Q14a

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Question 15 (1 MARK)

The students want to use the motor to power a toy, and need to increase the speed of rotation of the coil. Which of the following changes will increase the speed of rotation? **(Select all that apply)**

A. Increase the battery voltage.

B. Increase the resistance of the coil.

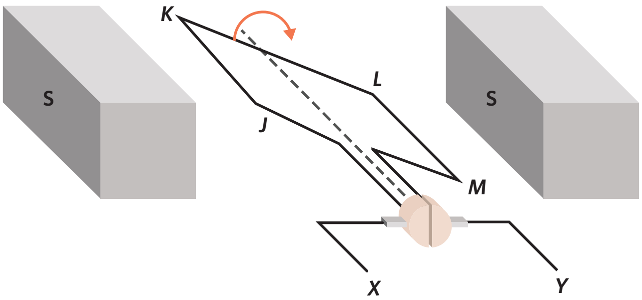
C. Increase the number of loops in the coil.

D. Reverse the poles of one of the permanent magnets.

Adapted from 2016 VCAA Exam Section B Q14c

Question 16 (4 MARKS)

A schematic diagram of a DC motor is shown. The motor has a coil consisting of 100 turns. The permanent magnets provide a uniform magnetic field of 0.45 T. The commutator connectors, X and Y, provide a constant DC current, I, to the coil. The length of the side JK is 5.0 cm. The rotation of the coil is shown.



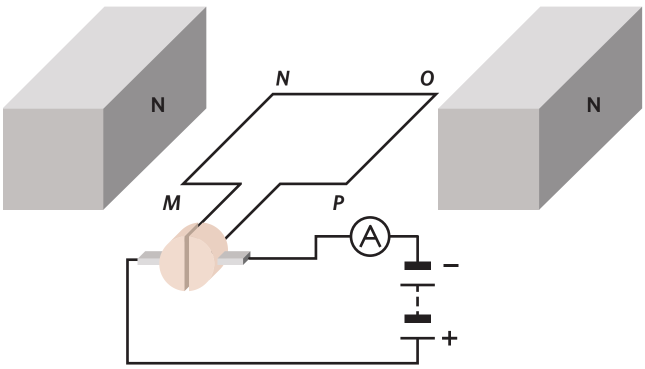
a. Draw an arrow on the diagram to indicate the direction of the magnetic force acting on the side JK. 1 MARK

b. Explain which terminal of the commutator is connected to the positive terminal of the power supply. 3 MARKS

Adapted from VCAA 2019 exam Short answer Q3

Question 17 (7 MARKS)

Prior to teaching about DC motors, a teacher shows her students a simple motor which includes a battery and a split ring commutator.



a. The teacher positions the coil in the horizontal position shown and turns on the power supply. Will the motor rotate in a clockwise or anticlockwise direction? Explain your answer. 3 MARKS

Adapted from 2016 VCAA Exam Section B Q3a

b. One of her students suggests that by replacing the split ring commutator with slip rings, there will be less friction and the coil will rotate at a faster rate. Explain the impact of replacing the commutator with slip rings on the operation of the motor. 2 MARKS

Adapted from 2016 VCAA Exam Section B Q3b

c. The students discover that the motor starts moving more easily with the coil in some orientations than in others. Explain the best orientation(s) for starting the motor to move from rest. 2 MARKS

Adapted from 2016 VCAA Exam Section B Q14b

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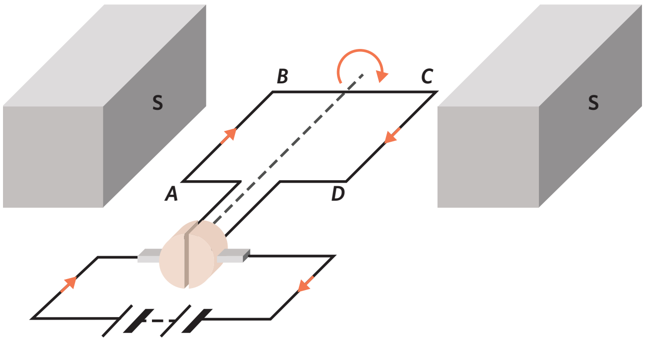
Question 18 (4 MARKS)

Students create a simple DC motor, as shown.



a. *Key science skill*

Draw a graph showing the magnitude of the magnetic force on side AB during half a period of the coil's rotation. Exact values are not required. 2 MARKS

FROM LESSON 12D

b. *Key science skill*

The students attach an ammeter to measure the magnitude of the current in the coil. Predict how the reading on the ammeter will change as the coil rotates. 2 MARKS

FROM LESSON 12C

Previous lessons

Question 19 (2 MARKS)

A person of mass 60 kg is sitting in a car, driving horizontally at 60 km h^{-1}. Explain the work done by the gravitational force on the person after they have travelled 40 m.

FROM LESSON 2A

Question 20 (2 MARKS)

Explain why the change in gravitational potential energy on an object moving a significant distance away from the Earth cannot be calculated using $\Delta GPE = mg\Delta h$.

FROM LESSON 3B

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Chapter 4 review

Mild 🌶 Medium 🌶🌶 Spicy 🌶🌶🌶

These questions are typical of one hour's worth of questions on the VCE Physics Exam.

Total marks: 50

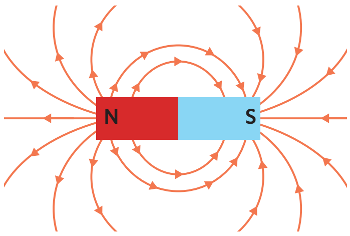
Section A

All questions in this section are worth one mark.

Unless otherwise indicated, the diagrams in this book are not drawn to scale.

Question 1 🌶

The diagram shows the field surrounding a stationary bar magnet.



This magnetic field can best be described as

A. static.

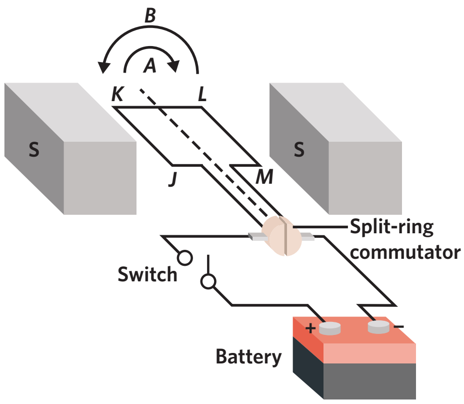
B. parallel.

C. uniform.

D. uniform and static.

Question 2 🌶🌶

The diagram below shows a small DC electric motor, powered by a battery that is connected via a split-ring commutator. The rectangular coil has sides *JK* and *LM*. The magnetic field between the poles of the magnet is uniform and constant. The switch is now closed, and the coil starts stationary and in the position shown in the diagram. Which one of the following statements best describes the motion of the coil when the switch is closed?



A. The coil will remain stationary.

B. The coil will rotate in direction *A*, as shown in the diagram.

C. The coil will rotate in direction *B*, as shown in the diagram.

D. The coil will oscillate regularly between directions *A* and *B*, as shown in the diagram.

Adapted from VCAA 2021 exam Multiple choice Q5

Question 3 🌶🌶

Which of the following correctly associates the type of field to its polar properties?

	Gravitational field	Electric field
A.	Monopole	Dipole
B.	Dipole	Monopole
C.	Monopole or dipole	Dipole
D.	Monopole	Monopole or dipole

Adapted from VCAA 2020 exam Short answer Q2

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Question 4

The strength of an electric field surrounding a charged object is 6.8×10^{-6} N C^{-1} at a distance d from the object. What is the strength of the electric field at a distance $3d$ from the object?

A. 3.4×10^{-7} N C^{-1}

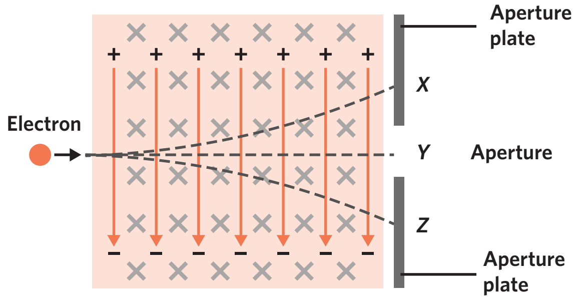
B. 7.6×10^{-7} N C^{-1}

C. 2.3×10^{-6} N C^{-1}

D. 2.0×10^{-5} N C^{-1}

Question 5

Electron microscopes use a high-precision electron velocity selector consisting of an electric field, E, perpendicular to a magnetic field, B. Electrons travelling at the required velocity, v_0, exit the aperture at point Y.



If an electron is travelling faster than v_0, it will hit the aperture plate at

A. point *X*.

B. point *Y*.

C. point *Z*.

D. either point *X* or point *Z*.

Adapted from VCAA 2020 exam Short answer Q3ci

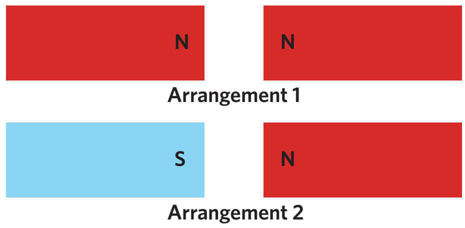
Section B

In questions where more than one mark is available, appropriate working must be shown.

Unless otherwise indicated, the diagrams in this book are not drawn to scale.

Question 6 (2 MARKS)

Two bar magnets are positioned in two different arrangements as shown in the diagram. For each arrangement draw at least four magnetic field lines to represent the magnetic field. Include arrowheads to show direction.



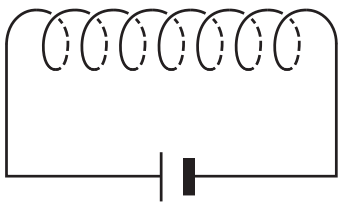
Adapted from VCAA 2016 exam Short answer Q12

Question 7 (2 MARKS)

Draw the field pattern that exists between a positive point charge and a negative point charge. Use at least five electric field lines.

Question 8 (2 MARKS)

Draw five lines to represent the magnetic field produced by the solenoid shown below.



Adapted from VCAA 2015 exam Short answer Q15

Question 9 (4 MARKS)

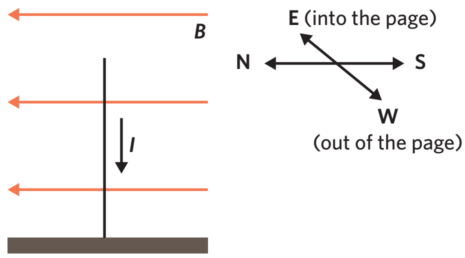
After sliding down a plastic slide, a primary school student has acquired a charge of 4.0×10^{-7} C on the tip of their finger. They are going to use this charge to try to zap their best friend's nose. Their friend's nose is 2.25 m away from the student's finger. Take $k = 8.99 \times 10^{9}$ N m^2 C^{-2}.

a. Calculate the strength of the electric field due to the student's charged fingertip at their best friend's nose. 2 MARKS

b. Calculate the force that an electron in the best friend's nose experiences due to the student's charged finger. 2 MARKS

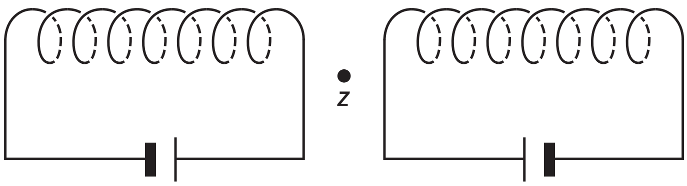
Question 10 (3 MARKS)

Bart builds a house on the equator to test which direction water spirals down a toilet in both hemispheres. To power his equipment, there is a 3.2 m vertical power line on the side of his house which carries 6.6 A of current towards the ground. The strength of the magnetic field at the equator is 3.1×10^{-5} T directed north, which is horizontally to the left as shown. What is the magnitude and direction of the magnetic force acting on the power line?



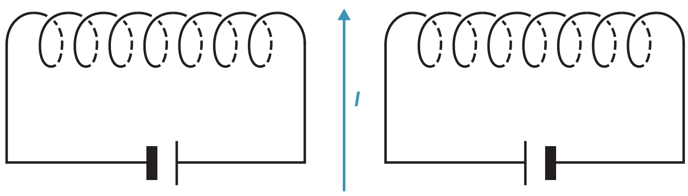
Question 11 (6 MARKS)

A student sets up two solenoids next to each other with their current running in opposite directions as shown. The magnitude of the currents are the same in both solenoids. Ignore the Earth's magnetic field.



a. If a small magnetic compass needle was placed at point Z, what direction would its north pole point? Explain your answer. 3 MARKS

b. A current-carrying wire is placed vertically between the two solenoids. The current flows up the wire as shown. What is the direction of the electromagnetic force, if any, on the current-carrying wire? Explain your answer. 3 MARKS



Adapted from VCAA 2017 NHT exam Short answer Q12

Question 12 (5 MARKS)

A DC motor is constructed to be used in a clock. A current of 1.75 A flows through the coil which is placed in a uniform magnetic field of 750 mT. It uses 100 square turns of wire.

a. Given that the force on a side length of the coil which is perpendicular to the magnetic field is 4.0 N, what is the side length of the coil? 2 MARKS

b. In order to make the clock tick smoother, someone suggests that the split ring commutator on the DC motor should be replaced by slip rings. Explain the effect that replacing the commutator with slip rings would have on the operation of the motor. 3 MARKS

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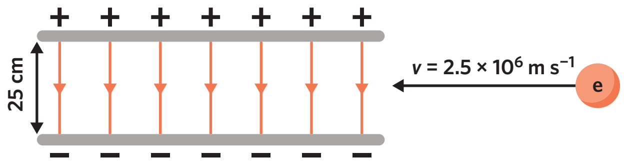
Question 13 (8 MARKS)

Two oppositely charged parallel plates which are 25 cm apart create a uniform electric field of 7.0×10^3 V m^{-1}. An electron is travelling at a speed of 2.5×10^6 m s^{-1} when it enters the field halfway between the plates. Ignore relativistic effects.



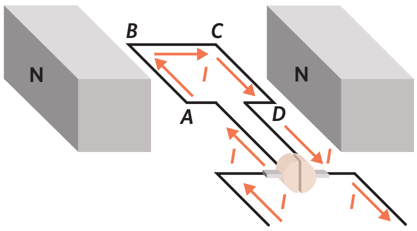
a. What is the voltage difference between the two plates? 2 MARKS

b. Draw the path of the electron once it enters the electric field. The electron does not leave the uniform field. 2 MARKS

c. Calculate the speed of the electron as it reaches the charged plate. 4 MARKS

Question 14 (6 MARKS)

In the attempt to build a helicopter and arrive fashionably at the Year 12 formal, Elle designs a simple DC motor. The motor consists of a single square loop of wire with side lengths of 15.0 cm. A current of 3.5 A flows through the loop which is placed within a uniform magnetic field of 45.0 mT.



a. Explain the function of a split ring commutator in a DC motor. 3 MARKS

Adapted from VCAA 2019 exam Short answer Q3c

b. *Key science skill*

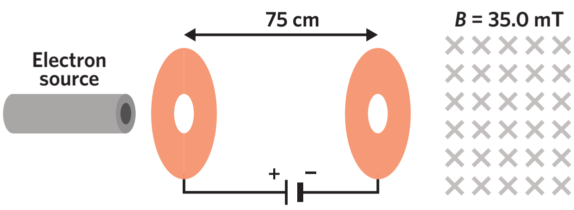
State three changes to the apparatus that would increase the rate of rotation of the DC motor. 3 MARKS

Adapted from VCAA 2016 exam Short answer Q14c

Question 15 (7 MARKS)

Two plates separated by 75 cm are connected to a 0.45 V power supply, as shown. An electron is ejected by the source, and moves between the two charged parallel plates before entering a uniform magnetic field of 35.0 mT at right angles to its path. Ignore relativistic effects.

Charge on electron	1.6×10^{-19} C
Mass of electron	9.1×10^{-31} kg
Strength of magnetic field	35.0 mT
Speed of electron as it leaves the source	2.9×10^6 m s^{-1}



a. Draw the path of the electron from when it leaves the electron source to when it exits the magnetic field. 3 MARKS

b. What is the radius of the path that the electron follows whilst in this magnetic field? 4 MARKS

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Unit 3 AOS 2 review

Mild 🌶 Medium 🌶🌶 Spicy 🌶🌶🌶

These questions are typical of one hour's worth of questions on the VCE Physics Exam.

Total marks: 50

Section A

All questions in this section are worth one mark.

Unless otherwise indicated, the diagrams in this book are not drawn to scale.

Question 1 🌶🌶

Diagrams 1 and 2 represent different types of fields.

Which of the following options best identifies the type of field that could be represented by each diagram?

Diagram 1

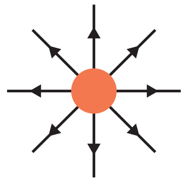


Diagram 2

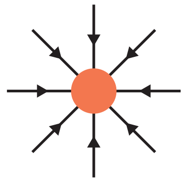


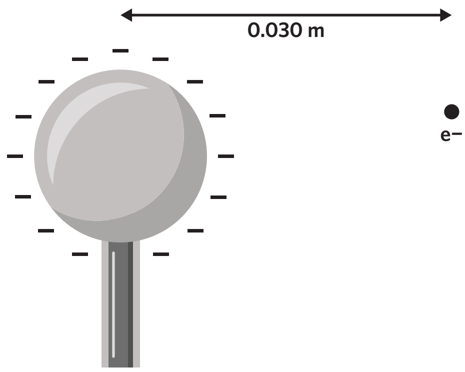
	Diagram 1	Diagram 2
A.	Electric or gravitational field	Electric field
B.	Electric or gravitational field	Gravitational field
C.	Electric field	Electric or gravitational field
D.	Gravitational field	Gravitational field

Adapted from VCAA 2017 Sample exam Multiple choice Q2

Use the following information to answer questions 2 and 3.

A Van de Graaff generator, pictured in the diagram, consists of a small charged sphere.

This particular Van de Graaff generator has a charge of -2.0×10^{-7} C. Take Coulomb constant to be $k = 8.99 \times 10^{9}$ N m^2 C^{-2}.



Question 2 🌶

Which of the following gives the magnitude of the electric field due to the charge on the generator at the position of the electron shown in the diagram?

A. 2.0×10^{4} V m^{-1} **B.** 4.4×10^{4} V m^{-1} **C.** 2.0×10^{6} V m^{-1} **D.** 4.4×10^{6} V m^{-1}

Adapted from VCAA 2018 NHT exam Multiple choice Q3

Question 3 🌶🌶

Which of the following gives the direction of force on the electron?

A. left **B.** right **C.** into the page **D.** out of the page

Question 4

The following data relates to a planet named Vesta.

Mass of Vesta	2.59×10^{20} kg
Radius of Vesta	2.63×10^{5} m
Universal gravitational constant, *G*	6.67×10^{-11} N m^2 kg^{-2}

What would be the gravitational force on a 65 kg person on the surface of Vesta?

A. 16 N

B. 32 N

C. 65 N

D. 72 N

Adapted from VCAA 2018 NHT exam Multiple choice Q2

Question 5

When a spacecraft orbits Earth, its orbital period does not depend on the

A. mass of Earth.

B. mass of the spacecraft.

C. velocity of the spacecraft.

D. height of the spacecraft above Earth.

Adapted from VCAA 2021 NHT exam Multiple choice Q5

Section B

In questions where more than one mark is available, appropriate working must be shown.

Unless otherwise indicated, the diagrams in this book are not drawn to scale.

Question 6 (2 MARKS)

Three point charges are lined up horizontally.

a. Draw an arrow at point *X* to indicate the direction of the resultant electric field at *X*. 1 MARK

Adapted from VCAA 2017 exam Short answer Q1

b. Identify whether the field between the three charges is uniform or non-uniform. 1 MARK

Question 7 (5 MARKS)

According to one model of a hydrogen atom, an electron moves in a circular orbit around a single proton. To model the atom, students used a large positively charged metal sphere as the proton, and a smaller negatively charged sphere as the electron. The smaller sphere is made to orbit the larger sphere at a radius of 5.3 cm. Take the magnitude of the charge on the two spheres to be 2.4×10^{-6} C, and $k = 9.0 \times 10^{9}$ N m^2 C^{-2}.

a. Determine the magnitude of the electric field due to the larger sphere at a distance of 5.3 cm. Show your working. 2 MARKS

b. If the force of the larger sphere acting on the smaller sphere is 18.5 N, calculate the speed of the smaller sphere around its circular path. Take the mass of the smaller sphere to be 25 g. 3 MARKS

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Question 8 (8 MARKS)

A spacecraft is in orbit at an altitude of 8.39×10^5 m above the surface of Mars. The mass of Mars is 6.4×10^{23} kg and its radius is 3.4×10^6 m. The mass of the spacecraft is 4.3×10^4 kg. Take the universal gravitational constant, G, to be 6.67×10^{-11} N m^2 kg^{-2}.

a. Calculate the spacecraft's period of orbit around Mars. 3 MARKS

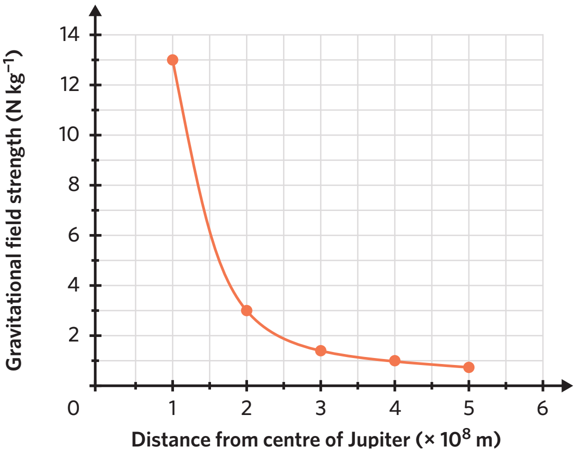
b. The satellite's altitude above the surface of Mars is halved and it is now in a new stable orbit. Will the speed of the spacecraft need to be greater, the same, or lower in this new orbit? Explain your reasoning. 2 MARKS

c. An astronaut leaves the spacecraft to conduct repairs. They are not attached physically to the craft. Compare the motion of the astronaut and the spacecraft as the spacecraft continues to orbit Mars. 3 MARKS

Adapted from VCAA 2019 NHT exam Short answer Q10

Question 9 (5 MARKS)

A group of scientists plot the gravitational field strength around Jupiter.



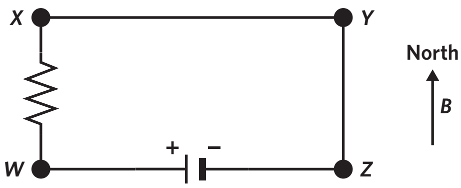
a. Determine the change in gravitational potential energy per kilogram as a mass moves from 4×10^8 m to 1.5×10^8 m from the centre of Jupiter. 3 MARKS

b. *Key science skill*
One of the scientists suggests using the area of a trapezium with side lengths 6 N kg^{-1} and 1 N kg^{-1} to calculate the answer to part **a**. Explain whether using this method would lead to a more or less accurate estimation compared to counting the squares underneath the graph. 2 MARKS

FROM LESSON 12C

Question 10 (5 MARKS)

A heavy duty electric circuit is set up.



The circuit carries a current of 958 A and lies within Earth's magnetic field. At the point of measurement, the Earth's magnetic field runs parallel to side YZ and its strength is 8.0×10^{-5} T.

a. What is the direction of the force on wire XY? 1 MARK

b. The wire between X and Y is 2.6 cm long. What is the magnitude of the force on the wire? 2 MARKS

c. What is the magnitude of the force acting on the side YZ? Explain your answer. 2 MARKS

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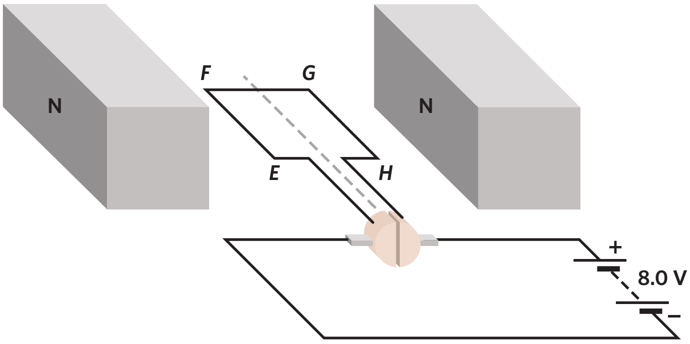
Question 11 (11 MARKS)

A simple DC motor consists of 30 turns of a square loop of wire with 20 cm side lengths, a magnetic field of strength 4.0×10^{-3} T, and a split ring commutator connected to an 8.0 V battery. The current in the loop is 1.5 A.



a. The motor is set with coils horizontal, as shown, and the power source is turned on. Viewing the loop from the split ring commutator, will the motor rotate clockwise or anticlockwise? Explain your answer. 3 MARKS

Adapted from 2013 VCAA Exam Section A Q16a

b. Calculate the magnitude of the force on side *EF*. 2 MARKS

Adapted from 2013 VCAA Exam Section A Q16b

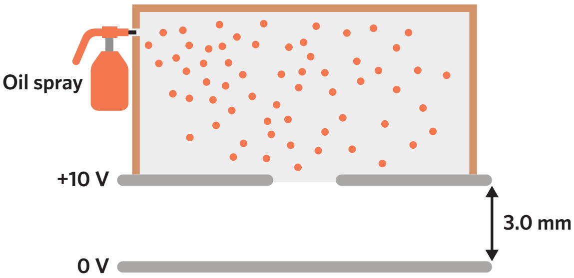
c. What is the magnitude of the net force acting on the motor? 1 MARK

d. Explain the role of the split ring commutator in a DC motor. 3 MARKS

e. Explain the effect that replacing the split ring commutator with slip rings would have on the operation of the motor, if no other change was made. 2 MARKS

Question 12 (9 MARKS)

Droplets of oil, with a charge of -1.59×10^{-19} C are sprayed into a chamber. The droplets fall downwards due to the force of gravity. Some of the falling droplets become suspended in between two charged parallel plates with a potential difference of 10 V, separated by 3.0 mm, at the bottom of the chamber.



a. Draw a diagram showing the forces acting on an oil drop that's suspended between the two charged plates 2 MARKS

b. Calculate the mass of the suspended droplets. 4 MARKS

c. *Key science skill*

The exact same experiment is now repeated on a newly built colony on Mars. Using the following data, predict what will happen to the oil drops that previously remained suspended between the two charged plates. 3 MARKS

Mass of Mars	6.4×10^{23} kg
Radius of Mars	3396 km

FROM LESSON 12A

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UNIT 3 AOS 3

How are fields used in electricity generation?

The production, distribution and use of electricity has had a major impact on the way that humans live. In this area of study, students use empirical evidence and models of electric, magnetic and electromagnetic effects to explain how electricity is produced and delivered to homes. They explore the transformer as critical to the performance of electrical distribution systems in minimising power loss.

Outcome 3

On completion of this unit the student should be able to analyse and evaluate an electricity generation and distribution system.

Reproduced from VCAA VCE Physics Study Design 2024–2027

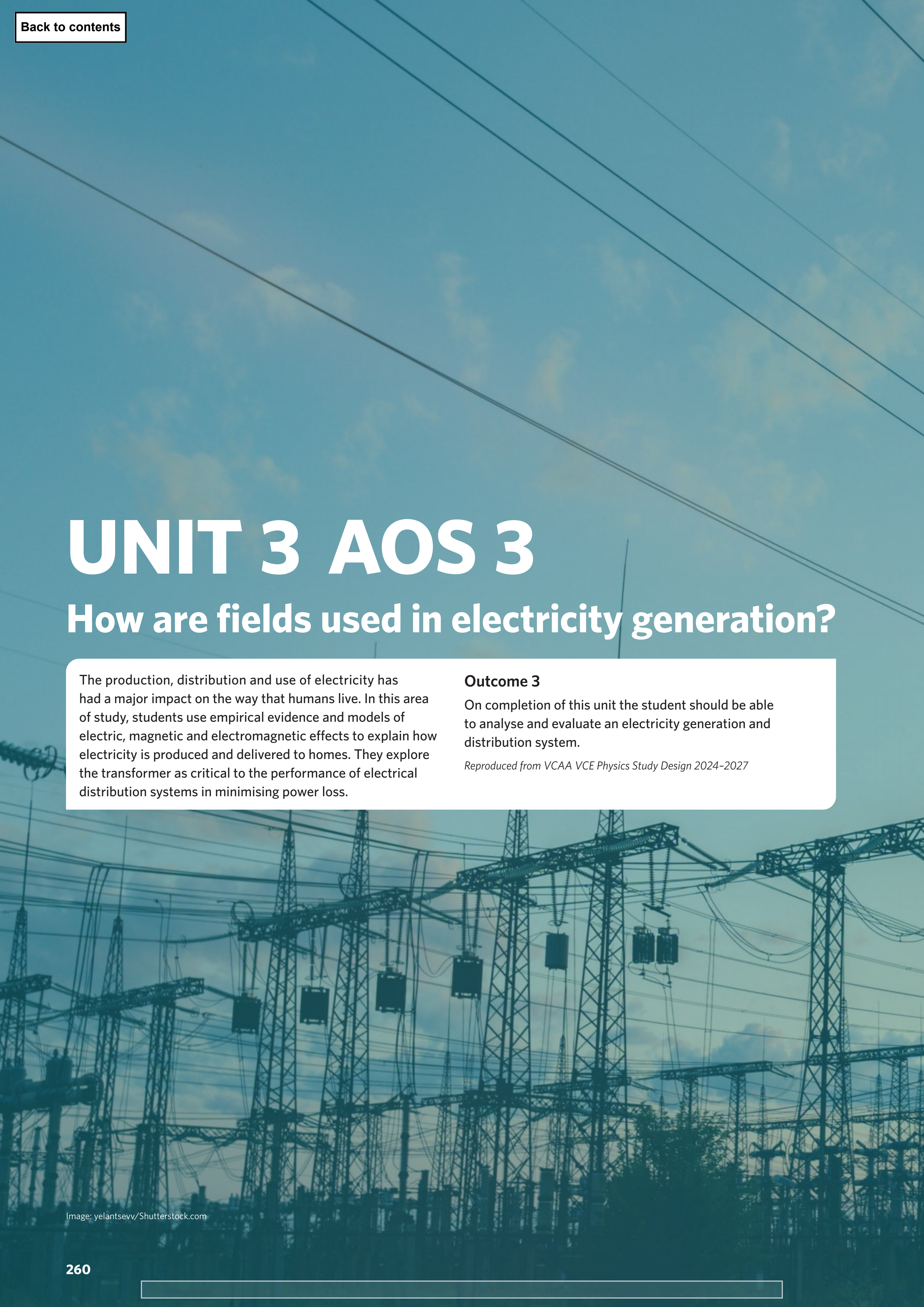

Image: yelantsevv/Shutterstock.com

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5

CHAPTER 5

Generating electricity

STUDY DESIGN DOT POINTS

- calculate magnetic flux when the magnetic field is perpendicular to the area, and describe the qualitative effect of differing angles between the area and the field: $\Phi_B = B_{\perp}A$
- investigate and analyse theoretically and practically the generation of electromotive force (emf) including AC voltage and calculations using induced emf: $\varepsilon = -N\frac{\Delta\Phi_B}{\Delta t}$, with reference to:
  - rate of change of magnetic flux
  - number of loops through which the flux passes
  - direction of induced emf in a coil
- explain the production of DC voltage in DC generators and AC voltage in alternators, including the use of split ring commutators and slip rings respectively
  - describe the production of electricity using photovoltaic cells and the need for an inverter to convert power from DC to AC for use in the home (not including details of semiconductors action or inverter circuitry)

Reproduced from VCAA VCE Physics Study Design 2024–2027

LESSONS

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5A EMF and Faraday's law

STUDY DESIGN DOT POINTS

- calculate magnetic flux when the magnetic field is perpendicular to the area, and describe the qualitative effect of differing angles between the area and the field: $\Phi_B = B_{\perp}A$
- investigate and analyse theoretically and practically the generation of electromotive force (EMF) including AC voltage and calculations using induced EMF: $\varepsilon = -N\frac{\Delta\Phi_B}{\Delta t}$, with reference to:
  - rate of change of magnetic flux
  - number of loops through which the flux passes
  - direction of induced EMF in a coil

5A 5B 5C 5D

3.3.1.1 Magnetic flux

3.3.2.1 Faraday's law

ESSENTIAL PRIOR KNOWLEDGE

4B Magnetic field direction

4B Into and out of the page conventions

See questions 50–51.


Image: Lee Charlie/Shutterstock.com

How does wireless charging work?

In Chapter 4, we learned how the force exerted by a magnetic field on a current-carrying wire can be used to construct a DC motor. This lesson explores how changing the magnetic flux through a loop of wire induces an electromotive force that can be used for a range of applications, including wireless charging and large-scale electricity generation.

KEY TERMS AND DEFINITIONS

magnetic flux a measure of the number of magnetic field lines passing through an area

electromotive force (EMF) the voltage created or supplied due to energy being transformed into electrical potential energy

electromagnetic induction the production of an electromotive force (EMF) due to the change in magnetic flux through a conducting loop

FORMULAS

- **magnetic flux**
  $\Phi_B = B_{\perp}A$
- **electromotive force (EMF)**
  $\varepsilon = -N\frac{\Delta\Phi_B}{\Delta t}$

Magnetic flux 3.3.1.1

Magnetic flux is the number of magnetic field lines flowing through a given area. The size of the area, magnetic field strength, and the angle between the area and the field lines determine the magnitude of the magnetic flux. The unit of magnetic flux is the weber (Wb).

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How can we calculate magnetic flux?

Magnetic flux can be calculated by multiplying the strength of the magnetic field by the area of the loop perpendicular to the field. If the perpendicular area is kept constant then magnetic flux can be changed by changing the strength of the magnetic field or by moving the loop in and out of the field. The magnetic flux through the loop in Figure 1a is greater than in Figure 1b, as more magnetic field lines are passing through the same surface area *A*.

FORMULA

$$\Phi_B = B_{\perp}A$$

Φ_B = magnetic flux (Wb)
B = magnetic field strength (T)
A = area perpendicular to the magnetic field (m^2)

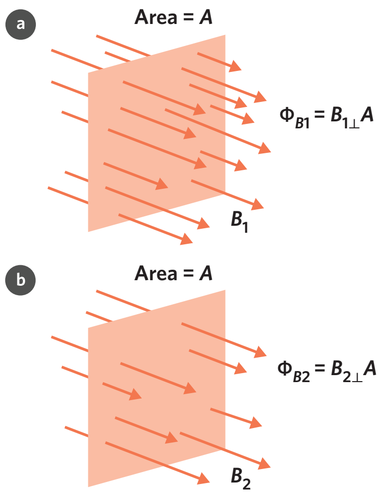


Figure 1 More magnetic field lines pass through the same area in **(a)** compared to **(b)**, therefore diagram **(a)** has more magnetic flux.

A magnetic flux graph can be used to visualise how the magnetic flux through a loop changes with time. Figure 3 shows a loop moving at a constant speed through a uniform magnetic field.

- When the loop is outside the magnetic field (Position *W*), there is no magnetic field passing through the loop, so the flux through the loop is zero.
- As the loop moves into the magnetic field (Position *W* to Position *X*), the flux through the loop increases from zero to maximum.
- When the loop is entirely within the magnetic field (Position *X* to Position *Y*), the magnetic flux stays at a maximum.
- As the loop exits the magnetic field (Position *Y* to Position *Z*), the flux through the loop decreases from maximum to zero.
- When the loop is once again outside the magnetic field (Position *Z*), there is no magnetic field passing through the loop, so the flux through the loop is zero.

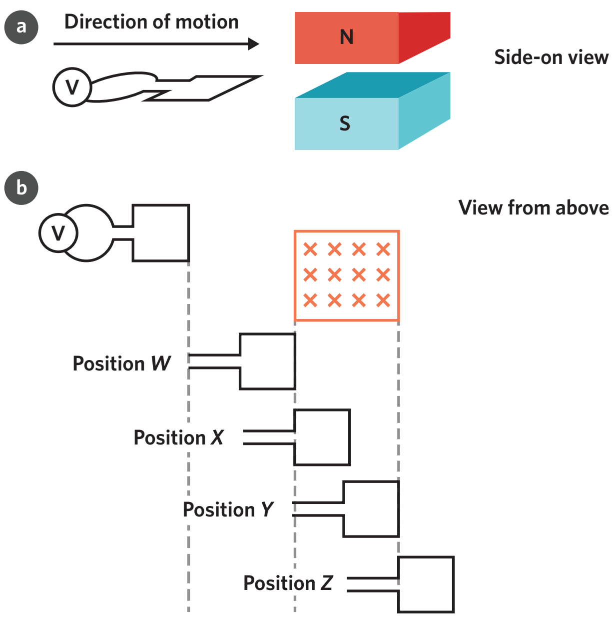


Figure 3 A loop of wire moving through a magnetic field as viewed from **(a)** side-on and **(b)** above.

USEFUL TIP

When finding the magnetic flux through a circular loop of wire, the area of the loop can be calculated using $A = \pi r^2$.

USEFUL TIP

Area is often given in the units cm^2. In order to calculate magnetic flux in weber the perpendicular area needs to be converted from cm^2 to m^2 (Figure 2).

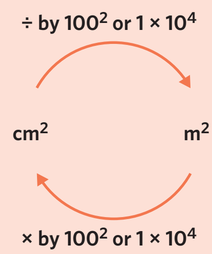


Figure 2 Converting between cm^2 and m^2

The corresponding graph of magnetic flux vs. time for the movement of the wire is shown in Figure 4.

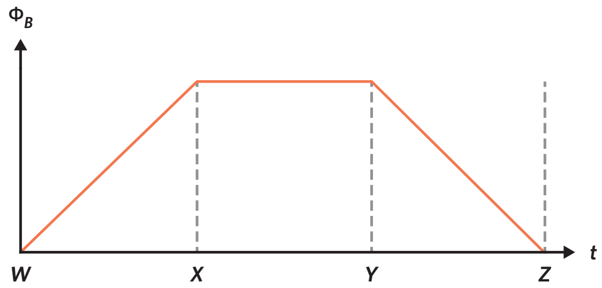


Figure 4 Magnetic flux graph for a loop passing through a magnetic field

USEFUL TIP

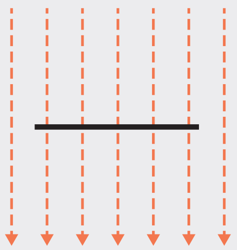
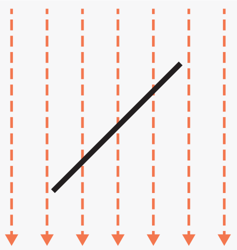
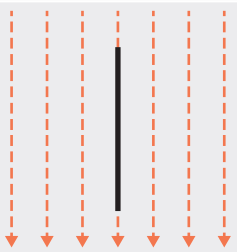
There are four ways to change the magnetic flux through a loop:

1. Change the strength of the magnetic field.
2. Move the loop into or out of the field.
3. Change the area of the loop while it's inside the field.
4. Rotate the loop inside the field.

The first three methods always have magnetic flux travelling through the loop in one direction, which means the magnetic flux will increase or decrease in the same direction. However, rotating the loop within the field causes magnetic flux to travel through the loop in both directions as it rotates. Therefore, it's important to consider the direction of the change in magnetic flux to accurately draw a magnetic flux vs. time graph.

The magnetic flux through a loop can also change by rotating a loop of wire in a magnetic field. As we rotate a loop of wire in a magnetic field, the area perpendicular to the magnetic field, $A_\perp$, changes. Table 1 shows three different orientations of a loop in a magnetic field and the magnet flux in each situation.

Table 1 Magnetic flux through a loop in different orientations to the magnetic field

Diagram	Loop orientation	Magnetic flux (Wb)
	Perpendicular to the magnetic field	The magnetic flux is at a maximum and can be calculated using $\Phi_B = B_\perp A$.
	Somewhere between parallel and perpendicular to the magnetic field	The area perpendicular to the magnetic field is reduced and so is the magnetic flux. This calculation is not required in VCE Physics.
	Parallel to the magnetic field	There are no field lines passing through the loop so the magnetic flux is zero.

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WORKED EXAMPLE 1

A circular loop with a radius of 0.25 m is placed with its plane perpendicular to the direction of a changing magnetic field. The magnetic field increases at a constant rate from 0.040 T at $t = 0.0$ s to 0.10 T at $t = 1.0$ s. Draw a magnetic flux vs. time graph to show how the flux changes with time.

Step 1

Identify known and unknown variables and write down the formula that relates these variables.

$A = \pi r^2 = \pi \times (0.25)^2 = 0.196\ m^2$, $B_i = 0.040$ T, $B_f = 0.10$ T, $\Phi_{Bi} = ?$, $\Phi_{Bf} = ?$

Note that the plane of the coil is perpendicular to the direction of the magnetic field. Therefore Φ_B can be calculated using BA.

$\Phi_{Bi} = B_i A$

$\Phi_{Bf} = B_f A$

Step 2

Substitute values into the formula and solve for the initial and final magnetic flux.

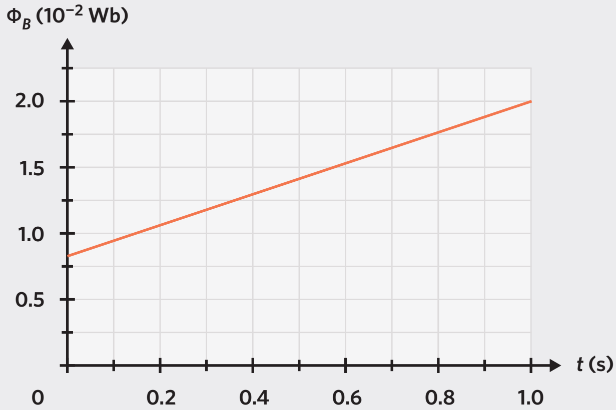
$\Phi_{Bi} = 0.040 \times 0.196 = 7.84 \times 10^{-3}$ Wb

$\Phi_{Bf} = 0.10 \times 0.196 = 1.96 \times 10^{-2}$ Wb

Step 3

Draw a graph starting at the point $(0, 7.84 \times 10^{-3})$ and ending at the point $(1, 1.96 \times 10^{-2})$.

Note that a straight line will connect these points as the magnetic field increases at a constant rate.



PROGRESS QUESTIONS

Question 1

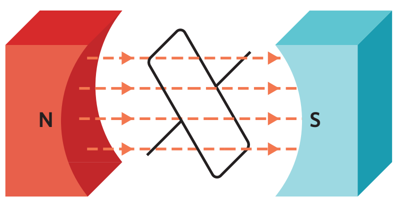
A coil with an area of 10 cm^2 is placed in a uniform magnetic field of strength 0.030 T so that the plane of the coil is perpendicular to the field direction. The magnetic flux through the loop is closest to

A. 0 Wb. **B.** 3.0×10^{-5} Wb. **C.** 6.0×10^{-4} Wb. **D.** 3.0×10^{-1} Wb.

Adapted from VCAA 2020 exam Multiple choice Q5

Question 2

A loop with an area of 1.0 m^2 is placed in a uniform magnetic field of strength 0.5 T, as shown in the following diagram. Which of the following statements is correct?



A. There is no magnetic flux through the loop.

B. There is some magnetic flux through the loop, but it is less than $\Phi_B = BA$.

C. There is some magnetic flux through the loop, and it can be calculated using $\Phi_B = BA$.

D. There is a maximum magnetic flux through the loop, and it can be calculated using $\Phi_B = BA$.

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5A THEORY

Faraday's law 3.3.2.1

An **electromotive force (EMF)** is induced when a loop experiences a change in magnetic flux. The amount of EMF induced can be calculated using Faraday's law.

MISCONCEPTION

'EMF and voltage are the same.'

EMF refers to the force that drives charge through a circuit whereas voltage refers to the difference in electrical potential energy between two points. Both are measured in volts.

How can we calculate the electromotive force induced due to a change in flux?

When the magnetic flux through a loop or coil changes over time, an electromotive force (EMF) is induced. This is known as **electromagnetic induction**. The greater the rate of change of the magnetic flux, the greater the EMF produced.

Faraday's law defines the EMF induced in a coil with N turns (loops of wire) as:

USEFUL TIP

A change in a particular value a can be found through the subtraction of the initial value from the final value, $\Delta a = a_f - a_i$.

FORMULA

$$\varepsilon = -N\frac{\Delta\Phi_B}{\Delta t}$$

ε = EMF (V)
N = number of turns of wire
$\Delta\Phi_B$ = change in magnetic flux (Wb)
Δt = change in time (s)

The negative sign in Faraday's law indicates the direction of the induced EMF and current. This direction can be determined separately and will be investigated further in Lesson 5B.

It is common to use magnetic flux vs. time (Φ_B vs. t) graphs and EMF vs. time (ε vs. t) graphs to represent scenarios where electromagnetic induction occurs. Notice that Faraday's law includes the term $\frac{\Delta\Phi_B}{\Delta t}$, which represents the gradient of a Φ_B vs. t graph (Figure 5).

Gradient of Φ_B vs. t graph

$$\varepsilon = -N\boxed{\frac{\Delta\Phi_B}{\Delta t}}$$

Figure 5 EMF is equal to the negative of the number of turns of wire multiplied by the gradient of a Φ_B vs. t graph at a particular time.

The negative sign in Faraday's law indicates that the direction of the induced EMF is opposite in direction to the change in flux with respect to time:

- The EMF graph should be negative when the magnetic flux graph has a positive gradient.
- The EMF graph should be positive when the magnetic flux graph has a negative gradient.

There are four ways we can change the magnetic flux, and therefore induce an EMF in a loop:[1]

1. Change the strength of the magnetic field – usually by moving the magnet or using an electromagnet.
2. Move the loop into or out of the magnetic field.
3. Change the shape of the loop while it's inside the field.
4. Rotate the loop inside the magnetic field – this changes the area of the loop perpendicular to the magnetic field.

According to Faraday's law, we can increase the amount of EMF induced in a loop by:

- increasing the area of the loop
- increasing the magnetic field strength
- increasing the rate at which magnetic flux changes by moving the loop faster or changing the magnetic field strength more quickly.

KEEN TO INVESTIGATE?

[1] **How can we induce an EMF in a loop of wire?**
Search: Faraday's law simulation

USEFUL TIP

When flux is changing at a constant rate, the gradient of the graph will be constant, and so too is the magnitude of the induced EMF. It is acceptable to exclude the negative sign, which means that a positive EMF could represent an increasing flux and vice versa.

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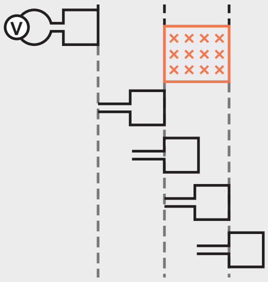
MISCONCEPTION

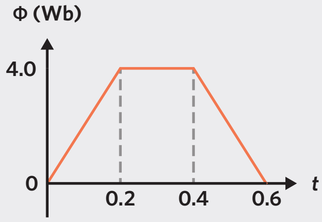
'Moving a loop through a magnetic field will induce an EMF in the loop.'

An EMF is only induced in a loop if the magnetic flux through the loop changes. If the magnetic field strength and the area of the loop perpendicular to the magnetic field remain constant, no EMF is induced.

WORKED EXAMPLE 2

A square loop of 5 turns is moved through a uniform magnetic field. Using the included magnetic flux-time graph, draw a corresponding EMF-time graph.





Step 1

Identify any EMFs induced in the coil by analysing the gradient of the magnetic flux-time graph.

From $t = 0$ to $t = 0.2$ seconds, the magnetic flux increases linearly. Therefore there will be a constant negative EMF induced.

From $t = 0.2$ to $t = 0.4$ seconds, the magnetic flux through the loop does not change. Therefore there is no EMF induced.

From $t = 0.4$ to $t = 0.6$ seconds, the magnetic flux decreases linearly. Therefore there is a constant positive EMF induced.

Step 2

Identify the known and unknown variables and write down the formula that relates these variables.

Note that the magnitude of the EMF induced between $t = 0$ to $t = 0.2$ and $t = 0.4$ to $t = 0.6$ will be the same, as the magnitude of the gradient is the same. However, the direction will be opposite.

$N = 5$, $\Phi_{B,i} = 0$ Wb, $\Phi_{B,f} = 4.0$ Wb, $\Delta t = 0.2$ s, $\varepsilon = ?$

$$\varepsilon = -N\frac{\Delta\Phi_B}{\Delta t}$$

Step 3

Substitute values into the formula and solve for the induced EMF.

$$\varepsilon = -5 \times \frac{4.0 - 0}{0.2}$$

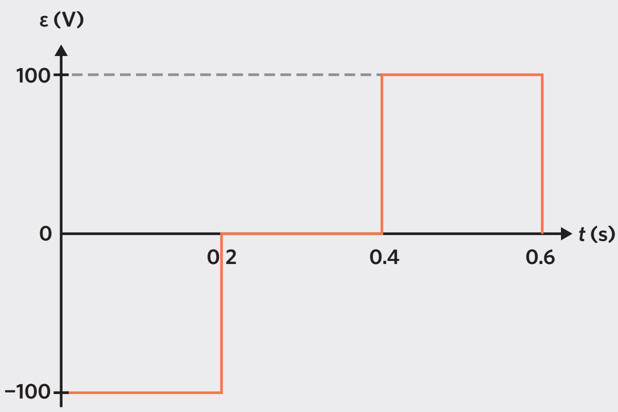
$$\varepsilon = -100 \text{ V}$$

The magnitude of the induced EMF is 100 V.

Step 4

Graph the EMF with respect to time.

- The sign of an EMF-time graph should reflect how the magnetic flux is changing. It is good practice to draw a negative EMF when the flux is increasing, and a positive EMF when the flux is decreasing, however, an inverted version of the EMF-time graph is acceptable.
- When the magnetic flux-time graph increases with a constant gradient, such as from 0 to 0.2 s, the EMF is constant.
- When the magnetic flux-time graph has a gradient of zero (horizontal), such as from 0.2 to 0.4 s, the EMF is zero.



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PROGRESS QUESTIONS

Question 3

An EMF will not be induced in a loop when

A. magnetic flux through the loop decreases.

B. magnetic field strength through the loop increases.

C. the area of the loop perpendicular to a magnetic field changes.

D. a loop is moved horizontally with its area always entirely within a uniform magnetic field.

Question 4

A coil moves at a constant speed into a uniform magnetic field. Its area is perpendicular to the magnetic field lines. Which of the following changes will increase the magnitude of the EMF induced in the coil? **(Select all that apply)**

A. Increasing the area of the coil.

B. Increasing the speed of the coil.

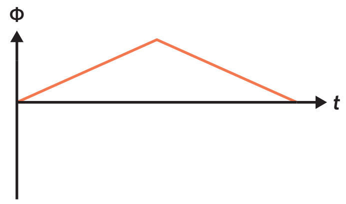
C. Increasing the magnetic field strength.

D. Increasing the number of turns in the coil.

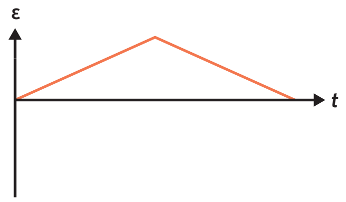
Question 5

The following graph shows the change in magnetic flux, Φ, through a coil of wire as a function of time, *t*.

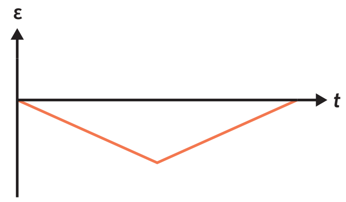
Which of the following graphs best represents the induced EMF (ε) across the coil of wire as a function of time (*t*)?



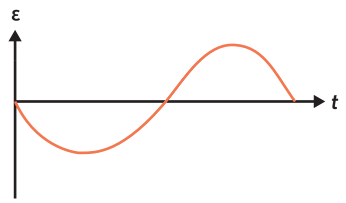
A.



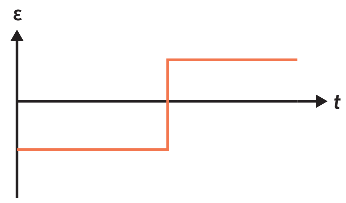
B.



C.



D.



Adapted from VCAA 2017 exam Multiple choice Q6

Theory summary

Magnetic flux is a measure of the number of magnetic field lines passing through an area.

- $\Phi_B = B_\perp A$
- Magnetic flux graphs are used to show the change in flux over time.

A change in magnetic flux induces an EMF (voltage) in a loop or coil.

- Faraday's law: $\varepsilon = -N\frac{\Delta\Phi_B}{\Delta t}$
- Induced EMF graphs are derived from Φ_B vs. t graphs: the EMF is proportional to the rate of change of magnetic flux through the loop. This can be found from the gradient of the Φ_B vs. t graph.

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5A Questions

Mild 🌶 Medium 🌶🌶 Spicy 🌶🌶🌶

Deconstructed exam-style

Use the following information to answer questions 6–9.

A square loop of wire made out of 20 turns has side lengths of 10 cm and passes into a uniform magnetic field of strength 0.15 T. The loop takes 0.25 s to move from completely outside the magnetic field to fully inside the magnetic field.

Question 6 🌶 (1 MARK)

What is the area of the square loop of wire?

A. $1.0 \times 10^{-2}\ m^2$

B. $3.1 \times 10^{-2}\ m^2$

C. $1.0 \times 10^{2}\ m^2$

D. $3.1 \times 10^{2}\ m^2$

Question 7 🌶 (1 MARK)

What is the magnetic flux passing through the loop before it enters the uniform magnetic field?

Question 8 🌶 (1 MARK)

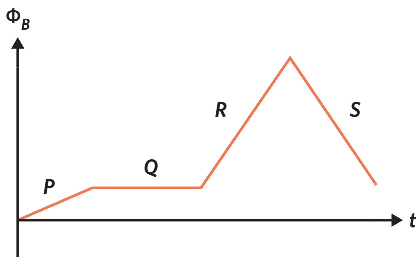
What is the magnetic flux passing through the loop once it is fully inside the magnetic field?

Question 9 🌶🌶 (3 MARKS)

Calculate the magnitude of the average EMF induced in the loop as it moves from completely outside the magnetic field to completely inside.

Exam-style

Use the following graph to answer questions 10 and 11.



Question 10 🌶 (3 MARKS)

The corresponding section of the EMF vs. *t* graph for section *P* is negative. For the three subsequent sections (*Q*–*S*) of the Φ_B vs. t graph, determine whether the corresponding section of the EMF vs. time graph should be positive, negative, or zero.

Question 11 🌶 (1 MARK)

Which of the following options correctly compares the magnitude of the EMF corresponding to sections *P* and *R*?

A. The magnitude of the EMF is the same for sections *P* and *R*.

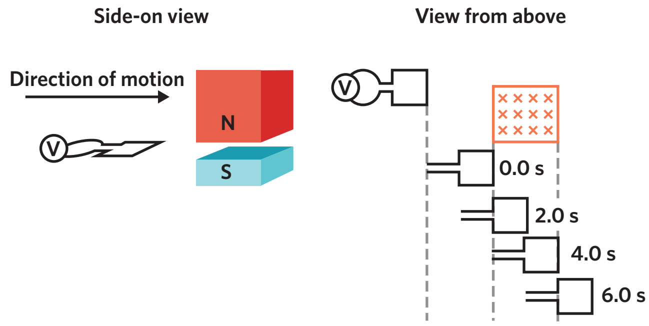
B. The magnitude of the EMF is greater for section *P* than section *R*.

C. The magnitude of the EMF is greater for section *R* than section *P*.

D. We need to know the strength of the magnetic field to be able to answer the question.

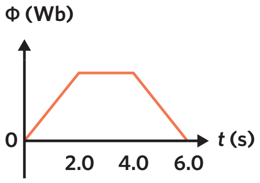
Use the following information to answer questions 12–14.

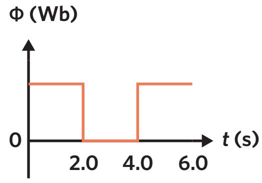
A square loop of 15 turns starts in a region with no magnetic field and passes at a constant speed into, through, and out of a uniform magnetic field, as shown in the diagram. The region of the magnetic field is large enough to fit the entire loop within it. The magnetic field strength is 0.040 T and the loop has an area of 2.5×10^3 cm^2. The diagram is not drawn to scale.

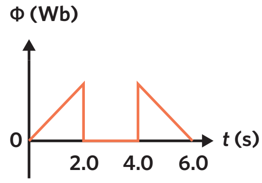


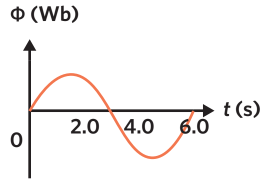
Question 12 (1 MARK)

Select which magnetic flux-time graph best represents the variation of the magnetic flux through the loop in this situation.

A.


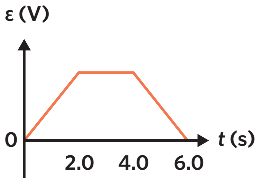
B.


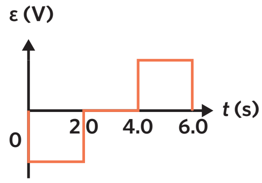
C.


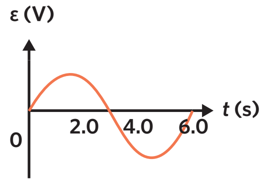
D.


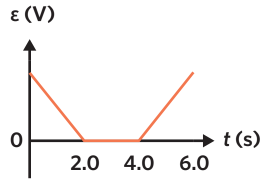
Question 13 (1 MARK)

Select which EMF-time graph best represents the variation of the EMF in the loop in this situation.

A.


B.


C.


D.


Question 14 (3 MARKS)

Determine the magnitude of the average EMF induced in the loop while it is moving into the magnetic field (between $t = 0.0$ s and $t = 2.0$ s),

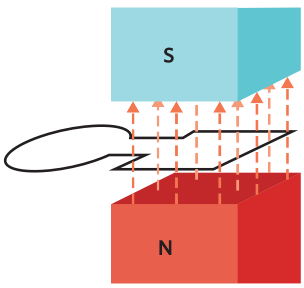
---

Question 15 (2 MARKS)

A loop of wire is being held inside a uniform magnetic field as shown.

Identify two actions that when applied to the loop would cause an EMF to be induced in the loop, without changing the shape of the loop of wire.

Adapted from VCAA 2014 exam Short answer Q13a



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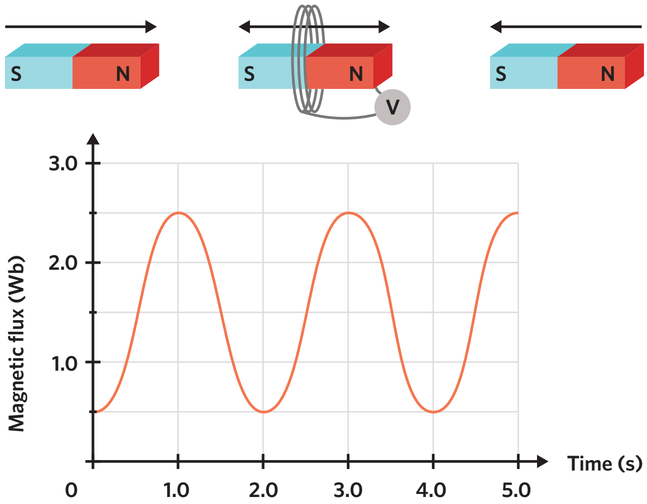
Question 16 (4 MARKS)

A bar magnet oscillates through a metallic coil with 4 turns. The graph shows the magnetic flux through the loop as the magnet oscillates.



a. Identify at which times on the graph the EMF induced in the loop is zero. 1 MARK

Adapted from VCAA 2013 exam Short answer Q17b

b. Calculate the magnitude of the average EMF in the loop between 1.0 and 2.0 s. 2 MARKS

c. Determine at which times on the graph the magnet is in the middle of the loop. 1 MARK

Question 17 (7 MARKS)

A physics class is investigating the effect of the rate of change of magnetic flux on the magnitude of the induced EMF in a coil. They use an electromagnet to vary the magnetic flux passing through a coil of wire at a constant rate. They record the magnetic flux at various times as shown in the table.

t (s)	Φ (Wb)
0	0
0.6	0.30
1.0	0.61
1.4	0.90
2.0	1.15
2.5	1.50
3.0	1.80

While varying the magnetic flux, the class measures the EMF produced in the coil to have a constant magnitude of 6 V.

a. *Key science skill*

Plot a graph of the data collected by the class with flux on the vertical axis and time on the horizontal axis. Label the axes, use an appropriate scale, and include a line of best fit. 4 MARKS

b. *Key science skill*

Use the gradient of the line of best fit to approximate the number of turns in the coil. Your answer should be a whole number. 3 MARKS

FROM LESSON 12D

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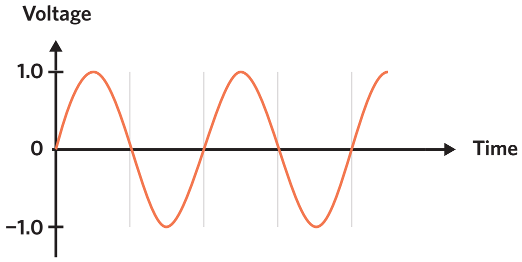
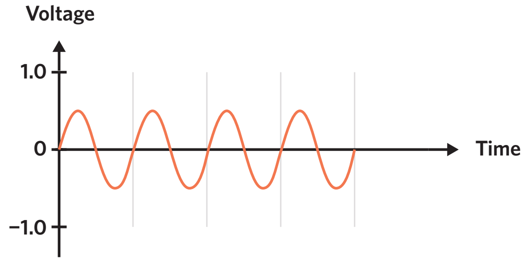
Question 18 🌶🌶🌶 (1 MARK)

A coil is rotated in a uniform magnetic field at a frequency of 50 Hz. A graph of the EMF versus time for this coil is shown.

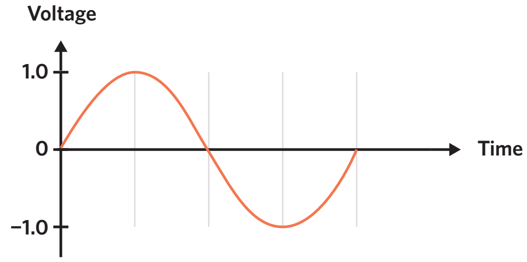
Which of the following graphs best represents the output voltage if the rate of rotation is changed to 25 Hz?



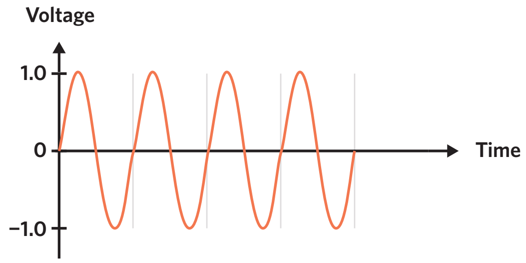
A.



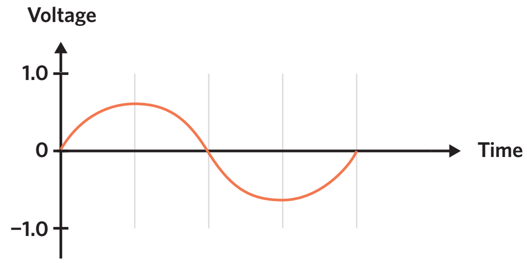
B.



C.



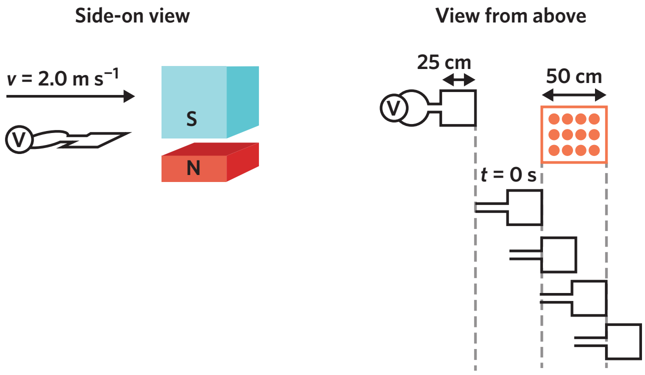
D.



Adapted from VCAA 2019 exam Multiple choice Q7

Question 19 (7 MARKS)

A square coil with 6 turns starts in a region with no magnetic field and then passes at a constant speed of 2.0 m s^{-1} into, through, and out of a uniform magnetic field ($B = 3.0 \times 10^{-2}$ T) between the poles of two bar magnets as indicated by the diagram. Assume that the uniform magnetic field is a square shape with side length of 50 cm, and the loop has a side length of 25 cm.



a. Plot a graph of the magnetic flux through the coil against time. Assume $t = 0$ s when the front edge of the coil is just about to enter the magnetic field. Appropriate values should be included on the graph. 🌶🌶🌶 4 MARKS

b. Plot a graph of the EMF in the coil against time. Appropriate values should be included on the graph. 🌶🌶🌶 3 MARKS

Adapted from VCAA 2015 exam Short answer Q13

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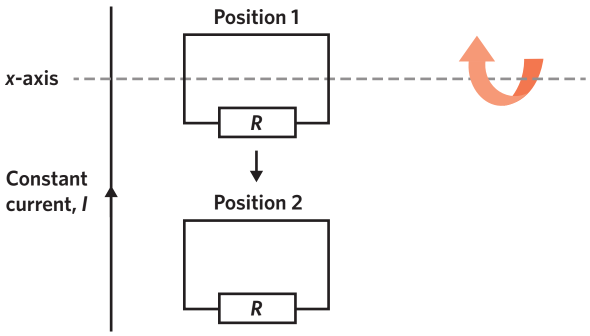
Question 20 (4 MARKS)

A square loop of wire connected to a resistor, R, is placed close to a long wire carrying a constant current, I, in the direction shown in the diagram. The square loop is moved twice in the following order:

- Movement A – Starting at Position 1, the square loop rotates one full rotation at a steady speed about the x-axis. The rotation causes the resistor, R, to first move out of the page.
- Movement B – The square loop is then moved at a constant speed, parallel to the current carrying wire, from Position 1 to Position 2.



Describe the how the magnitude of the EMF generated in the square loop changes during movement A and movement B.

Adapted from VCAA 2022 exam Short answer Q4

Previous lessons

Question 21 (2 MARKS)

A cue ball is struck into another billiard ball, and a loud sound is produced. Discuss whether this was an elastic or inelastic collision.

FROM LESSON 2B

Question 22 (2 MARKS)

Discuss how an object is able to undergo circular motion around a planet without the use of propulsion engines.

FROM LESSON 3C

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5B Direction of induced current and Lenz's law

STUDY DESIGN DOT POINT

- investigate and analyse theoretically and practically the generation of electromotive force (EMF) including AC voltage and calculations using induced $\varepsilon = -N\frac{\Delta\Phi_B}{\Delta t}$, with reference to:
  - rate of change of magnetic flux
  - number of loops through which the flux passes
  - direction of induced EMF in a coil

5A 5B 5C 5D

3.3.2.2 Lenz's law

ESSENTIAL PRIOR KNOWLEDGE

4B Magnetic fields
4B Right-hand coil rule
5A Magnetic flux
See questions 52-54.

Image: Tomasz Majchrowicz/Shutterstock.com

How do metal detectors work?

Metal detectors use the magnetic field produced by an electric current to detect metallic objects hidden underground. Faraday's law tells us that when the detector moves across something metallic, the changing magnetic field produced by the detector induces a current in the hidden metal object. This lesson will investigate how Lenz's law can be used to determine the direction of this induced current which then allows the metal detector to sense the presence of the metal and beep.

KEY TERMS AND DEFINITIONS

induced current the current produced in a conductor due to a changing magnetic flux

Lenz's law 3.3.2.2

A change in magnetic flux through a coil of wire produces an **induced current** in the coil. The direction of the induced current can be determined using Lenz's law and the right-hand coil rule.

How can we use Lenz's law to find the direction of induced current?

In previous lessons we've learned:

- An electric current in a wire generates a magnetic field (4B).
- A changing magnetic flux in a conducting loop induces an EMF in the loop (5A).

This lesson we will learn that:

- an induced EMF in a loop causes charges to move in a closed circuit, creating an induced current.
- The induced current will generate its own magnetic field.

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Lenz's law allows us to determine the direction of the induced current. To do this we need to identify:

1. The direction that magnetic flux passes through the loop (upwards, downwards, left, right etc.).
2. Whether the flux is increasing or decreasing.

The magnetic flux through a loop of wire is in the same direction as the magnetic field lines passing through it. In Figure 1, the magnetic flux through the loop of wire is downwards, as the direction of the magnetic field between the north and south pole is also downward.

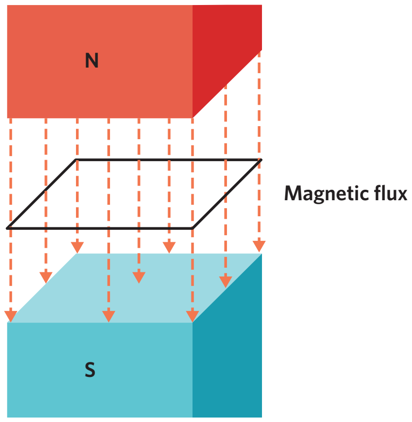

Figure 1 Direction of magnetic flux through a loop

There are four ways the magnetic flux through a loop can increase:

1. A loop can move into a magnetic field.
2. The area of the loop can increase.
3. The perpendicular area of the loop can increase e.g. a coil rotating from parallel to perpendicular to the magnetic field.
4. The strength of the magnetic field can increase.

There are four ways the magnetic flux through a loop can decrease:

1. A loop can move out of a magnetic field.
2. The area of the loop can decrease.
3. The perpendicular area of the loop can decrease e.g. a coil rotating from perpendicular to parallel to the magnetic field.
4. The strength of the magnetic field can decrease.

Figure 2 shows a loop of wire moving through a static, uniform magnetic field. Table 1 describes how the magnetic flux changes. The direction of the magnetic field is into the page when viewed from the top.

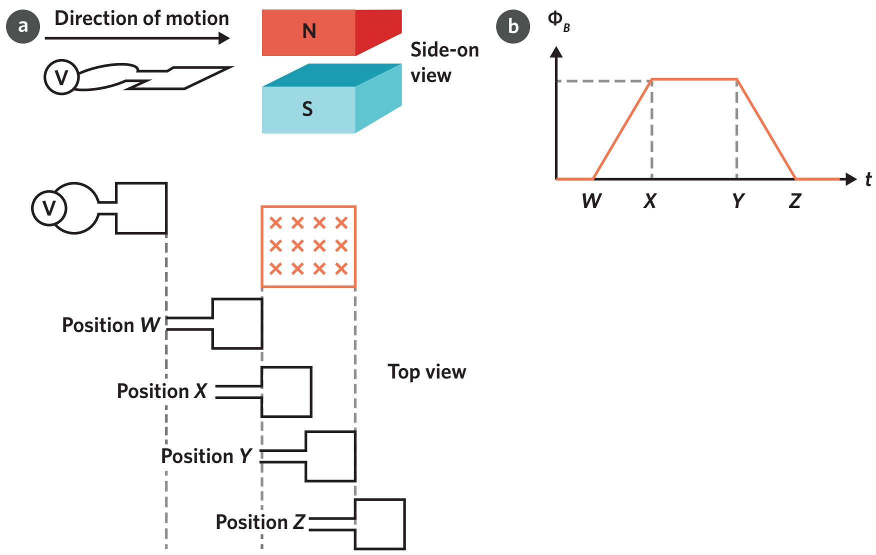

Figure 2 **(a)** A loop of wire moving through a magnetic field and **(b)** the magnetic flux graph

Table 1 Changes in magnetic flux as a loop of wire moves through a magnetic field (Figure 2)

Position	Position of loop	Change in magnetic flux
W to *X*	entering magnetic field	increasing into the page
X to *Y*	moving through field	no change
Y to *Z*	exiting magnetic field	decreasing into the page

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These changes in magnetic flux through the loop induce a current. Lenz's law tells us that:

- an induced current will flow in a direction so that the magnetic field created by the current will oppose the change in flux that induced the current

To put it another way:

- A magnet produces a magnetic flux through a loop.
- Any change to the magnetic flux through the loop induces an EMF in the wire.
- If the wire forms a closed circuit, an induced current will flow.
- This current generates its own magnetic field.
- The induced current flows in a direction so that its magnetic field opposes the original change in flux.

We use Lenz's law to help determine the direction an induced current flows.

USEFUL TIP

Faraday's law gives us the magnitude of the EMF induced in a loop due to a change in flux through it, whereas Lenz's law tells us the direction of the induced EMF and current in the loop. Lenz's law helps explain the negative sign in Faraday's law.

USEFUL TIP

The right-hand grip rule can also be used to determine the direction of the induced current. When using the right-hand grip rule, the fingers point in the direction of the induced magnetic field and the thumb goes in the direction of the induced current.

STRATEGY

To determine the direction of an induced current:

1. Identify whether the magnetic flux is increasing or decreasing.
2. Identify the direction of the original magnetic field ('up', 'right', 'into the page', etc.).
3. Identify the direction of the induced magnetic field.
   - If the flux is increasing, then to oppose this increase, the induced magnetic field is in the opposite direction to the original field.
   - If the flux is decreasing, then to reinforce the decreasing field, the induced magnetic field is in the same direction as the original field.
4. Apply the right-hand coil rule, with the thumb pointing in the direction of the induced magnetic field and the fingers curling in the direction of the induced current (Figure 3).

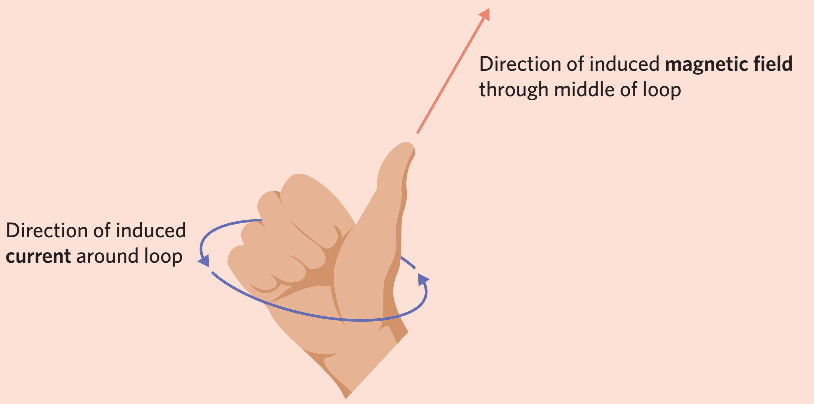

Figure 3 Right-hand coil rule for finding direction of induced current

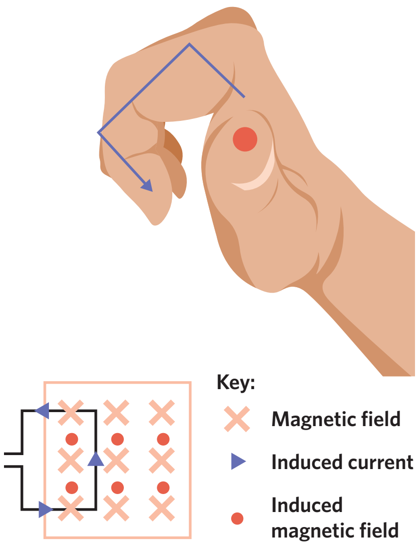

Figure 4 Right-hand coil rule applied to a loop entering a magnetic field

Consider a loop entering a magnetic field (directed into the page):

1. The magnetic flux increases as the loop enters the field.
2. The original magnetic field is into the page.
3. Since the magnetic flux is increasing, the induced current will produce a magnetic field out of the page to oppose the increase.
4. Using the right-hand coil rule, with the thumb pointing out of the page, the induced current flows in an anticlockwise direction when viewed from above (Figure 4).

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Now consider a loop exiting a magnetic field (directed into the page):

1. The magnetic flux decreases as the loop exits the field.
2. The original magnetic field is into the page.
3. Since the magnetic flux is decreasing, the induced current will produce a magnetic field into the page to oppose the decrease.
4. Using the right-hand coil rule, with the thumb pointing into the page, the induced current flows in a clockwise direction when viewed from above (Figure 5).

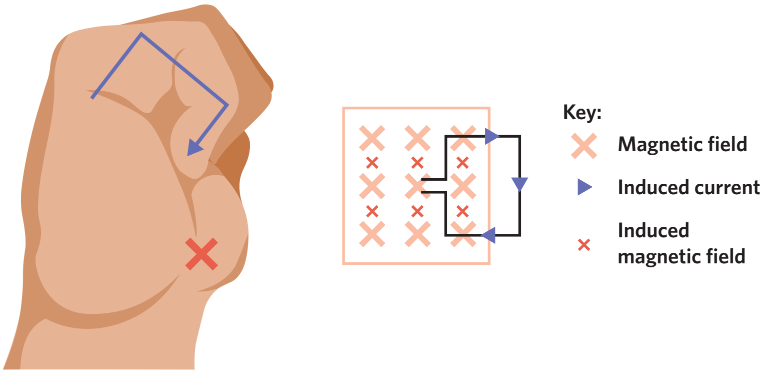

Figure 5 Right-hand coil rule applied to a loop exiting a magnetic field

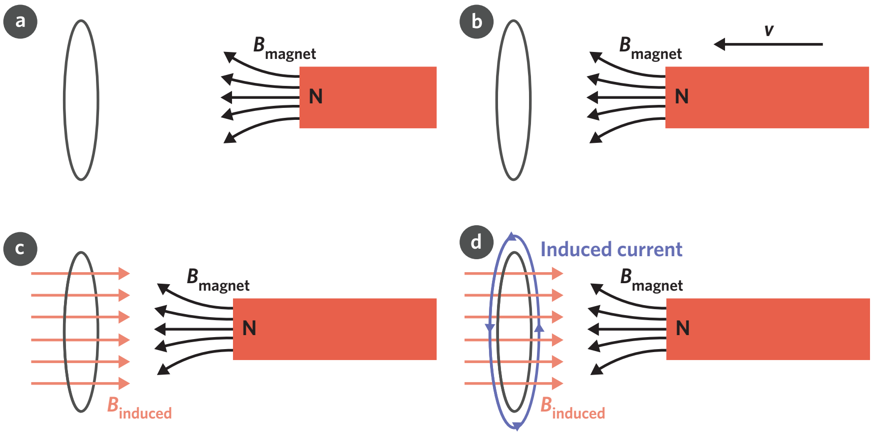

Figure 6 **(a)** A magnet moves towards a loop **(b)** increasing the flux. **(c)** The induced current produces a magnetic field that opposes this increase, **(d)** therefore the induced current flows anti-clockwise when viewed from the magnet.

Figure 6 depicts a current being induced in a conducting loop due to a changing magnetic field strength through the loop, rather than a changing area within the magnetic field.[1] The process for determining the direction of the induced current is the same.

1. As the magnet approaches the loop (Figure 6a), the magnetic field strength and magnetic flux through the loop increases (Figure 6b).
2. The original magnetic field is to the left (the direction of the magnetic field lines).
3. Since the magnetic flux is increasing, the induced current will produce a magnetic field to the right to oppose the increase. (Figure 6c).
4. Using the right-hand coil rule, with the thumb pointing to the right, the induced current is anticlockwise when viewed from the magnet (Figure 6d).

KEEN TO INVESTIGATE?

[1] **Where does electrical energy come from?**
Search YouTube: World's first electric generator

STRATEGY

VCAA exams commonly ask how the direction of induced current was determined. The following is a template for answering such questions.

- The magnetic flux through the loop is [increasing/decreasing] in [direction].
- Lenz's law states the induced EMF will produce a current that will have a magnetic field which opposes the [increase/decrease] in flux, so it will be [direction].
- Using the right-hand coil rule, the induced current will flow [direction].

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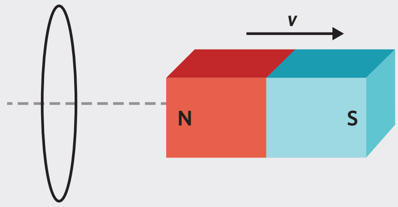
WORKED EXAMPLE 1

A bar magnet moves away from a loop of wire with the north pole facing a conducting loop. Use Lenz's law to determine the direction of the induced current.



Breakdown	Answer
Identify if the magnetic flux through the loop is increasing or decreasing and the direction of the change in flux.	The magnetic flux through the loop is decreasing to the left.
Use Lenz's law to determine the direction of the induced magnetic field.	Lenz's law states that the induced EMF will produce a current that will have a magnetic field which will oppose this decrease in flux, so it will be directed to the left.
Identify the direction of the induced current.	Using the right-hand coil rule, the induced current will flow clockwise when viewed from the magnet.

PROGRESS QUESTIONS

Question 1

Lenz's law states that the direction of the induced current in a coil will

A. oppose the original magnetic field through the coil.

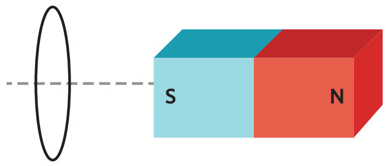
B. oppose the change in magnetic flux through the coil.

C. create a magnetic field that opposes the change in magnetic flux through the coil.

D. create a magnetic field that supports the change in magnetic flux through the coil.

Question 2

A bar magnet is positioned near a loop of wire with the south pole facing the loop, as shown.



If the magnet moves towards the loop (to the left), in what direction will the induced current flow around the loop?

A. There will be zero induced current.

B. Not enough information to answer the question.

C. It will flow in a clockwise direction when viewed from the magnet.

D. It will flow in an anticlockwise direction when viewed from the magnet.

Theory summary

- Lenz's law states that the induced current will flow in a direction such that the magnetic field it creates will oppose the change in flux that induced the current.
  - If magnetic flux through a loop is increasing, the induced magnetic field will be in the opposite direction to the original magnetic field.
  - If magnetic flux through a loop is decreasing, the induced magnetic field will be in the same direction as the original magnetic field.
  - The right-hand coil rule is used to determine the direction of the induced current once the direction of the induced magnetic field has been identified.

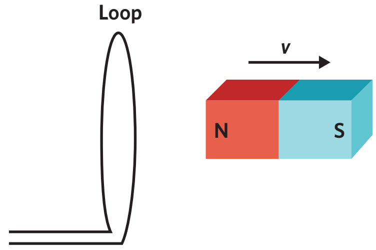
5B Questions

Mild 🌶 Medium 🌶🌶 Spicy 🌶🌶🌶

Deconstructed exam-style

Use the following information to answer questions 3–6.

A magnet moves away from a loop and a current is detected.



Question 3 🌶 (1 MARK)

As the magnet moves away, is the magnitude of the magnetic flux increasing or decreasing?

Question 4 🌶 (1 MARK)

Identify the direction of the magnetic flux through the loop.

A. to the left

B. to the right

C. into the page

D. out of the page

Question 5 🌶 (1 MARK)

According to Lenz's law, the induced current will produce a magnetic field that

A. is directed to the left.

B. is directed to the right.

C. is directed into the page.

D. is directed out of the page.

Question 6 🌶🌶 (3 MARKS)

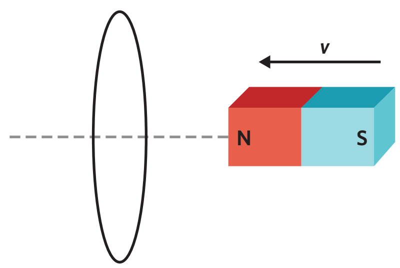
Use Lenz's law to explain why the current flows in an anticlockwise direction.

Adapted from VCAA 2011 Exam 2 Area of Study 1 Section A Q12

Exam-style

Use the following information to answer questions 7–8.

A magnet moves towards a loop and induces a current.



Question 7 🌶 (1 MARK)

Is the magnetic flux increasing or decreasing?

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Question 8 (1 MARK)

Identify the direction of the induced magnetic field.

A. to the left

B. to the right

C. into the page

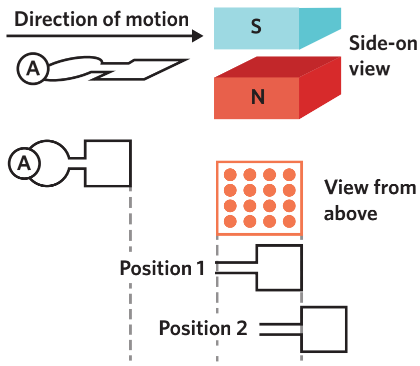
D. out of the page

Question 9 (1 MARK)

A square loop of wire is moving at a constant speed and passes into and then out of a uniform magnetic field as shown in the diagram.

Identify the direction of the induced current (clockwise or anticlockwise) when viewed from above as it exits the magnetic field (moves from position 1 to position 2).

Adapted from VCAA 2018 NHT exam Short answer Q4d



Question 10 (1 MARK)

A moving magnet induces a current in a loop.

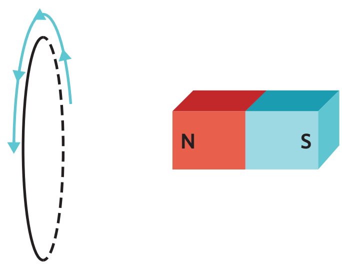
How must the magnet move to induce a current anticlockwise around the loop, when viewed from the magnet?

A. stay stationary

B. move towards the loop

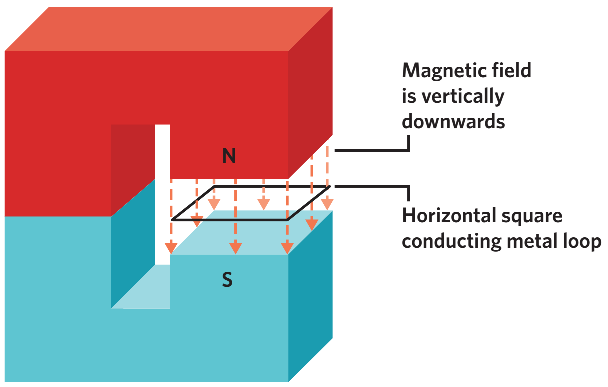
C. move away from the loop

D. rotate on its horizontal axis



Use the following information to answer questions 11–13.

A student has set up a conducting metal loop in a uniform magnetic field, as shown in the diagram. Assume there are no other magnetic sources nearby.



Question 11 (1 MARK)

Key science skill

To gain a better understanding of Lenz's law, the student conducts an experiment where she moves the loop of wire in and out of the magnetic field and records the direction of induced current. She does this so she can compare the direction of the induced current when the loop is moving towards the magnetic field vs. when it is moving away.

Identify a controlled variable in this experiment.

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Question 12 🌶🌶 (1 MARK)

Which of the following would cause current to flow in the loop?

A. Moving the whole system up and down.

B. Moving the loop to the left and out of the field.

C. Moving the loop directly downwards in the field.

D. Moving the loop to the right but it stays completely inside the field.

Adapted from VCAA 2014 exam Short answer Q13a

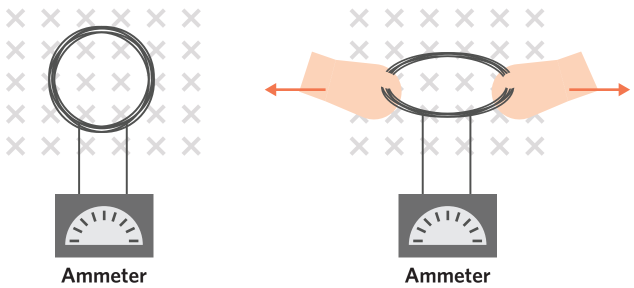
Question 13 🌶🌶 (3 MARKS)

If the magnetic field is reduced to zero, determine the direction the induced current will travel when viewed from above. Explain your answer.

Adapted from VCAA 2014 exam Short answer Q13c

Question 14 (6 MARKS)

Two Physics students hold a coil of wire in a constant uniform magnetic field. The ends of the wire are connected to a sensitive ammeter. The students then change the shape of the coil by pulling each side of the coil in the horizontal direction, as shown. They notice a current register on the ammeter.



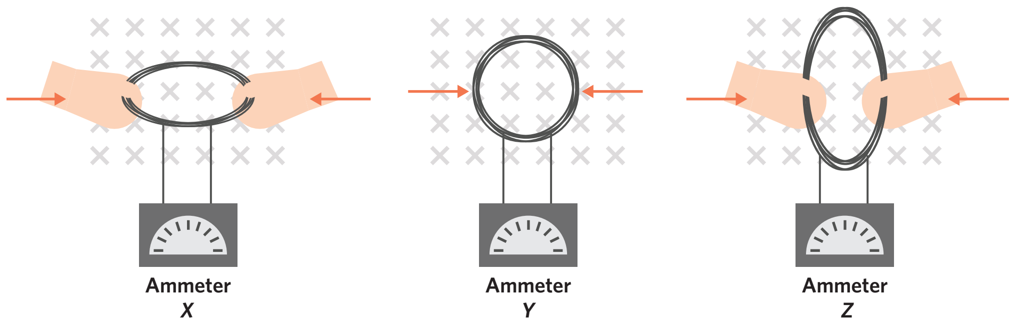
a. Will the magnetic flux through the coil increase, decrease or stay the same as the students change the shape of the coil? 🌶 1 MARK

Taken from VCAA 2020 exam Short answer Q6a

b. Explain, using appropriate physics, why the ammeter registered a current in the coil and determine the direction of the induced current. 🌶🌶 3 MARKS

Taken from VCAA 2020 exam Short answer Q6b

c. The students then push each side of the coil together (X) so that the coil returns to its original circular shape (Y), and then continue to push so it becomes an oval again (Z).



Describe the direction of any induced currents in the coil during these changes. Give your reasoning. 🌶🌶 2 MARKS

Taken from VCAA 2020 exam Short answer Q6c

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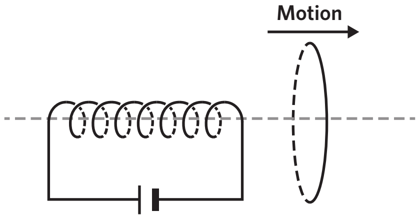
Question 15 (9 MARKS)

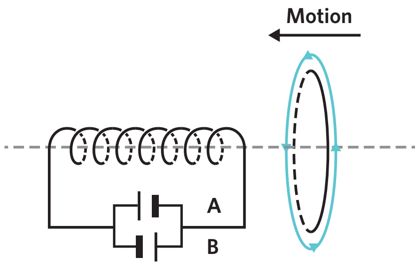
Attempting to understand the brilliance of wireless power, Sebastian is experimenting with a loop of wire and a solenoid. For his first experiment, shown in the diagram, Sebastian moves the loop away from the solenoid (to the right) and measures the direction of the induced current.



a. *Key science skill*
When documenting the direction of the induced current, is Sebastian more likely to record his results using qualitative or quantitative data? 1 MARK

b. Determine the direction of the induced current (clockwise or anticlockwise) in the loop of wire, as viewed from the solenoid. Explain your answer. 4 MARKS

c. After replacing the solenoid's cell, Sebastian has forgotten which side of the cell is positive and which is negative. Sebastian moves the loop of wire towards the solenoid and measures an anticlockwise current, as viewed from the solenoid. This is shown in the diagram.



Determine the direction current is flowing in the solenoid circuit and, hence, in which orientation (A or B) the cell has been connected. Justify your answer. 4 MARKS

Adapted from VCAA 2016 exam Short answer Q15b

Previous lessons

Question 16 (1 MARK)

A bowling ball collides elastically with a stationary bowling pin. After the collision both the bowling ball and the pin move off with some velocity. Which of the following statements is incorrect about the collision?

A. Momentum is conserved

B. Kinetic energy is conserved.

C. Some momentum was converted into kinetic energy.

D. The bowling ball transferred some kinetic energy to the pin.

FROM LESSON 2B

Question 17 (1 MARK)

Calculate the electric field strength due to a proton, with a charge of 1.6×10^{-19} C, at a distance of 1.4 m. Take k to be 8.99×10^{9} N m^2 C^{-2}.

FROM LESSON 4A

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5C Alternators and DC generators

Image: Sundry Photography/Shutterstock.com

How do electric cars charge their batteries?

Electric and hybrid cars can recharge at a charging station, but did you know they also recharge while braking? They have motors that convert electrical energy into kinetic energy. When the brake pedal is pressed, some of the kinetic energy of the car's motion is used to reverse this process and recharge the battery. This is called regenerative braking, and uses principles of electrical generation that we will explore in this lesson.

KEY TERMS AND DEFINITIONS

generator a device that transforms kinetic energy into electricity (either AC or DC) by electromagnetic induction

alternator a device that transforms kinetic energy into AC electricity by electromagnetic induction; an AC generator

alternating current (AC) electricity electricity with a periodically alternating direction of current and voltage

slip rings a component used to maintain a constant electrical connection between a stationary external circuit and a rotating coil

amplitude the distance from the x-axis to the top or bottom of the wave

frequency the number of cycles completed per second

period the time taken to complete one cycle

direct current (DC) electricity electricity with a constant direction of current and voltage

split ring commutator a component used to reverse the electrical connection between a stationary external circuit and a rotating coil every half rotation

FORMULAS

- **magnetic flux**
  $\Phi_B = B_{\perp}A$
- **Faraday's law**
  $\varepsilon = -N\frac{\Delta\Phi_B}{\Delta t}$
- **frequency**
  $f = \frac{1}{T}$

STUDY DESIGN DOT POINTS

- explain the production of DC voltage in DC generators and AC voltage in alternators, including the use of split ring commutators and slip rings respectively
- compare sinusoidal AC voltages produced as a result of the uniform rotation of a loop in a constant magnetic field with reference to frequency, period, amplitude, peak-to-peak voltage ($V_{p\text{-}p}$) and peak-to-peak current ($I_{p\text{-}p}$)

5A 5B **5C** 5D

3.3.3.1 & 3.3.5.1 Alternators and AC power

3.3.3.2 DC generators

ESSENTIAL PRIOR KNOWLEDGE

- AC and DC power
- Wave fundamentals

5A Faraday's law

See questions 55–57.

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Alternators and AC power 3.3.3.1 & 3.3.5.1

A **generator** is a device that uses a rotating coil within a magnetic field to generate electricity. An **alternator** is a generator that generates **alternating current (AC) electricity**.

How are alternators constructed?

In Lesson 5A, we learned that an EMF is induced when there is a changing magnetic flux through a coil. We also learned that one way to change the flux through a coil is to rotate the coil within a magnetic field. This is the basis of how a generator works (Figure 1). The kinetic energy used to rotate the coil is transformed into electrical energy, the opposite energy transformation to a motor.[1]

KEEN TO INVESTIGATE?

1 **How can we visualise the movement of a motor?**
Search: Generator simulation fendt

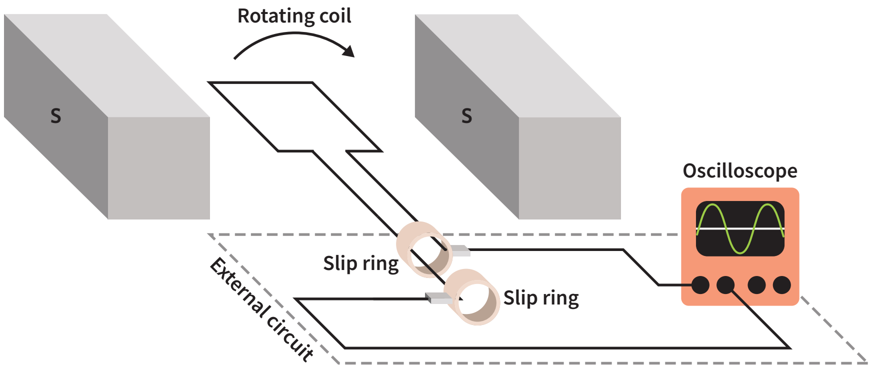


Figure 1 Construction of an alternator

Table 1 Features of an alternator with reference to Figure 1

Part	Function
Magnet	Provides a uniform magnetic field for the coil to rotate in
Rotating coil	Rotates to create a change in magnetic flux through the loop which induces a current
Slip rings	Two metal rings that allow the coil to keep constant contact with the external circuit while rotating
External circuit	Allows induced current to flow

Slip rings are conducting rings that allow the coil in an alternator to rotate while maintaining electrical contact with a stationary external circuit. Each end of the coil slides around the surface of its ring. By maintaining contact, the alternating EMF creates an alternating current (AC) that flows into the external circuit.

USEFUL TIP

EMF refers to energy given to each coulomb of charge whereas voltage refers to the difference in electrical potential energy between two points. Both are measured in volts (V) and are used somewhat interchangeably in this context.

PROGRESS QUESTIONS

Question 1

What is the main energy transformation that occurs in an alternator?

A. electrical energy to kinetic energy
B. kinetic energy to electrical energy
C. chemical energy to electrical energy
D. electrical energy to chemical energy

Question 2

The purpose of a slip ring is to

A. generate a magnetic field.
B. change the direction of the induced EMF.
C. measure the flow of current as a result of the induced EMF.
D. allow the rotating coil to remain in constant contact with the external circuit.

How does magnetic flux and induced EMF change as an alternator rotates?

Figure 2 shows the magnetic flux, in blue, and the EMF, in red, for a coil as it rotates at a constant speed through one full rotation in an alternator. Note that the vertical axis represents a different quantity for each graph. In the situation shown, the coil starts parallel to the magnetic field, so there is no magnetic flux passing through the loop. The angle of rotation for each orientation shown is measured from the starting position.

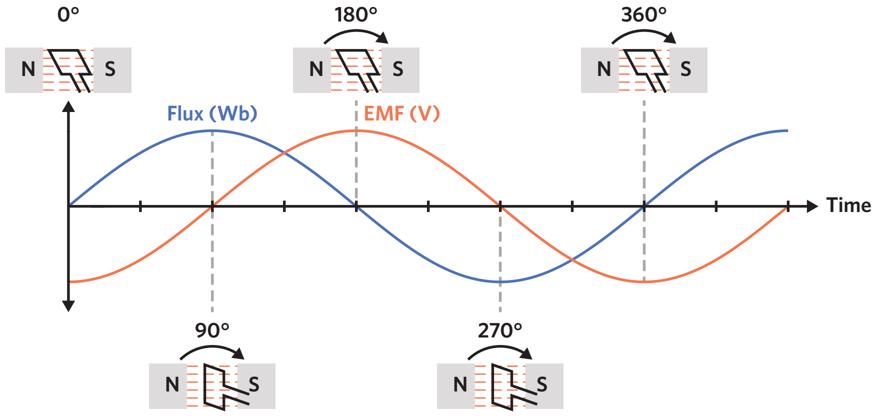
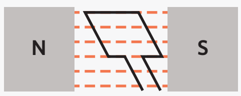
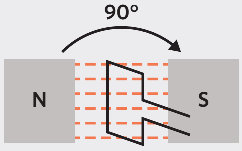
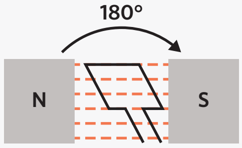
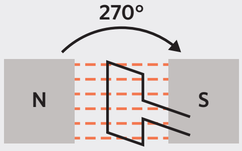


Figure 2 The magnetic flux and EMF in a coil that is rotating uniformly within a constant magnetic field

The relationship between magnetic flux and induced EMF follows Faraday's law. This means that the induced EMF is proportional to the negative rate of change of the flux (the negative of the gradient of the blue line in Figure 2).

$$\varepsilon \propto -\frac{\Delta\Phi_B}{\Delta t}$$

Table 2 How flux and EMF vary with time in an alternator

Diagram	Coil position relative to field	Magnetic flux (Wb)		EMF (V)	Explanation
		Value	Change in flux		
0° or 360° 	Parallel	0	Positive maximum	Negative maximum	The flux is zero whenever the coil is parallel to the magnetic field. However, the rate of change (gradient) of the flux is a positive maximum at this point, therefore, according to Faraday's law, the EMF induced will be a negative maximum.
90° 	Perpendicular	Positive maximum	0	0	The magnitude of the flux is a maximum whenever the coil is perpendicular to the magnetic field. However, the gradient of the flux graph is zero, therefore the change in flux is zero and the EMF induced will be zero.
180° 	Parallel	0	Negative maximum	Positive maximum	The flux is zero whenever the coil is parallel to the magnetic field. However, the gradient of the flux graph is a negative maximum, therefore, according to Faraday's law, the EMF induced will be a positive maximum.
270° 	Perpendicular	Negative maximum	0	0	The magnitude of the flux is a maximum whenever the coil is perpendicular to the magnetic field. However, the gradient of the flux graph is zero, therefore the change in flux is zero and the EMF induced will be zero.

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KEEN TO INVESTIGATE?

[2] **How do we explain the movement of current in AC generators?**
Search YouTube: How electricity is generated AC Electrical Basics

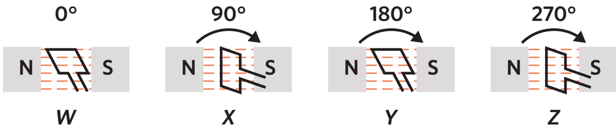
From Figure 2 and Table 2, we can draw the following conclusions:

- A negative flux indicates that the magnetic field lines are passing through the coil in the opposite direction to a positive flux, relative to the coil. The choice of which direction is positive is not important, but we must be consistent.
- The flux varies sinusoidally (in the shape of a sine wave) with time.
- The EMF varies sinusoidally with time. The maximum value of the EMF graph occurs one quarter of a cycle later than the maximum value of the magnetic flux.[2]

PROGRESS QUESTIONS

Use the following information to answer questions 3-6.

The diagrams show the coil of an alternator at four different orientations during its uniform rotation.



Question 3

Which of the following best corresponds to the maximum magnitude of magnetic flux through the coil?

A. X only **B.** Y only **C.** W and Y **D.** X and Z

Question 4

Which of the following best corresponds to zero magnetic flux through the coil?

A. X only **B.** Y only **C.** W and Y **D.** X and Z

Question 5

Which of the following best corresponds to the maximum magnitude of EMF in the coil?

A. X only **B.** Y only **C.** W and Y **D.** X and Z

Question 6

Which of the following best corresponds to zero EMF in the coil?

A. X only **B.** Y only **C.** W and Y **D.** X and Z

How can we analyse AC electricity?

AC voltage can be measured using the **amplitude**, **frequency**, and **period** of a voltage vs. time graph (Figure 3). Each of these quantities is affected by the speed of rotation of the coil in an alternator.

FORMULA

$$f = \frac{1}{T}$$

f = frequency (Hz)
T = period (s)

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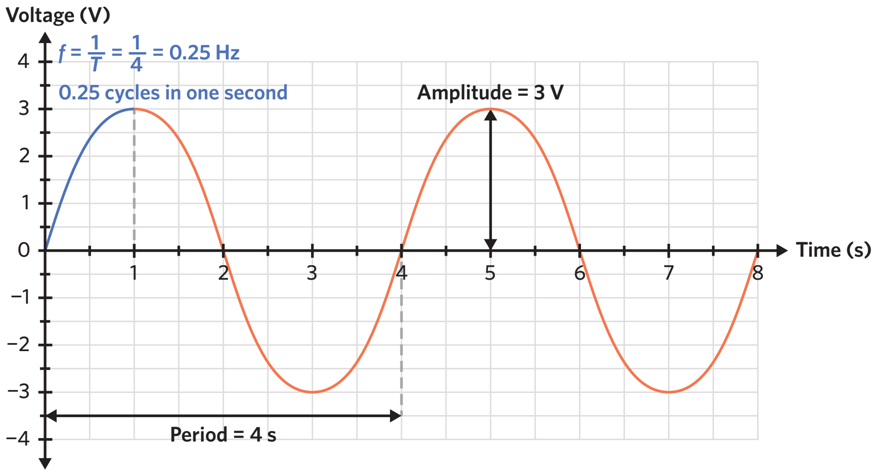

Figure 3 Frequency, period, and amplitude of a voltage-time graph

When the speed of rotation of the coil in an alternator is increased:

- The coil rotates faster, so the frequency increases.
- The time taken to complete one full rotation decreases, so the period decreases.
- The rate of change of flux through the coil increases, so the amplitude of the induced EMF as described by $\varepsilon = -N\frac{\Delta\Phi_B}{\Delta t}$ increases.

In Figure 4, a coil is run at two different frequencies, f and twice that frequency, $2f$:

- The amplitude of $2f$ is double amplitude of f, i.e. the voltage is doubled.
- The frequency of $2f$ is double the frequency of f, i.e. the coil rotates twice as fast.
- The period of $2f$ is half the period of f.

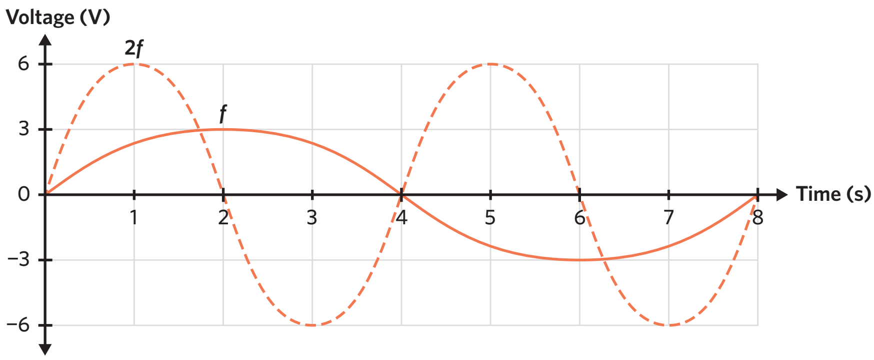

Figure 4 The voltage vs. time output for a coil rotating at frequency f (solid line), and a coil rotating at $2f$ (dotted line)

USEFUL TIP

The amplitude of the induced EMF is proportional to the frequency (and inversely proportional to the period). So if the frequency doubles, the induced EMF will double as well.

STRATEGY

Questions in this topic will often ask about the "average EMF" induced over a period of time or revolution of the coil. Using Faraday's Law, $\varepsilon = -N\frac{\Delta\Phi_B}{\Delta t}$, the average EMF induced is the amount induced over the period of time, Δt.

Make sure to calculate the change in flux, $\Delta\Phi_B$, over the period, Δt, that we are calculating the average over.

WORKED EXAMPLE 1

An alternator is being used to produce electricity. The alternator coil has five turns and an area of $0.40\ m^2$. Starting at an orientation perpendicular to the field, the coil completes three full rotations per second inside a uniform magnetic field of strength 5.0×10^{-3} T.

a. Calculate the magnitude of the average EMF in the coil as it completes one quarter of a revolution from the vertical to the horizontal position.

Step 1

Identify known and unknown variables and write down the formula that relates these variables.

$A = 0.40\ m^2$, $B_i = 5.0 \times 10^{-3}$ T, $N = 5$, $f = 3.0$ Hz, $\Delta\Phi_B = ?$, $\Delta t = ?$, $\varepsilon = ?$

$$\varepsilon = -N\frac{\Delta\Phi_B}{\Delta t}$$

$$\Phi_B = BA$$

$$T = \frac{1}{f}$$

Continues →

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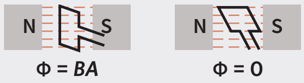
Step 2

Calculate the change in magnetic flux through the loop.

Note that in one quarter of a revolution, magnetic flux changes from a maximum ($\Phi_B = BA$) to zero.



$$\Delta\Phi_B = \Phi_{Bf} - \Phi_{Bi}$$

$$\Delta\Phi_B = 0 - BA$$

$$\Delta\Phi_B = 0 - (5.0 \times 10^{-3} \times 0.40) = -2.0 \times 10^{-3}\ \text{Wb}$$

Step 3

Calculate the time it takes to perform one quarter of a revolution.

Note that the question gives us the frequency by saying that the loop completes three revolutions per second.

$$T = \frac{1}{f} = \frac{1}{3} = 0.333\ \text{s}$$

$$\Delta t = \frac{T}{4} = \frac{0.333}{4} = 0.0833\ \text{s}$$

Step 4

Calculate the final answer using the equation found in Step 1.

$$\varepsilon = -N\frac{\Delta\Phi_B}{\Delta t}$$

$$\varepsilon = -5 \times \frac{-2.0 \times 10^{-3}}{0.0833}$$

$$\varepsilon = 0.120 = 0.12\ \text{V}$$

---

b. Determine the magnitude of the average EMF if the frequency is increased to nine rotations per second.

Step 1

Repeat part **a** to calculate the EMF in the same manner with $f = 9.0$ Hz

OR

Recognise that the frequency has tripled so the magnitude of induced EMF must also triple as it is proportional to the number of rotations per second.

$$T = \frac{1}{f} = \frac{1}{9} = 0.111\ \text{s}$$

$$\Delta t = \frac{T}{4} = \frac{0.111}{4} = 0.02777\ \text{s}$$

$$\varepsilon = -N\frac{\Delta\Phi_B}{\Delta t}$$

$$\varepsilon = -5 \times \frac{-2.0 \times 10^{-3}}{0.02777}$$

$$\varepsilon = 0.360 = 0.36\ \text{V}$$

OR

$\varepsilon \propto f$ so if frequency triples so must ε.

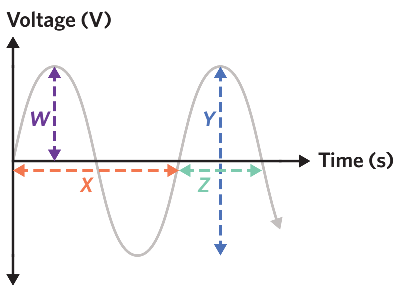
$$\varepsilon_{part\ b} = 3 \times \varepsilon_{part\ a} = 3 \times 0.12 = 0.36\ \text{V}$$

PROGRESS QUESTIONS

Question 7

The diagram shows an AC voltage-time graph with features labelled W, X, Y, Z.

Which row of the table correctly identifies the period and amplitude of the graph?



	Period	Amplitude
A.	X	Y
B.	Z	Y
C.	X	W
D.	Z	W

Continues →

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Question 8

An alternator rotates 30 times per second producing a voltage of 10 V. If its frequency is halved, what is the value of its new amplitude?

A. 5 V **B.** 10 V **C.** 15 V **D.** 30 V

Question 9

Which of the following correctly describes the effect increasing the rotation speed of an alternator has on the frequency, period, and amplitude of the AC voltage produced?

	Frequency	Period	Amplitude
A.	Increase	Decrease	Increase
B.	Increase	Increase	Decrease
C.	Decrease	Increase	Decrease
D.	Decrease	Decrease	Increase

DC generators 3.3.3.2

DC generators (also known as 'dynamos') operate on a similar principle to alternators, however they output **direct current (DC) electricity** to an external circuit through the use of a **split ring commutator**.

How does a DC generator differ from an alternator?

An alternator relies on slip rings (Figure 5a) to maintain a constant connection between the coil and the external circuit. This results in an AC output (Figure 5b). On the other hand, a DC generator (Figure 6) can be created by replacing the slip rings of an alternator with a split ring commutator (Figure 7a).

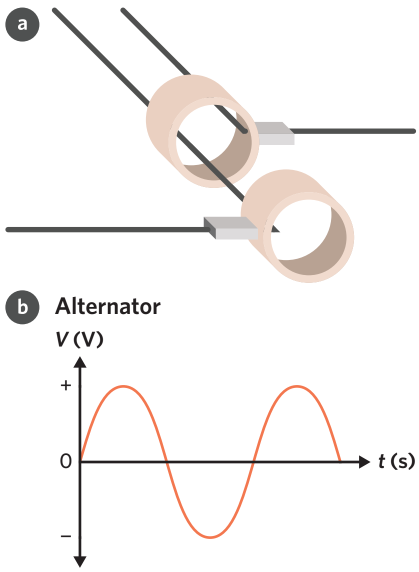

Figure 5 **(a)** Slip rings are used in an alternator to generate **(b)** AC output.

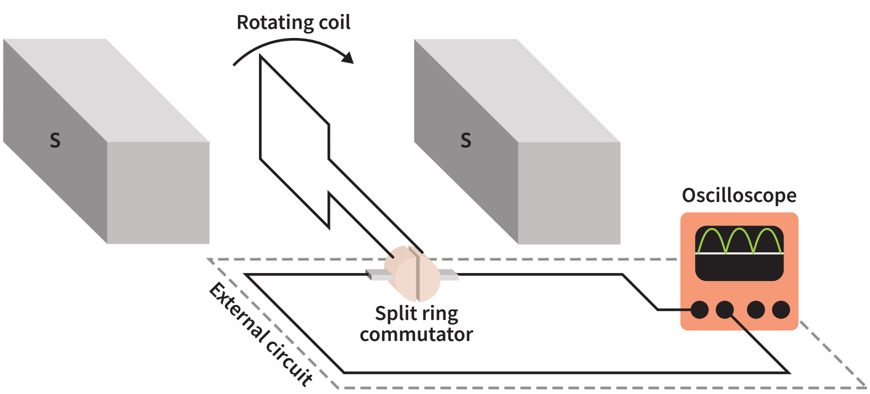

Figure 6 A DC generator with a split ring commutator which reverses the direction of the current when the loop is vertical

The split ring commutator reverses the connection between the rotating coil and the external circuit every half rotation (or twice a revolution). This allows the output voltage to maintain a constant direction. It is important to understand that the output voltage still changes over time, but it always has the same sign, as shown in Figure 7b.[3]

The apparatus of an alternator is similar to a DC generator, which is also similar to a DC motor, however their functions are different. Table 3 summarises the similarities and differences between the three. Note that AC motors are not part of the VCE Physics course.

KEEN TO INVESTIGATE?

[3] **How do you build a generator?**
Search YouTube: Simple explanation of a generator

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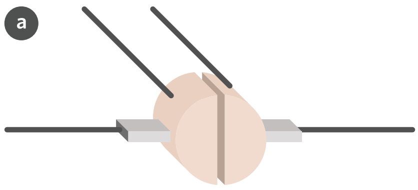
a



b DC generator

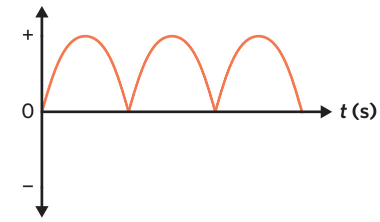


Figure 7 **(a)** A split ring commutator is used in a DC generator to generate **(b)** DC output.

USEFUL TIP

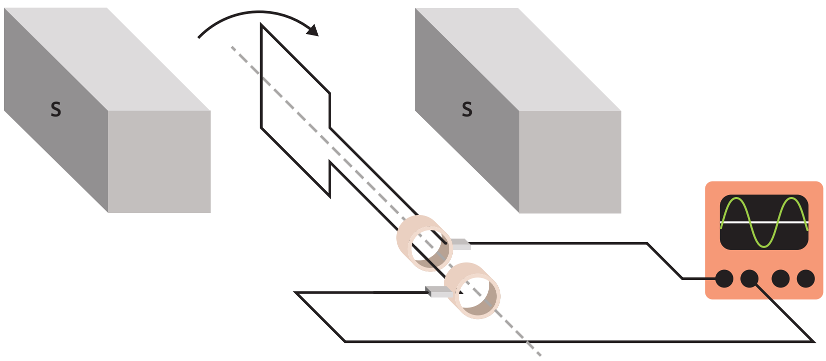
The easiest way to distinguish between slip rings (AC) and split ring commutators (DC) on a diagram of a generator is that slip rings always have two separate rings (Figure 7a) while split rings have one (Figure 7b).

Table 3 The similarities and differences between alternators, DC generators, and DC motors

	Alternator	DC generator	DC motor
Energy transformation	KE → Electrical	KE → Electrical	Electrical → KE
Function	Generate AC electricity	Generate DC electricity	Use electricity to drive movement
Connection between coil and external circuit	Slip rings	Split ring commutator	Split ring commutator
Input	Rotation of coil in one direction	Rotation of coil in one direction	DC electricity
Output	AC electricity	DC electricity	Rotation of coil in one direction

PROGRESS QUESTIONS

Question 10



Which of the following applies to the apparatus? **(Select all that apply)**

A. It has slip rings

B. It is an alternator

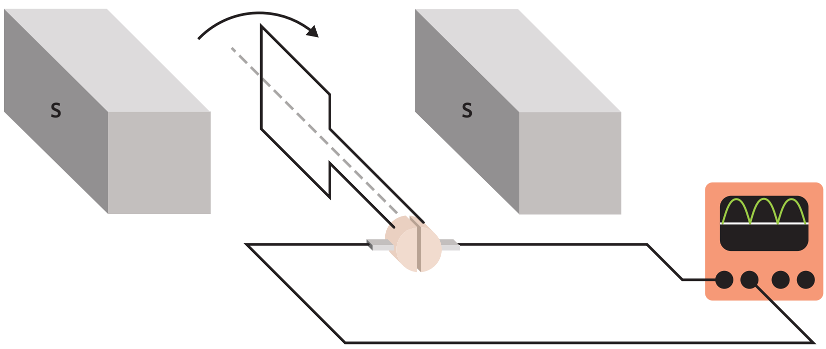
C. It produces AC output

D. It produces DC output

E. It is a DC generator

F. It has a split ring commutator

Question 11



Which of the following applies to the apparatus? **(Select all that apply)**

A. It has slip rings

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C. It produces AC output

D. It produces DC output

E. It is a DC generator

F. It has a split ring commutator

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Theory summary

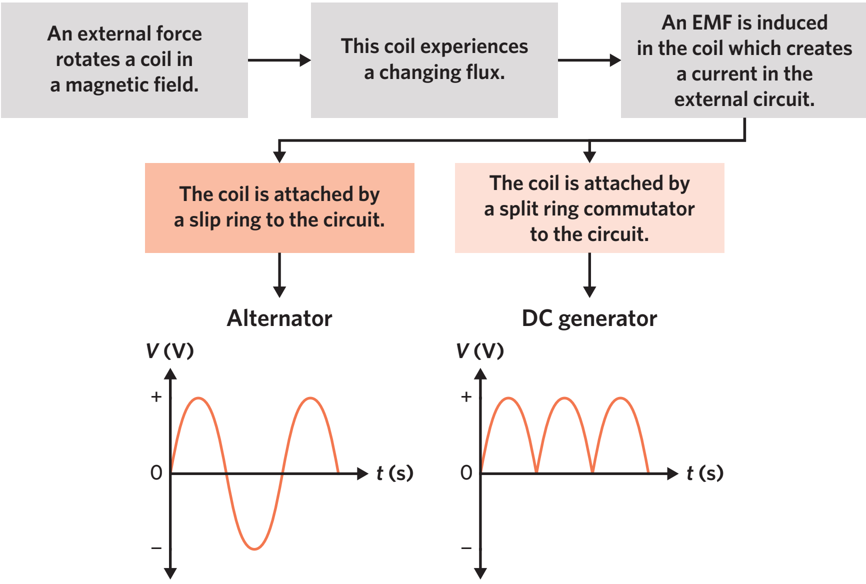


Figure 8 Flow chart summary of alternators and DC generators

- All generators, whether they produce AC or DC, convert kinetic energy to electrical energy.
- The AC voltage produced by an alternator can be characterised in terms of its:
  - amplitude – the magnitude of the output voltage.
  - frequency (f) – the number of cycles completed per second.
  - period (T) – the time for the coil to complete one full cycle.
- The magnitude of the EMF varies in proportion to the frequency.
- The output from the DC generator still varies, but only in one direction.

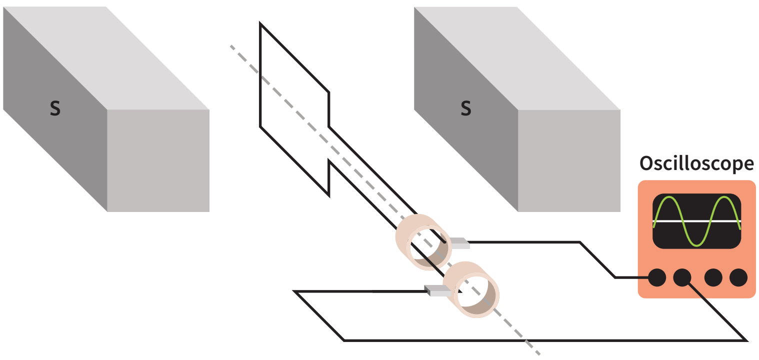
5C Questions

Mild 🌶 Medium 🌶🌶 Spicy 🌶🌶🌶

Deconstructed exam-style

Use the following information to answer questions 12–14.

A square loop of wire with a cross-sectional area of 0.020 m^2 and 30 turns rotates in a magnetic field of strength 4.5×10^{-2} T. The wires of the loop are connected to two slip rings and an oscilloscope, as shown.



The loop takes 0.20 seconds to make a full rotation.

Question 12 🌶 (1 MARK)

Calculate the change in the magnetic flux experienced by the loop as it makes a quarter rotation (from a position perpendicular to the field to a position parallel to the field).

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Question 13 (1 MARK)

Calculate how long it takes the loop to make a quarter rotation (from a position perpendicular to the field to a position parallel to the field).

Question 14 (3 MARKS)

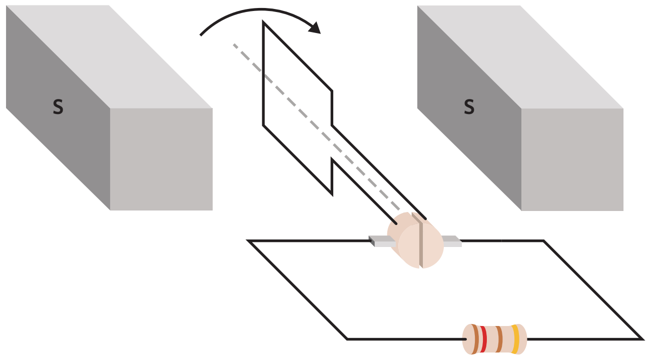
Calculate the average magnitude of the induced EMF in the loop as it makes a quarter rotation (from a position perpendicular to the field to a position parallel to the field). Show your working.

Adapted from VCAA 2019 NHT exam Short answer Q2a

Exam-style

Question 15 (1 MARK)

The diagram shows a simple electrical generator consisting of a wire loop in a magnetic field, connected to an external circuit with a resistor, a split ring commutator, and brushes. The direction of rotation is shown by the arrow.



Which of the following best describes the function of the split ring commutator in the external circuit?

A. It delivers a direct current (DC) to the resistor.

B. It delivers an alternating current (AC) to the resistor.

C. It ensures the force on the side of the loop nearest to the north magnetic pole is always up.

D. It ensures the force on the side of the loop nearest to the north magnetic pole is always down.

Adapted from VCAA 2021 exam Multiple choice Q8

Question 16 (8 MARKS)

Swathi and Javier are investigating the operation of a simple alternator. They rotate the coil at a constant speed within a uniform horizontal magnetic field so that each complete turn takes 20 ms.

a. Calculate the frequency of AC voltage that the alternator will output. 2 MARKS

b. Describe the orientation of the alternator coil when the EMF output has a maximum magnitude. Justify your answer. 2 MARKS

c. Javier is unhappy with the voltage output of the alternator, so Swathi suggests some changes that she believes will increase the amplitude of the EMF output. Copy and complete the table provided to indicate whether each of Swathi's suggestions will increase, decrease, or have no effect on the magnitude of the maximum EMF of the alternator. 4 MARKS

Suggested change	**Effect on EMF amplitude (increase, decrease, no effect)**
Decrease the period of rotation of the coil.	
Decrease the strength of the permanent magnets.	
Increase the number of turns in the coil.	
Increase the area of the coil.	

Adapted from VCAA 2016 exam Short answer Q17

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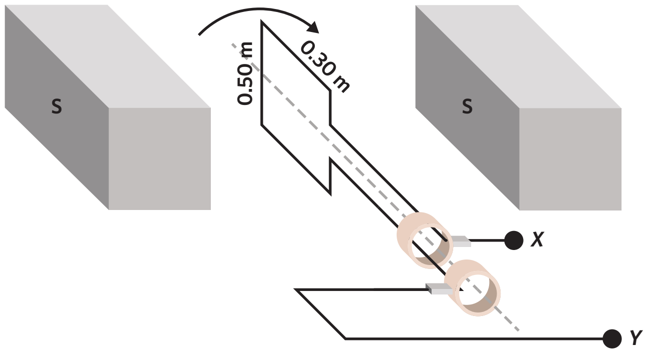
Question 17 (10 MARKS)

An alternator is constructed using a rectangular coil of 20 turns with dimensions 0.30 m × 0.50 m. The coil rotates at a constant speed within a uniform magnetic field such that it completes one full rotation every 0.50 s. The magnetic field strength is 0.090 T.



a. The rectangular loop is rotated clockwise from the vertical position shown. On a single set of axes like the ones provided, draw a graph of the variation in magnetic flux versus time and a graph of the variation in EMF versus time for two full rotations. Clearly label each of the graphs and include a scale on the time axis. No calculations should be completed for your answer. 3 MARKS

b. Calculate the magnitude of magnetic flux passing through one turn when it is in the vertical position shown. 2 MARKS

c. Calculate the frequency of the EMF output. 1 MARK

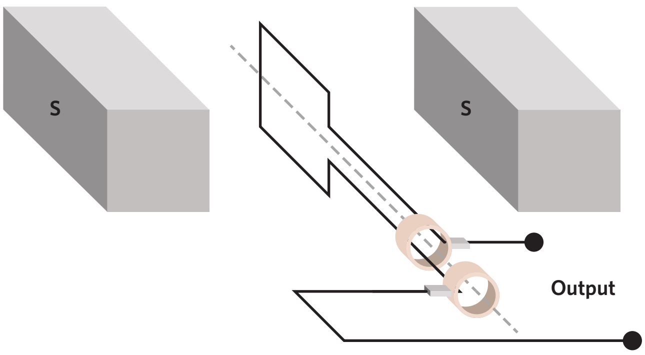
d. Determine the magnitude of the average EMF induced in the coil as it completes one-quarter of a revolution, from the vertical position to the horizontal position. 2 MARKS

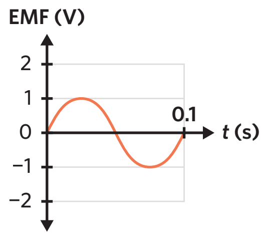
e. Explain the function of slip rings with reference to the output of an alternator. 2 MARKS

Adapted from 2012 VCE Physics Exam 2 Section A AoS 1 Q7

Question 18 (1 MARK)

A simple generator is shown in the diagram. The induced EMF across the slip rings is measured when the coil is rotated. The graph shows how the induced EMF varies with time.

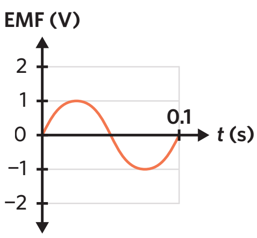




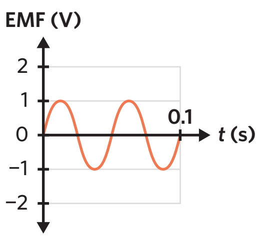
The generator is now rotating at twice the rate.

Which one of the following graphs best represents the induced EMF?

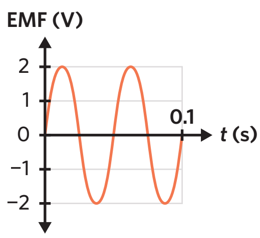
A.



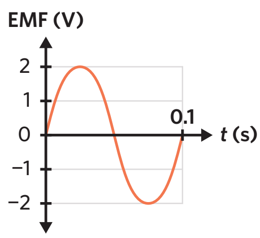
B.



C.



D.



Adapted from VCAA 2022 exam Multiple choice Q5

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Question 19 (10 MARKS)

Students measure the voltage output, at 0.5 second intervals, when a coil rotates uniformly inside a constant magnetic field. The voltage measurements have an uncertainty of ±0.5 V. Assume the uncertainty in measured time is negligible.

Time (s)	0.0	0.5	1.0	1.5	2.0	2.5	3.0	3.5	4.0	4.5	5.0	5.5	6.0
Voltage output (V)	7.6	5.3	0.2	5.8	7.7	6.0	0.3	5.7	8.1	5.7	0.1	5.9	8.0

a. *Key science skill*

Plot a graph of the voltage output on the vertical axis against time on the horizontal axis.

On your graph: 6 MARKS

- Include axis titles and units.
- Choose an appropriate scale and numbers for both axes.
- Include uncertainty bars in the vertical direction only.
- Draw an appropriate non-linear line of best fit.

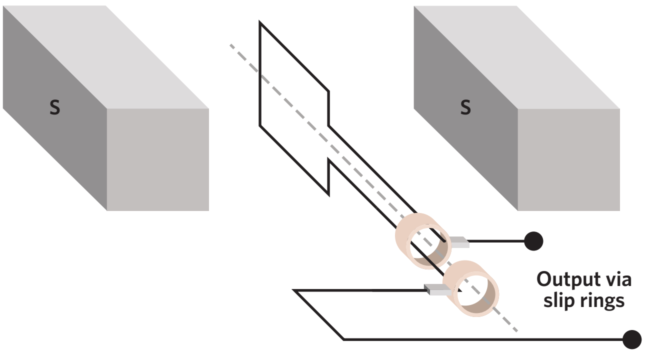
FROM LESSON 12D

b. Determine the frequency of rotation of the coil. 2 MARKS

c. Identify whether the coil was connected to the external circuit via slip rings or a split ring commutator. Explain your answer. 2 MARKS

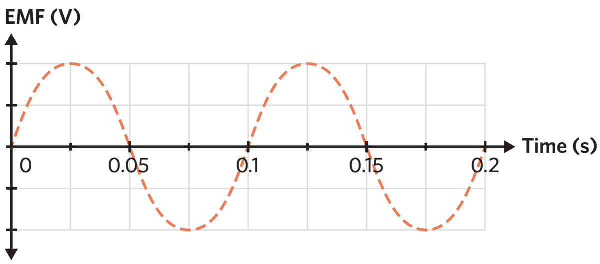
Question 20 (5 MARKS)

An alternator consists of a square coil of five turns connected to slip rings. It completes 10 full cycles per second. The loop is entirely within an external magnetic field of strength 8.0×10^{-3} T.



a. The magnitude of the average EMF induced in the coil as it completes a one-quarter turn, from a vertical position to a horizontal position, is 1.6 V. Determine the side length of the square coil in centimetres. 4 MARKS

b. The EMF-time graph below shows the output of the alternator for two complete rotations.



Sketch the voltage output for two complete rotations if the slip rings were replaced with a split ring commutator. 1 MARK

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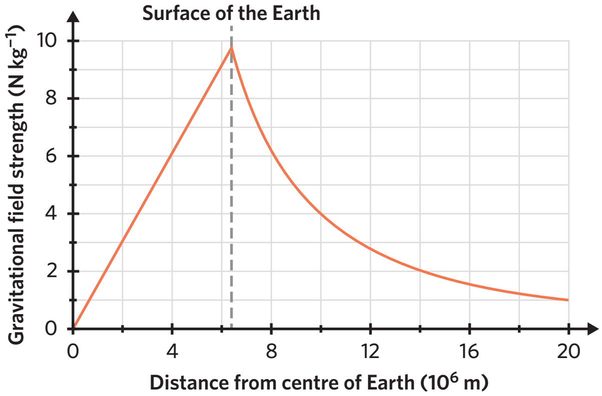
Previous lessons

Question 21 (5 MARKS)

Melon Husk launched his car from the surface of the Earth into space. Assume the car has a mass of 1300 kg and that it travelled to a distance of 20×10^6 m from the centre of the Earth.



a. What is the increase in gravitational potential energy of Melon Husk's car on this journey? 🌶🌶 3 MARKS

b. Calculate the decrease in gravitational potential energy for the car if Melon Husk were somehow able to drive it from the surface to the centre of the Earth. Assume Earth is a sphere with a uniform density and a radius of 6.37×10^6 m. 🌶🌶 2 MARKS

Adapted from VCAA 2019 exam Short answer Q4c

FROM LESSON 2C

Question 22 (4 MARKS)

Electrons travelling at 2.5×10^7 m s^{-1} enter a region of uniform magnetic field of strength $B = 8.0 \times 10^{-2}$ T that is at right angles to their path.

a. Calculate the magnitude of the force on each electron. 🌶🌶 2 MARKS

b. Describe the path of the electrons in this region of uniform magnetic field. Justify your answer. 🌶🌶 2 MARKS

Adapted from VCAA 2019 NHT exam Short answer Q1b–c

FROM LESSON 4B

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5D Photovoltaic cells

STUDY DESIGN DOT POINT

- describe the production of electricity using photovoltaic cells and the need for an inverter to convert power from DC to AC for use in the home (not including details of semiconductors action or inverter circuitry)

5A 5B 5C 5D

3.3.4.1 Photovoltaic cells for use in the home

ESSENTIAL PRIOR KNOWLEDGE

- DC circuits
- Series and parallel circuits

See questions 58–59.

Image: anatoliy_gleb/Shutterstock.com

Could solar panels power the whole world?

Solar panels use energy from the Sun to generate electricity. Covering 1% of the Sahara desert in solar panels would provide enough electricity to power the world. However, modern electrical grids are designed to run on AC so powering the world with solar panels would require changes to our electrical grid.

KEY TERMS AND DEFINITIONS

photovoltaic (PV) cell a device that converts light energy into electrical energy

semiconductor a material that can be modified to control how it conducts electricity

solar panel an array of photovoltaic cells connected to produce a desired voltage and current

inverter a device that converts direct current (DC) into alternating current (AC)

Photovoltaic cells for use in the home 3.3.4.1

Photovoltaic (PV) cells convert light energy into electrical energy. They can be connected in series or parallel to achieve a desired voltage or current. Because of their scalability and lack of reliance on fossil fuels, PV cells are used to power a wide range of devices from toys and drones to homes and satellites.

USEFUL TIP

'Photo' comes from the Greek word for light, and 'voltaic' comes from the surname of Alexandra Volta, the inventor of the battery. So when put together, photovoltaic means light battery.

How do photovoltaic cells produce electricity?

PV cells are made from four main layers:

- an antireflection layer to maximise the amount of light transmitted to the **semiconductors**
- an n-type semiconductor layer treated to absorb light and release electrons
- a p-type semiconductor layer treated to attract electrons
- front and back electrical contacts that allow electrons to flow and complete the circuit.

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Figure 1 shows the construction of these layers and how they work together to produce electricity.

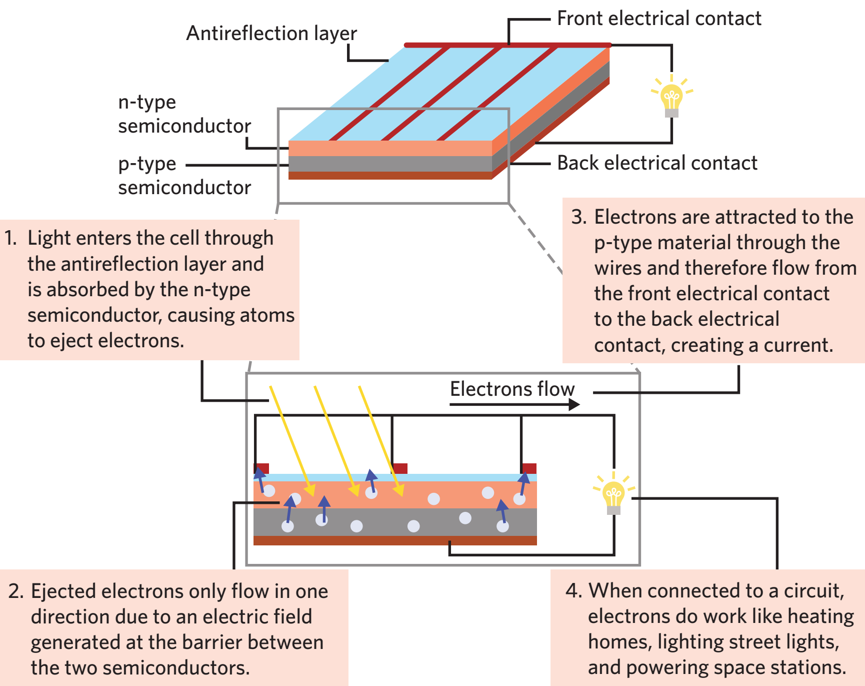

Figure 1 An array of photovoltaic cells connected to produce a desired voltage and current, as well as the different layers of a photovoltaic cell and how they produce electricity.

PV cells produce direct current (DC) because the electric field generated by the semiconductors forces electrons to flow in one direction. This makes them ideal for providing electricity to remote locations where installing conventional power sources would be impractical or expensive. PV cells also have no moving parts and do not require any fuel source other than the sun, making them suitable for use on satellites and space stations.

USEFUL TIP

The n- and p-type semiconductors get their names from negative and positive. The n-type layer can be thought of as the negative terminal of a battery while the p-type semiconductor can be thought of as the positive terminal of a battery.

PROGRESS QUESTIONS

Question 1

Which of the following is not a layer in a photovoltaic cell?

A. antireflection layer **B.** light emitting layer **C.** n-type semiconductor **D.** p-type semiconductor

Question 2

The purpose of the front and back electrical contacts is to

A. hold the PV cell together.
B. form a path for electrons to flow.
C. eject electrons after absorbing light.
D. attract electrons away from the semiconductors.

Question 3

Circle the correct terms to complete the paragraph.

Ejected electrons are (attracted to / repelled by) the (n-type / p-type) semiconductor and flow from the (front / back) electrical contact to the (front / back) electrical contact.

How do photovoltaic cells form solar panels?

A single PV cell produces around 0.5 V when exposed to sunlight. This is fine for powering small devices and toys, but is insufficient to power anything larger. In order to make PV cells useful on a large scale, they need to be connected together in series or parallel:

- Connecting PV cells in series increases the voltage while keeping the current constant (Figure 2a).
- Connecting PV cells in parallel increases the current while keeping the voltage constant (Figure 2b).

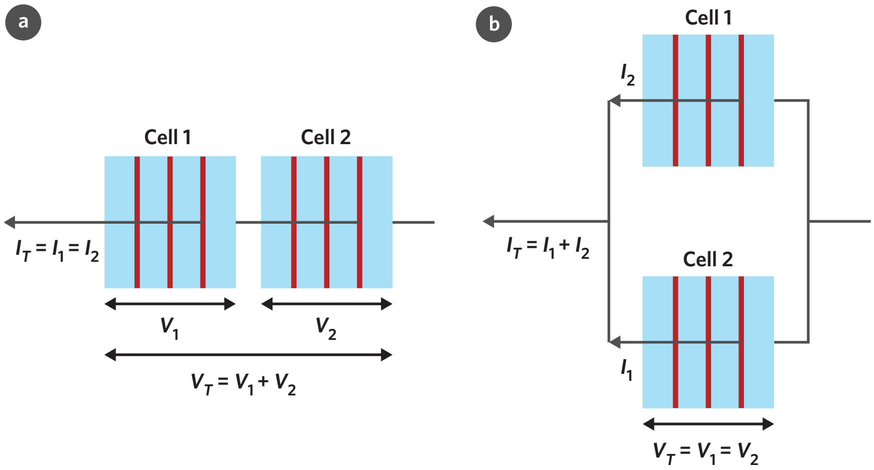

Figure 2 How photovoltaic cells combine in **(a)** series and **(b)** parallel arrangements

In order to generate enough power for commercial and industrial use, PV cells are grouped into modules (Figure 3). The cells in a module are connected in a combination of series and parallel arrangements to achieve a desired voltage and current:

- Cells connected in series form branches – the number of cells in a branch determines the output voltage, V_{out}, of the module.
- Branches are connected in parallel to complete the module – the number of branches in a module determines the output current, I_{out}, of the module.

By varying the number of cells and branches, modules can be designed to output almost any desired voltage and current.

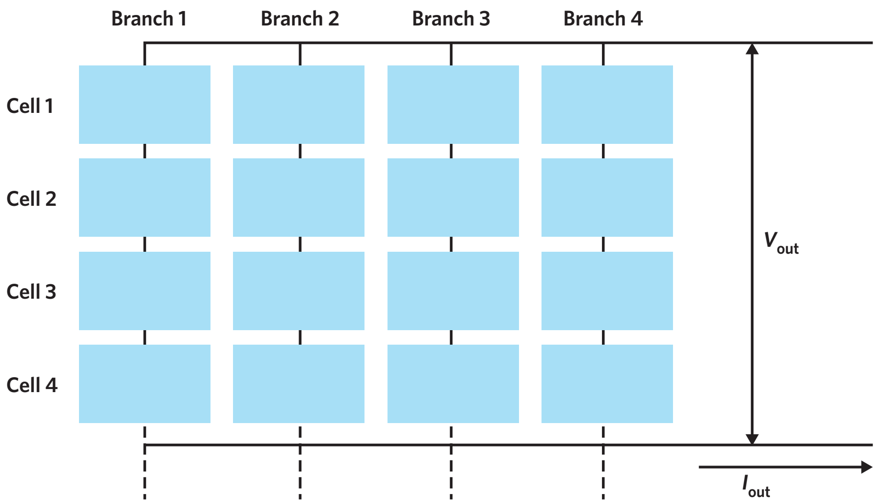

Figure 3 PV cells combine with different series and parallel arrangements to form solar modules.

In the same way PV cells are connected to form modules, any number of modules can be connected to form **solar panels** (Figure 4). In order to provide enough power for a home or industrial building, multiple solar panels are connected to form a solar array – these are the structures you typically see on the rooftops of buildings (Figure 5).

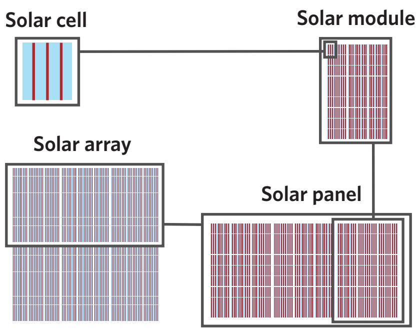

Figure 4 How PV cells and modules combine to form larger solar installations

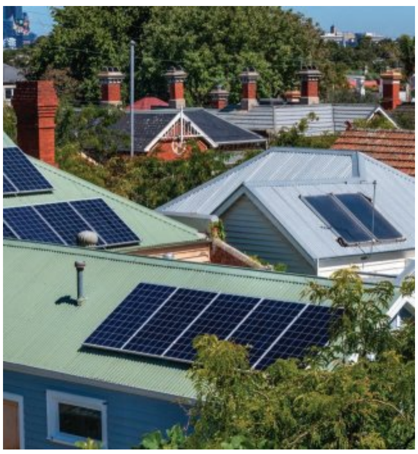

Image: Adam Calaitzis/Shutterstock.com

Figure 5 Common rooftop solar configurations

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PROGRESS QUESTIONS

Question 4

Connecting PV cells in parallel

A. increases the efficiency of each cell.

B. increases both the voltage and the current.

C. increases the voltage while keeping the current constant.

D. increases the current while keeping the voltage constant.

Question 5

Which of the following is not true of modules?

A. They can be combined to form PV cells.

B. They can be combined to form larger solar installations.

C. They can be designed to output a large range of voltages and currents.

D. They are a group of PV cells connected in a combination of series and parallel.

Why do we need inverters to use solar power?

While solar installations provide a renewable source of DC power that can be scaled to suit almost any application, integrating them into our existing electrical grids requires the use of an **inverter**.

Historically, most of our electricity has been generated through electromagnetic induction in turbines, meaning our modern electrical grids are designed to run on AC.[1] An inverter (Figure 6) converts DC electricity generated by solar installations into AC electricity that can be fed into our electrical grid and used to power our homes (Figure 7).

KEEN TO INVESTIGATE?

1 **Why do our electrical grids run on AC?**
Search YouTube: The war of the currents: Thomas Edison vs. George Westinghouse

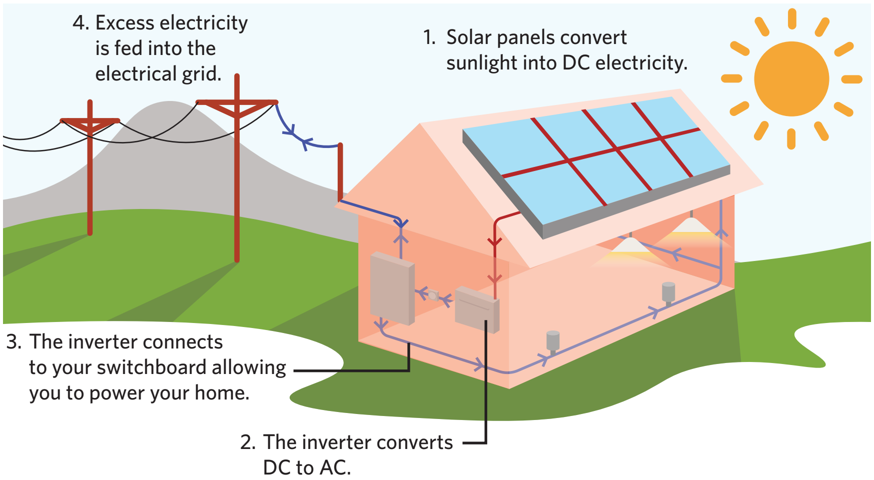

Figure 7 An inverter integrates electricity from solar panels into the existing grid.

Image: Douglas Cliff/Shutterstock.com

Figure 6 A solar inverter installed in a residential home

PROGRESS QUESTIONS

Question 6

PV cells convert sunlight into

A. AC electricity.

B. DC electricity.

C. light electricity.

D. static electricity.

Continues →

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Question 7

An inverter is used to convert

A. DC to AC.

B. AC to DC.

C. light to electricity.

D. p-type semiconductors to n-type semiconductors.

Theory summary

- Photovoltaic (PV) cells are made from four layers of different materials:
  - an antireflection layer
  - a n-type semiconductor layer
  - a p-type semiconductor layer
  - front and back electrical contacts.
- PV cells produce electricity through the following process:

1. Sunlight passes through the antireflection layer and is absorbed by the n-type semiconductor.	→	**2. Electrons are ejected and forced to travel in one direction by an electric field.**	→	**3. The electrons are attracted to the p-type material and travel from the front electrical contact to the back electrical contact.**

- PV cells can be connected in series and parallel to form larger solar installations like solar modules, solar panels, and solar arrays.
- An inverter converts DC to AC and is needed to connect a rooftop solar installation to the electrical grid.

5D Questions

Mild 🌶 Medium 🌶🌶 Spicy 🌶🌶🌶

Deconstructed exam-style

Use the following information to answer questions 8–11.

Solar panels are made from a collection of photovoltaic (PV) cells connected in series and parallel. These convert sunlight into electricity.

Question 8 🌶 (1 MARK)

When light enters a PV cell, it

A. is mostly absorbed by the antireflection layer.

B. is absorbed by the electrons in the p-type semiconductor.

C. passes through the semiconductors to the back electrical contact.

D. is absorbed by the n-type semiconductor causing atoms to eject electrons.

Question 9 🌶 (1 MARK)

State the purpose of the electric field generated at the barrier between the two semiconductors.

Question 10 (1 MARK)

Electricity can be defined as

A. electrons.

B. the flow of charge.

C. a force that powers electrical devices.

D. energy that can only come from batteries.

Question 11 (4 MARKS)

Describe how photovoltaic cells convert sunlight into electricity.

Exam-style

Question 12 (1 MARK)

The purpose of the antireflection layer is to

A. eject electrons.

B. reflect sunlight.

C. absorb sunlight.

D. transmit sunlight.

Question 13 (2 MARKS)

Why do rooftop solar installations require an inverter to connect them to homes?

Question 14 (8 MARKS)

Rui is trying to build a module using PV cells, and investigating the effects of increasing the number of cells connected in series has on the module's output. Each cell has an output voltage of 1.5 V and an output current of 0.7 A. He connects two cells in series and measures the output voltage and output current. He repeats this process connecting an extra cell in series, until he has 5 cells connected. His data is shown in the table.

Number of PV cells	Output voltage (V)	Output current (A)
0	0	0
1	1.62	0.72
2	3.33	0.70
3	4.43	0.71
4	6.03	0.69
5	7.51	0.70

a. *Key science skill*
Identify the independent variable of Rui's investigation. 1 MARK

b. *Key science skill*
Rui determines the uncertainty of the output voltage to be ± 0.2 V. Plot a graph of output voltage vs. number of PV cells making sure you include: 6 MARKS

- appropriate scales
- axis titles
- units for each axis
- a line of best fit
- appropriate uncertainty bars

c. Explain why the output current did not increase as Rui increased the number of PV cells. 1 MARK

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Question 15 🌶🌶🌶 (3 MARKS)

Phil and Elie are arguing over who generates more power from their rooftop solar installations. Phil argues that because he has more panels he must be generating more power. Elie argues that his inverter has a higher power reading so he must be generating more. Who is correct? Justify your answer.

Question 16 🌶🌶🌶 (2 MARKS)

The international space station (ISS) is powered by a solar array consisting of 262 400 PV cells. The cells take up a total space of 2500 m^2 and power everything on the station. Identify whether the ISS would need an inverter to use the electricity generated by the PV cells. Justify your answer.

Previous lessons

Question 17 🌶 (1 MARK)

The Moon orbits the earth in a nearly circular path. Which of the following correctly describes the direction of the centripetal force?

A. outwards

B. downwards

C. tangential to the moons orbit

D. towards the centre of the Earth

FROM LESSON 1E

Question 18 🌶 (2 MARKS)

A car of mass 1200 kg is travelling at 30 km h^{-1}. What is its kinetic energy?

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Chapter 5 review

Mild 🌶 Medium 🌶🌶 Spicy 🌶🌶🌶

These questions are typical of one hour's worth of questions on the VCE Physics Exam.

Total marks: 50

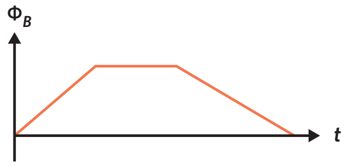
Section A

All questions in this section are worth one mark.

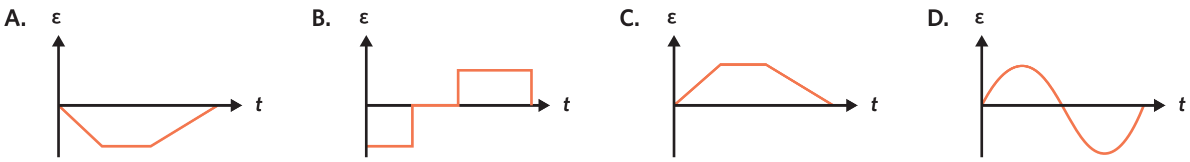
Unless otherwise indicated, the diagrams in this book are not drawn to scale.

Question 1 🌶

The graph shows the magnetic flux through a coil of wire over time.



Which of the following graphs shows the resulting EMF within the coil of wire over time?



Adapted from VCAA 2017 exam Multiple choice Q6

Question 2 🌶

The owner of a Commodore wishes to power a mini-fridge on the passenger seat of his car so he can store refreshing beverages at the worksite. To do this the voltage output of the car's alternator must be increased. Which of the following changes would increase the alternator voltage?

A. using stronger magnets in the alternator

B. reducing the area of the alternator's coils

C. reducing the number of loops in the alternator

D. increasing the period of rotation of the alternator

Question 3 🌶🌶

Key science skill

Physics students Kath and Kim are investigating the concept of electromagnetic induction and use a DC generator in their experiment. They measure the peak EMF produced in the generator by changing the strength of the magnetic field using electromagnets. Which of the following options best identifies the independent, dependent, and a possible controlled variable in Kath and Kim's experiment?

	Independent variable	Dependent variable	Controlled variable
A.	Period of rotation	Peak EMF	Strength of the magnetic field
B.	Strength of the magnetic field	Period of rotation	Peak EMF
C.	Strength of the magnetic field	Peak EMF	Period of rotation
D.	Peak EMF	Strength of the magnetic field	Strength of the magnetic field

FROM LESSON 12A

Adapted from VCAA 2018 exam Multiple choice Q20

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Question 4

Which of the following statements best describes what happens when light is incident on a photovoltaic cell?

A. Light moves through the circuit powering devices in your home.

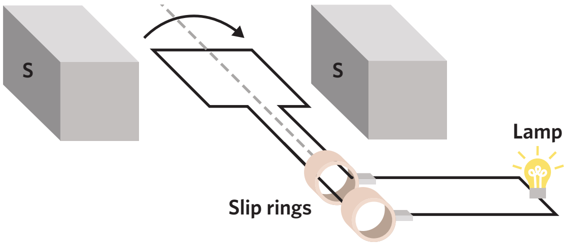
B. Light is absorbed by a semiconductor, causing atoms to eject electrons.

C. Light reflects off the solar panel and heats up a separate device which generates electricity.

D. Light is absorbed by the solar panel causing it to heat up. This is used to heat water which is then used to generate electricity.

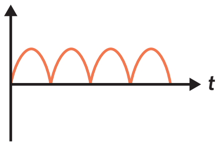
Question 5

The diagram depicts a generator being used to power a lamp.

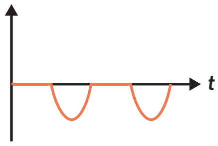


Which of the following graphs correctly shows how the output voltage of the generator varies as a function of time?

A.

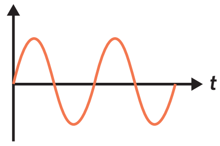


B.



C.

D.



Section B

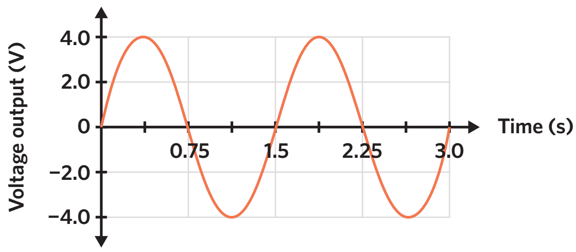
In questions where more than one mark is available, appropriate working must be shown.

Unless otherwise indicated, the diagrams are not drawn to scale.

Question 6 (3 MARKS)

Use the graph, which shows the output of a simple AC alternator, to complete the accompanying table.

Property	Value (with units)
Period	
Amplitude	
Frequency	



Question 7 (5 MARKS)

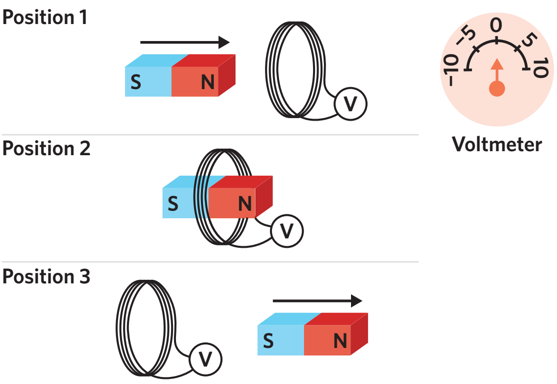
An apartment block installs solar panels on their roof and disconnects their connection to the main electricity grid. They calculate that the solar panels should generate enough electricity to power the whole apartment block.

a. Describe the production of electricity using photovoltaic cells. 3 MARKS

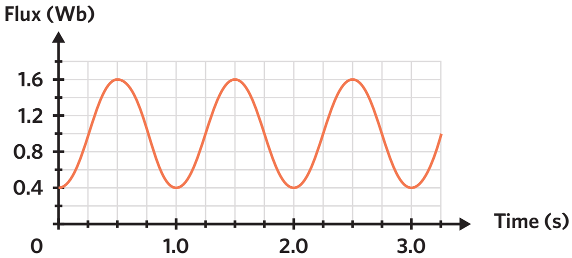
b. The apartments find that their household appliances no longer work as they used to. Identify what additional electrical infrastructure is required to allow photovoltaic cells to work within the home and provide a reason why this is the case. 2 MARKS

Question 8 (12 MARKS)

In Luke's backyard, three friends are goofing around with a bar magnet and a coil that has 4 loops of wire. They connect a voltmeter to the coil and oscillate the magnet from position 1 to position 3 and then back again.



The friends decide to calculate and graph magnetic flux as a function of time, as shown in the graph.



a. Calculate the magnitude of the average current through the coil between 2.0 s and 2.5 s. The resistance of the coil is known to be 0.80 Ω. 🌶🌶🌶 3 MARKS

Adapted from VCAA 2013 exam Short answer Q17a

b. Use the information from the graph to determine the times between $t = 0$ s and before $t = 3.0$ s when the magnitude of the EMF around the coil will be a maximum. 🌶 2 MARKS

Adapted from VCAA 2013 exam Short answer Q17b

c. When the bar magnet is moved from position 1 to position 2, a current is induced in the coil. Describe the direction of the current when viewed from the right (a diagram may be helpful). Explain your answer. 🌶🌶🌶 4 MARKS

Adapted from VCAA 2013 exam Short answer Q17c

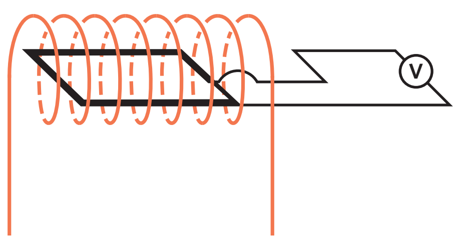
d. Using the previous graph, complete the table to identify all the times between $t = 0$ s and before $t = 3.0$ s the magnet is at position 1, position 2, and position 3. At $t = 0$ s, the magnet is in position 1. 🌶🌶 3 MARKS

Position of the magnet	Time (s)
Position 1	
Position 2	
Position 3	

Adapted from VCAA 2013 exam Short answer Q17d

Question 9 🌶🌶 (2 MARKS)

A square loop of wire connected to a voltmeter is placed inside of a solenoid. The square is comprised of 6 loops of wire and has an area of 0.10 m^2. The square loop is moved from outside of the solenoid to the inside in 0.25 s where there is a magnetic field of 300 mT.



What is the value of the magnetic flux passing through the square loop of wire? Explain your answer.

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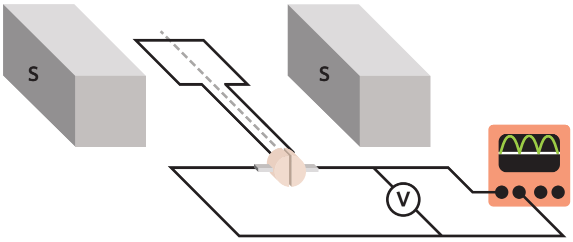
Question 10 (15 MARKS)

The DC generator in the diagram is comprised of a rectangular coil with 5 turns and sides 20 cm × 30 cm. The flux through the coil when in a vertical position is 0.15 Wb and it rotates 8.0 times every second.



a. Calculate the strength of the uniform magnetic field. 2 MARKS

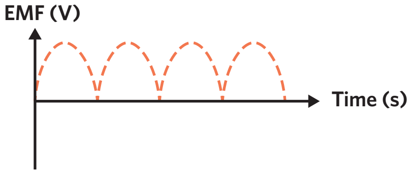
b. What is the magnitude of the average EMF generated in the coil during a quarter rotation from a horizontal position to a vertical position? 3 MARKS

c. Describe how the magnetic flux through the coil changes as it completes one revolution from the horizontal position. 4 MARKS

d. Identify which orientation(s) of the coil during its rotation corresponds to the maximum EMF produced. Explain your answer. 2 MARKS

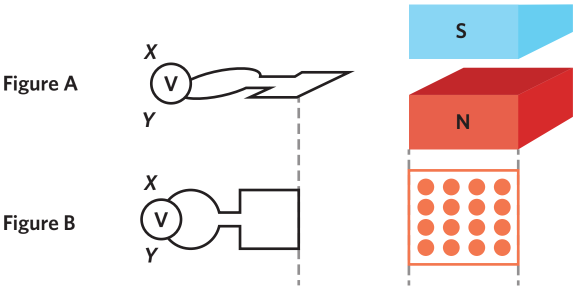
e. Explain how the generator can be changed to produce an AC output. 2 MARKS

f. A graph of the output for the DC generator is shown with a dotted line. The split ring commutator is replaced with slip rings. On a copy of this diagram, use a solid line to draw the output of the generator. 2 MARKS



Question 11 (8 MARKS)

A square loop of wire passes through two magnets at a constant speed in order to investigate electromagnetic induction. Figure B shows the apparatus when viewed from above. Consider the magnetic field as being confined to the space between the two magnets.



a. Sketch the magnetic flux versus time graph for this scenario. Begin with the loop completely outside the magnetic field and finish with the entire loop having exited the magnetic field. 2 MARKS

b. Sketch the EMF versus time graph for this scenario. Begin with the loop completely outside the magnetic field and finish with the entire loop having exited the magnetic field. 2 MARKS

c. As the loop enters the magnetic field, determine the direction that the current passes through the voltmeter, either from *X* to *Y* or from *Y* to *X*. Explain your answer. 4 MARKS

Adapted from VCAA 2015 exam Short answer Q13

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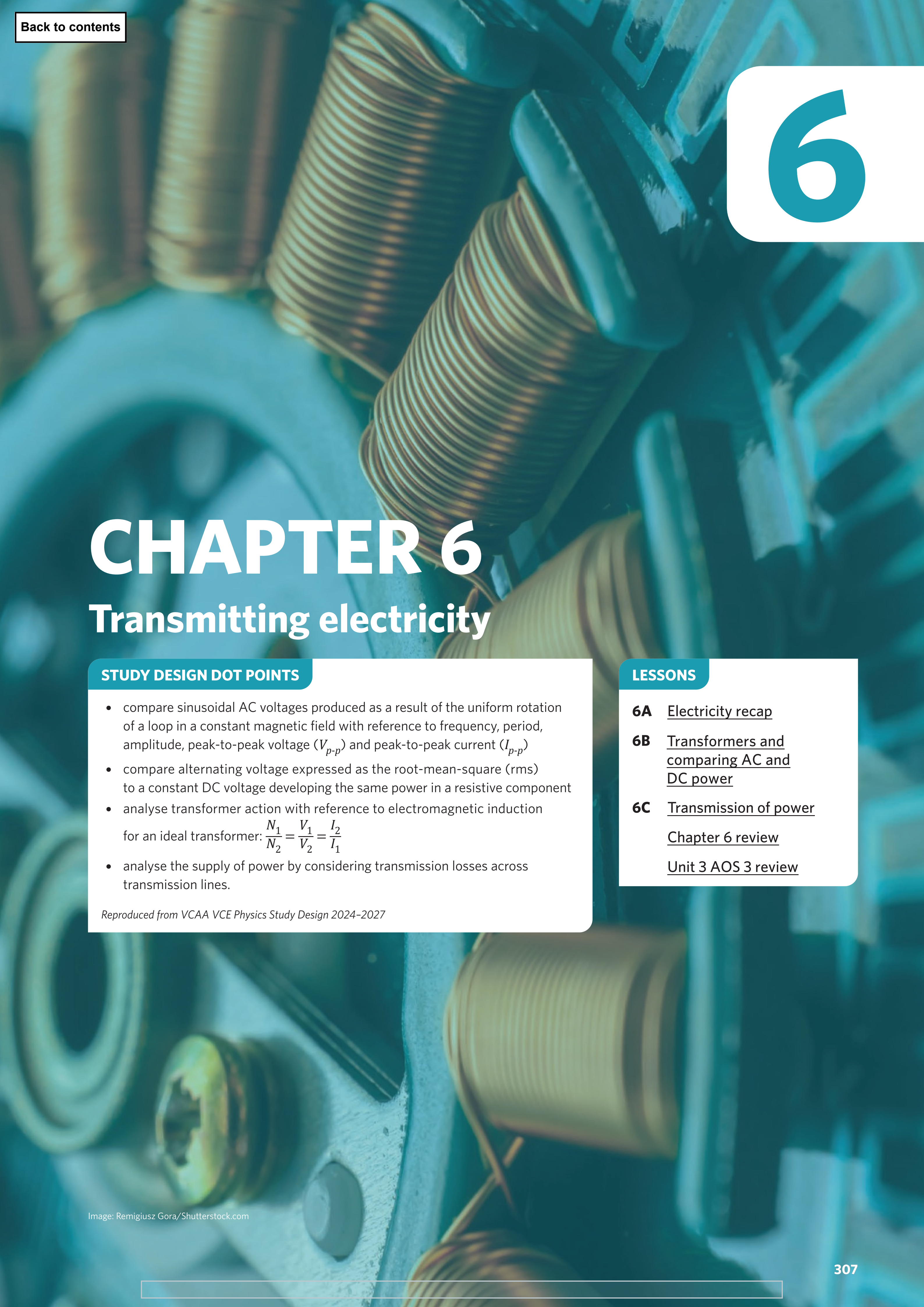

6

CHAPTER 6

Transmitting electricity

STUDY DESIGN DOT POINTS

- compare sinusoidal AC voltages produced as a result of the uniform rotation of a loop in a constant magnetic field with reference to frequency, period, amplitude, peak-to-peak voltage ($V_{p\text{-}p}$) and peak-to-peak current ($I_{p\text{-}p}$)
- compare alternating voltage expressed as the root-mean-square (rms) to a constant DC voltage developing the same power in a resistive component
- analyse transformer action with reference to electromagnetic induction for an ideal transformer: $\frac{N_1}{N_2} = \frac{V_1}{V_2} = \frac{I_2}{I_1}$
- analyse the supply of power by considering transmission losses across transmission lines.

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LESSONS

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6A Electricity recap

STUDY DESIGN DOT POINT

- There are no study design dot points for this lesson.

6A 6B 6C

1.3.1.2 & 1.3.3.1 & 1.3.6.1 & 1.3.6.2 Electrical quantities and Ohm's law

1.3.1.1 & 1.3.4.1 & 1.3.6.3 & 1.3.10.1 Circuit components and behaviour

What can be used to measure the power delivered by a power station?

The watt can be used to measure the power delivered by a power station. Electrical quantities, such as electrical power, potential difference, and current, can all be related to one another to predict the behaviour of an electrical circuit. This lesson covers electrical quantities, Ohm's law, circuit components, series circuits, and electric power. The content in this lesson is considered fundamental prior knowledge for Unit 3 and can be used as revision or to bridge understanding for students who have not studied Unit 1 Physics.

KEY TERMS AND DEFINITIONS

voltage a measure of the difference in electric potential energy between two points

current the rate of flow of electric charge, measured in amperes

resistance a measure of the opposition to the flow of electric current

resistor an electrical component that resists the flow of electric current and causes a drop in voltage

potential difference see voltage

series circuit an electric circuit where there is only one pathway for current to flow

parallel circuit an electric circuit where there are multiple pathways for current to flow

FORMULAS

- **Ohm's law**
  $V = IR$
- **power (electricity)**
  $P = VI = I^2R = \frac{V^2}{R}$
- **resistors in series**
  $R_{eq} = R_1 + R_2 + ... + R_n$

Electrical quantities and Ohm's law 1.3.1.2 & 1.3.3.1 & 1.3.6.1 & 1.3.6.2

There are many different electrical quantities that can be used to measure and predict the behaviour of an electrical circuit. Ohm's law defines the relationship between the **voltage** across an electrical component, the **current** through the component, and the **resistance** of the component.

How can we measure electricity?

Electricity is the flow of charge and is used to power everything from toy cars to cities and continents. The simplest electric circuit consists of a power supply, conducting wires, and a **resistor**.

Table 1 summaries common electrical quantities used in our investigation of electrical circuits.

Table 1 Electrical quantity summary

Electrical quantity	Symbol	Unit of measurement	Physical interpretation
Charge	Q	Coulombs (C)	A property of matter that allows it to experience a force in an electric field
Current	I	Amps (A)	The amount of charge moving past a point in an electrical circuit every second
Voltage (potential difference)	V	Volts (V)	The difference in electric potential energy between two points in a circuit
Resistance	R	Ohms (Ω)	A measure of the opposition to the flow of electric current
Power	P	Watts (W)	The rate at which energy is delivered or dissipated

Ohm's law (Figure 1) provides the basis of circuit analysis:

FORMULA

$$V = IR$$

V = voltage/potential difference (V)
I = current (A)
R = resistance (Ω)

USEFUL TIP

We often refer to current as running 'through' an electrical component or circuit, and voltage gained or dropped 'across' an electrical component, as current is the flow of charge and charges gain or lose energy as they pass across electrical components.

USEFUL TIP

In physics we consider the direction of conventional current, which flows from the positive terminal to the negative terminal of the voltage source. This is the opposite direction to the motion of electrons in the electrical circuit.[1]

KEEN TO INVESTIGATE?

1 **Why do we use conventional current?**
Search YouTube: Difference between electron current and conventional current

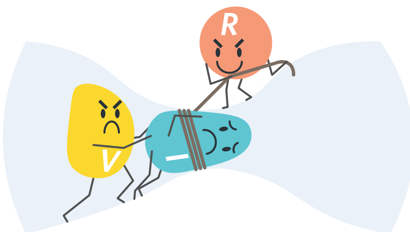

Figure 1 A representation of Ohm's law

WORKED EXAMPLE 1

A resistor, of resistance 5.0 Ω, has a current of 2.0 A through it. Calculate the voltage drop across the resistor.

Step 1

Identify known and unknown variables and write down the formula that relates these variables.

$I = 2.0$ A, $R = 5.0$ Ω, $V = ?$

$V = IR$

Step 2

Substitute values into the formula and solve for the voltage drop across the resistor.

$V = 2.0 \times 5.0$

$V = 10.0 = 10$ V

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PROGRESS QUESTIONS

Question 1

Which electrical quantity can be used to measure the number of electrons running through a circuit?

A. power **B.** charge **C.** current **D.** resistance

Question 2

Which electrical quantity can be used to measure the amount of electrical energy a charge in a circuit has?

A. power
B. current
C. resistance
D. voltage (potential difference)

Question 3

The correct form of Ohm's law is

A. $V = \frac{I}{R}.$ **B.** $I = VR.$ **C.** $V = IR.$ **D.** $R = \frac{I}{V}.$

Question 4

3.0 A of current runs through a resistor. There is a potential difference of 2.0 V across the resistor. What is its resistance?

A. 0.33 Ω **B.** 0.67 Ω **C.** 1.5 Ω **D.** 6.0 Ω

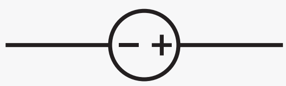
Circuit components and behaviour 1.3.1.1 & 1.3.4.1 & 1.3.6.3 & 1.3.10.1

VCE Physics Unit 1 introduced us to electrical circuit components, type of circuits, and circuit analysis.

How can we model and predict the behaviour of series circuits?

Table 2 shows a number of different electrical components we use to model electrical circuits.

Table 2 Electrical component summary

Electrical component	Diagram	Purpose
Wire		• Allows charge to flow between electrical components • Is assumed to have no resistance, unless otherwise stated in the question
DC voltage source (can consist of one or multiple cells)	 OR  OR 	• Supplies DC electricity to a circuit

Continues →

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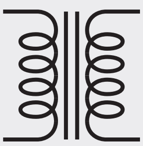
Table 2 Continued

Electrical component	Diagram	Purpose
AC voltage source		• Supplies AC electricity to a circuit. This will be explored further in Lesson 6B.
Resistor	 OR 	• Can be used to model electrical components such as light bulbs • Converts electrical energy into other forms of energy, such as heat and light
Light bulb	 OR 	• Converts electrical energy into light and heat
Switch		• Allows electricity to flow when closed • Stops electricity flowing when open
Voltmeter		• Measures the voltage (potential difference) across a component • Must be connected in parallel to the component across which voltage is being measured
Ammeter		• Measures the current at a point in an electrical circuit • Must be connected in series with the component through which current is being measured
Transformer		• Steps the current or voltage up or down depending on the ratio of turns of wire • The operation and purpose of a transformer will be explored in Lesson 6B

Series circuits are circuits where all components are connected one after the other by a single wire (Figure 2).

The total equivalent resistance is the total resistance the circuit experiences – this can be thought of as replacing all the electrical components in the circuit with just one resistor with an equivalent resistance. In a series circuit, it is equivalent to the sum of all the resistors' individual resistances.

$$R_T = R_{eq} = R_1 + R_2 + \ldots + R_n$$

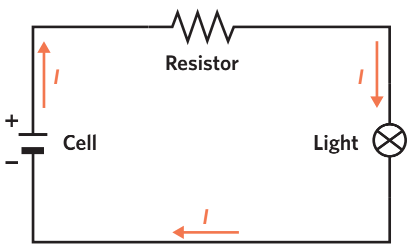


Figure 2 A series circuit consisting of a cell, a resistor, and a light bulb

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USEFUL TIP

When calculating the current using Ohm's law, $V = IR$, we must carefully choose the voltage and resistance between the same two points.

Since there is only one path along which charges can flow in a series circuit, the current at all positions in the series circuit is the same.

$$I = I_1 = I_2 = \ldots = I_n$$

Due to the law of conservation of energy, the total voltage supplied to a circuit must be equal to the sum of the voltage drops around the circuit. Another way of thinking about this is that there can be no leftover voltage running back into the power source. This means if a battery has 12 V, then a light bulb connected to it will use 12 V.

$$V_{supply} = V_1 + V_2 + \ldots + V_n$$

Figure 3 shows an example of how the voltage across components and current through components differs in a series circuit.

- The current is the same throughout the whole circuit. In Figure 3, the current through each component is 2 A.
- The sum of the voltage drop across each component in the series circuit must be equal to the voltage supply. In Figure 3, 14 V is supplied by the power source and 2 + 4 + 8 = 14 V is used by the resistors.

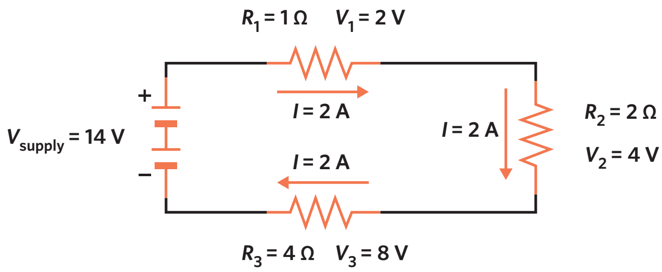
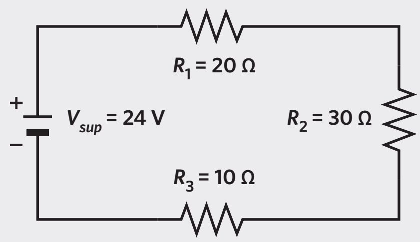


Figure 3 Series circuit example

WORKED EXAMPLE 2

An electrical circuit is created as shown.



a. Calculate the total equivalent resistance of the series circuit.

Step 1

Identify known and unknown variables and write down the formula that relates these variables.

$R_1 = 20\ \Omega, R_2 = 30\ \Omega, R_3 = 10\ \Omega$

$R_T = R_{eq} = R_1 + R_2 + R_3$

Step 2

Substitute values into the formula and solve for the total equivalent resistance of the series circuit.

$R_T = 20 + 30 + 10$

$R_T = 60\ \Omega$

b. Calculate the current in the series circuit.

Step 1

Identify known and unknown variables and write down the formula that relates these variables.

$V_{supply} = 24$ V, $R_T = 60\ \Omega$, $I = ?$

$V_{supply} = IR_{eq}$

Note that to find the current in the circuit, we need to consider the total voltage supplied to the circuit and the total equivalent resistance of the circuit.

Continues →

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Step 2

Substitute values into the formula and solve for the current in the series circuit.

$24 = I \times 60$

$I = 0.400 = 0.40$ A

---

c. Calculate the potential difference across R_2.

Step 1

Identify known and unknown variables and write down the formula that relates these variables.

$R_2 = 30\ \Omega$, $I = 0.40$ A, $V_2 = ?$

$V_2 = IR_2$

Note that to find the potential difference across R_2, we consider the current through R_2 and its individual resistance.

Step 2

Substitute values into the formula and solve for the potential difference across R_2.

$V_2 = 0.40 \times 30$

$V_2 = 12.0 = 12$ V

USEFUL TIP

In **parallel circuits** (Figure 4), components are connected so there are multiple pathways for current to run. In a parallel circuit:

- the current through each branch add up to the total current from the power supply
- the voltage drop across each branch is the same as the voltage supplied by the power supply

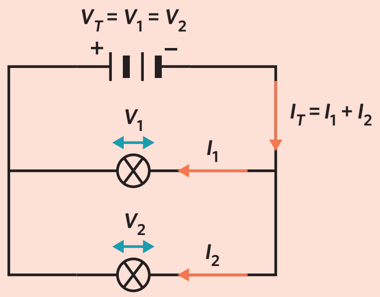

Figure 4 A parallel circuit

As explored in Lesson 2A, power is the rate of change of energy with respect to time. In an electrical context we can calculate power using:

FORMULA

$$P = VI = I^2R = \frac{V^2}{R}$$

P = power (W)
V = voltage (V)
I = current (A)
R = resistance (Ω)

USEFUL TIP

We often refer to power being 'supplied' by a power supply and being 'dissipated' (converted into other forms of energy) by other electrical components, such as resistors.

As the current is the same through all components of a series circuit, the total power supplied to a circuit must be equal to the total power dissipated around the circuit. This is due to $P = VI$, with the voltage supplied to a circuit equivalent to the total voltage used in a circuit.

$$P_{supply} = P_1 + P_2 + ... + P_n$$

USEFUL TIP

In a parallel circuit, $P_{supply} = P_1 + P_2 + ... + P_n$ can still be used to analyse how power is dissipated in the circuit.

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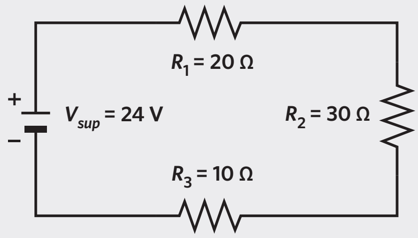
WORKED EXAMPLE 3

The current in the circuit shown is 0.40 A. The total equivalent resistance of the circuit is 60 Ω.



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a. Calculate the total power supplied by the power supply.

Step 1

Identify known and unknown variables and write down the formula that relates these variables.

Note that as the power supply provides the power for the entire circuit, we consider the current through the circuit and the total equivalent resistance of the circuit.

$I = 0.40$ A, $R_T = 60$ Ω, $P_{supply} = ?$

$P_{supply} = I^2 R_T$

Step 2

Substitute values into the formula and solve for the power supplied by the power supply.

$P_{supply} = (0.40)^2 \times 60$

$P_{supply} = 9.60 = 9.6$ W

---

b. Determine the power dissipated by R_1.

Step 1

Identify known and unknown variables and write down the formula that relates these variables.

Note that to find the power dissipated by R_1, we consider the current through R_1 and its individual resistance.

$I = 0.40$ A, $R_1 = 20$ Ω, $P_1 = ?$

$P_1 = I^2 R_1$

Step 2

Substitute values into the formula and solve for the current in the series circuit.

$P_1 = (0.40)^2 \times 20$

$P_1 = 3.20 = 3.2$ W

PROGRESS QUESTIONS

Question 5

Which of the following equations are correct about the voltage and current in a series circuit? **(Select all that apply)**

A. $I = I_1 + I_2 + I_3$

B. $I = I_1 = I_2 = I_3$

C. $P_{supply} = P_1 + P_2 + P_3$

D. $V_{supply} = V_1 = V_2 = V_3$

Question 6

A series circuit is created as shown.

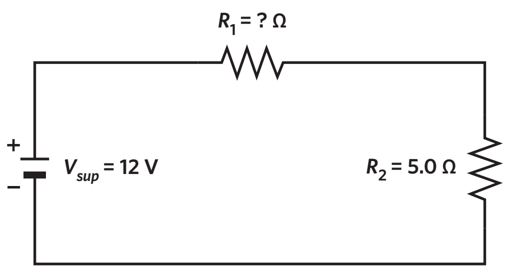
If the power dissipated by R_2 is 3.5 W, what is the current through the circuit?

A. 0.35 A

B. 0.70 A

C. 0.84 A

D. 1.3 A



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Theory summary

- Current is the rate of flow of charge with respect to time.
- A voltage (potential difference) causes a current to run through a circuit.
- A resistor opposes the flow of current.
- Ohm's law $V = IR$ relates the voltage across a resistor to the current through it.
- In a series circuit:
  - Current is constant through all components:
    $I = I_1 = I_2 = ... = I_n$
  - The total equivalent resistance of the circuit is the sum of the individual resistances:
    $R_T = R_{eq} = R_1 + R_2 + ... + R_n$
  - The total voltage supplied must equal the total voltage dropped around the circuit:
    $V_{supply} = V_1 + V_2 + ... + V_n$
- Power, $P = VI$, is dissipated by resistors and delivered by sources.
- In a series circuit:
  - The total power supplied must equal the total power dissipated around the circuit:
    $P_{supply} = P_1 + P_2 + ... + P_n$
  - By combining $V = IR$ and $P = VI$, a power wheel displays a number of transposed formulas relating to different electrical quantities (Figure 5).

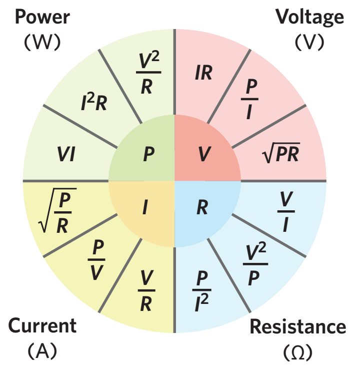


Figure 5 The power formula wheel

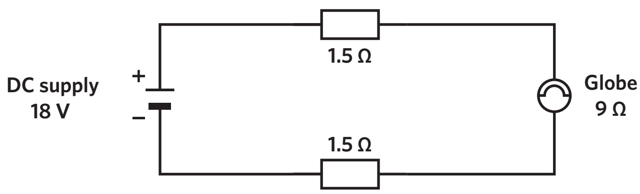
6A Questions

Mild 🌶 Medium 🌶🌶 Spicy 🌶🌶🌶

Deconstructed exam-style

Use the following information to answer questions 7–10.

Ruby and Max are investigating the transmission of electric power using a model system. Ruby and Max use an 18 V DC power supply, as shown. The two transmission lines have a resistance each of 1.5 Ω. Assume that the resistance of the globe is constant at 9.0 Ω and that the other connecting wires have zero resistance.



Question 7 🌶 (1 MARK)

Calculate the total equivalent resistance of the circuit.

Question 8 🌶 (1 MARK)

Which of the following correctly calculates the current through the globe?

A. $V_{Globe} = IR_T$

B. $I = P_{Globe}R_{Globe}$

C. $V_T = IR_T$

D. $V_T = IR_T^{\,2}$

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Question 9 (1 MARK)

Which of the following can be used to calculate the power dissipated by the globe?

A. $P_{Globe} = V_T I$

B. $P_{Globe} = I^2 R_{Globe}$

C. $P_{Globe} = I^2 R_T$

D. $P_{Globe} = I_T R_{Globe}$

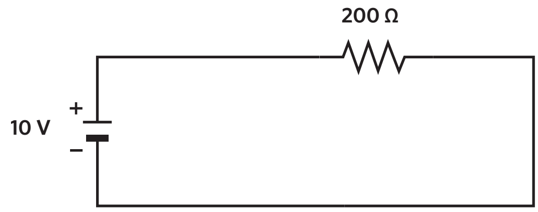
Question 10 (3 MARKS)

Calculate the power dissipated by the globe.

Adapted from VCAA 2016 exam Short answer Q16c

Exam-style

Question 11 (3 MARKS)



a. 10 V is supplied to a 200 Ω resistor as shown. Determine the current that will flow through the resistor. 1 MARK

b. Identify the current through the power supply. 1 MARK

c. Determine the power dissipated by the 200 Ω resistor. 1 MARK

Question 12 (1 MARK)

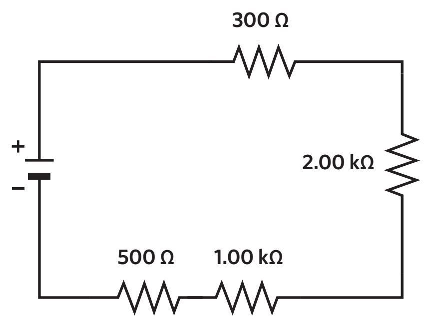
What is the total equivalent resistance of the following circuit?

A. 2.00 kΩ

B. 3.80 kΩ

C. 5.50 kΩ

D. 11.0 kΩ



Question 13 (3 MARKS)

A current of 5.0 A is flowing from a 10.0 V battery through a series circuit.

a. Show that the total equivalent resistance of the circuit is 2.0 Ω. 1 MARK

b. The circuit consists of two resistors. One of the resistors is 1.5 Ω. Find the resistance of the other resistor. 2 MARKS

Question 14 (1 MARK)

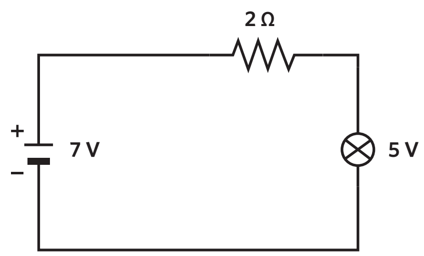
The light globe in the circuit diagram operates correctly when there is a potential difference of 5 V across it. What is the power dissipated by the light bulb when it is operating correctly?

A. 1 W

B. 5 W

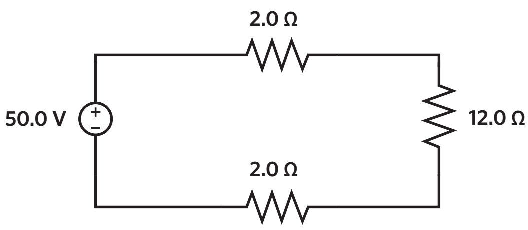
C. 1×10^2 W

D. 2×10^2 W



Question 15 (6 MARKS)

Consider the circuit shown.



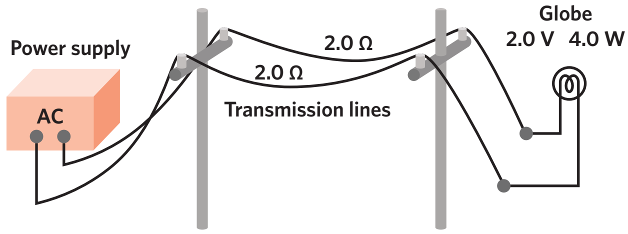
a. Determine the total power dissipated in this series circuit. 2 MARKS

b. Calculate the voltage drop across the 12 Ω resistor. 2 MARKS

c. What is the total power dissipated by the two 2.0 Ω resistors? 2 MARKS

Question 16 (3 MARKS)

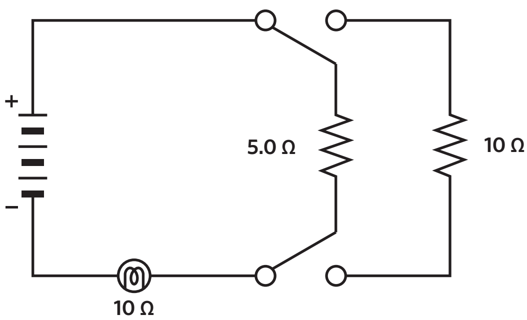
Two students, Alan and Becky, are constructing a model of an electricity transmission system to demonstrate power loss in transmission lines. The purpose of the model is to operate a 2.0 V, 4.0 W lamp as the load. They set up the model as shown. Each of the transmission lines has a resistance of 2.0 Ω. Ignore the resistance of other connecting wires.



Calculate the total power dissipated by the transmission lines. Show your working.

Adapted from VCAA 2015 exam Short answer Q16e

Question 17 (8 MARKS)



Students create an electrical circuit consisting of two switches, as shown.

a. Explain what the current running through the 10 Ω resistor is, when the switches are in the position as shown. 2 MARKS

b. The light globe is designed to operate at 6.0 W. Calculate the required voltage that should be supplied to the circuit so that the globe operates correctly, when the switches still are in the position as shown. 3 MARKS

c. Both switches are flicked at the same time. Explain how the power dissipated by the light globe changes as a result. No values are required. 3 MARKS

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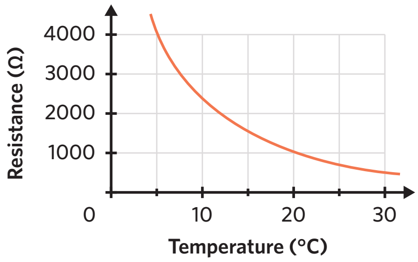
Question 18 (8 MARKS)

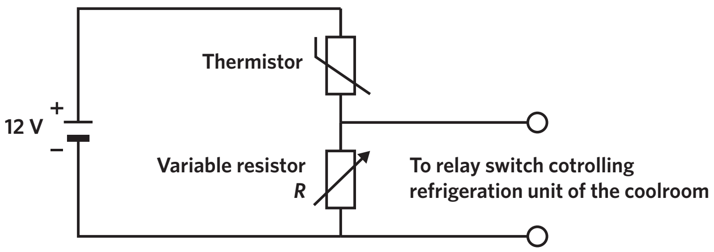
A thermistor is an electrical component whose resistance varies with temperature.
The resistance-temperature characteristic for a thermistor is shown.



a. *Key science skill*
What is the value of the resistance when the temperature is 20°C? 🌶 1 MARK
Adapted from VCAA 2011 Exam 1 Area of Study 2 Section A Q5

FROM LESSON 12D

b. The thermistor is incorporated into the control circuit for the refrigeration unit of a coolroom.



The relay switches the refrigeration unit ON when the voltage across the variable resistor is greater than or equal to 4.0 V and switches OFF when less than 4.0 V. The refrigeration unit must turn on when the temperature of the coolroom rises to, or exceeds, 5°C. At what value should the variable resistor, *R*, be set so that the refrigeration unit turns on at this temperature? 🌶🌶🌶 4 MARKS
Adapted from VCAA 2011 Exam 1 Area of Study 2 Section A Q10

c. *Key science skill*
The coolroom is not cold enough. To set the temperature lower, should *R* be increased or decreased? Explain your answer. 🌶🌶🌶 3 MARKS
Adapted from VCAA 2011 Exam 1 Area of Study 2 Section A Q11

Previous lessons

Question 19 🌶 (2 MARKS)

A spring extended by 16 cm has a strain potential energy of 140 J. What is its spring constant?

FROM LESSON 2D

Question 20 🌶🌶 (2 MARKS)

A proton, travelling at 1.4×10^5 m s^{-1}, travels along a horizontal path by balancing its gravitational force, $F_g = mg$, with a magnetic force. Calculate the strength of the magnetic field required to provide the force required. The mass of a proton is 1.67×10^{-27} kg.

FROM LESSON 4C

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6B Transformers and comparing AC and DC power

What do these boxes do?

These boxes are electrical transformers. They allow the power from the electricity grid to be delivered at a voltage suitable for our homes. In this lesson, we will explore the similarities and differences between AC and DC power. We will also draw upon our understanding of electric and magnetic fields to understand how electrical transformers work, and why they rely on an alternating current.

STUDY DESIGN DOT POINTS

- compare sinusoidal AC voltages produced as a result of the uniform rotation of a loop in a constant magnetic field with reference to frequency, period, amplitude, peak-to-peak voltage (V_{p-p}) and peak-to-peak current (I_{p-p})
- compare alternating voltage expressed as the root-mean-square (RMS) to a constant DC voltage developing the same power in a resistive component
- analyse transformer action with reference to electromagnetic induction for an ideal transformer: $\frac{N_1}{N_2} = \frac{V_1}{V_2} = \frac{I_2}{I_1}$

6A 6B 6C

3.3.5.2 & 3.3.6.1 Comparing AC and DC power

3.3.7.1 Transformers

ESSENTIAL PRIOR KNOWLEDGE

6A Electrical formulas

6A Series circuits

See questions 60–61.

KEY TERMS AND DEFINITIONS

alternating current (AC) electricity electricity with a periodically alternating direction of current and voltage

root-mean-square (RMS) the DC voltage or current that would deliver the same average power as an AC source

transformer a device that uses electromagnetic induction to transfer power from one electrical circuit to another

FORMULAS

- **Ohm's law**
  $V = IR$
- **power (electricity)**
  $P = VI = I^2R = \frac{V^2}{R}$
- **RMS voltage**
  $V_{RMS} = \frac{1}{\sqrt{2}}V_{peak}$
- **RMS current**
  $I_{RMS} = \frac{1}{\sqrt{2}}I_{peak}$
- **ideal transformer ratios**
  $\frac{V_1}{V_2} = \frac{N_1}{N_2} = \frac{I_2}{I_1}$

Comparing AC and DC power 3.3.5.2 & 3.3.6.1

The output from an AC power source varies with time, whereas the output from a DC power source is constant. RMS values of voltage and current are used to compare DC and AC power sources.

How can we compare AC and DC power?

Alternating current (AC) electricity describes electricity with a changing direction of current and voltage. It is common for the voltage and current of AC electricity to vary sinusoidally with time (Figure 1). This means that the voltage, current, and power are constantly changing from one moment to the next.

The current and voltage in an AC circuit can be measured three ways: peak, peak-to-peak, and **root-mean-square (RMS)**.

- The peak value describes the amplitude (maximum value) of the voltage or current.
- The peak-to-peak value describes the difference between the maximum voltage in the positive and negative directions.
- The RMS value represents the voltage of an equivalent DC source. This value allows us to compare AC to DC electricity. A 240 V_{RMS} AC power source delivers the same average power as a 240 V DC source.[1]

KEEN TO INVESTIGATE?

[1] **Where does the RMS value come from?**
Search: RMS voltage: what is it?

A light bulb rated at 12 V could be powered by a 12 V DC source, like a battery, or it could be powered by a 12 V_{RMS} AC source that would have a peak value close to 17 V, and a peak-to-peak value close to 34 V (Figure 2).

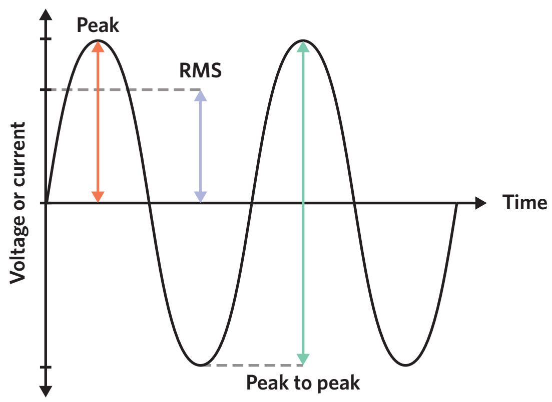

Figure 1 A voltage (or current) against time graph with indications of peak, peak-to-peak, and RMS values

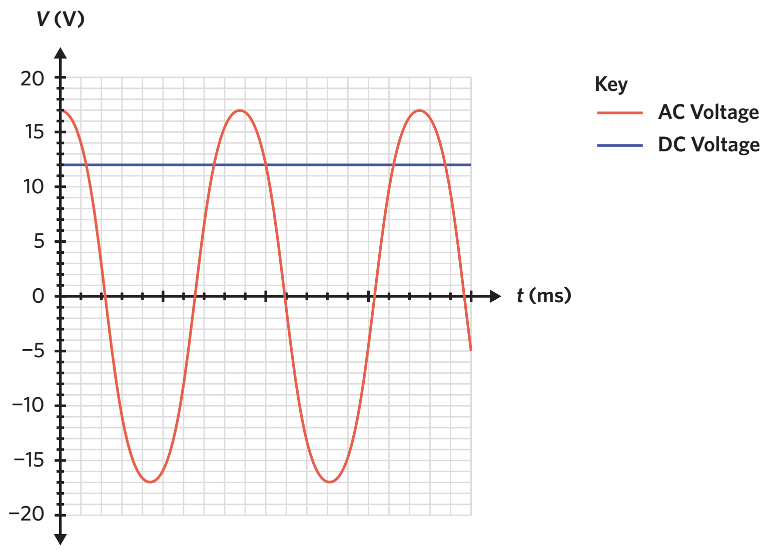

Figure 2 A 17 V_{peak} AC source (red line) provides the same average power as a 12 V DC source (blue line).

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RMS values are related to peak values as shown:

FORMULA

$$V_{RMS} = \frac{1}{\sqrt{2}} V_{peak}$$

V_{RMS} = root-mean-square voltage (V)
V_{peak} = peak voltage (V)

USEFUL TIP

A question may indicate the type of value given with the units associated with the value. For example, an RMS value may be stated as 2.0 A_{RMS} or a peak value may be stated as 4.0 V_{peak}.

FORMULA

$$I_{RMS} = \frac{1}{\sqrt{2}} I_{peak}$$

I_{RMS} = root-mean-square current (A)
I_{peak} = peak current (A)

USEFUL TIP

The RMS value is always less than the corresponding peak value. It can help to keep this in mind to check the appropriateness of your calculations.

From Figure 1, we can see that the peak-to-peak value is double the peak value:

$$V_{p-p} = 2V_{peak}$$
$$I_{p-p} = 2I_{peak}$$

USEFUL TIP

We can relate the peak-to-peak value to the RMS value by substituting $V_{RMS} = \frac{1}{\sqrt{2}} V_{peak}$ into the above relation:

$$V_{p-p} = 2\sqrt{2} V_{RMS}$$
$$I_{p-p} = 2\sqrt{2} I_{RMS}$$

The average power delivered by AC electricity can be calculated from the RMS values of voltage and current by using the same formulas that we would use for DC electricity.

$$P = V_{RMS} I_{RMS} = I_{RMS}{}^2 R = \frac{V_{RMS}{}^2}{R}$$

WORKED EXAMPLE 1

An AC power source outputs a peak voltage of 170 V, at an RMS current of 34.0 A.

---

a. Calculate the RMS voltage.

Step 1

Identify known and unknown variables and write down the formula that relates these variables.

$V_{peak} = 170$ V, $V_{RMS} = ?$

$V_{RMS} = \frac{1}{\sqrt{2}} V_{peak}$

Step 2

Substitute values into the formula and solve for the RMS voltage.

$V_{RMS} = \frac{1}{\sqrt{2}} \times 170$

$V_{RMS} = 120.2 = 120$ V

Continues →

b. Calculate the peak-to-peak current.

Step 1

Identify known and unknown variables and write down the formula that relates these variables.

$I_{RMS} = 34.0\text{ A}, I_{peak} = ?$

$I_{RMS} = \frac{1}{\sqrt{2}} I_{peak}$

Step 2

Substitute values into the formula and solve for the peak current.

$34.0 = \frac{1}{\sqrt{2}} I_{peak}$

$I_{peak} = 48.08\text{ A}$

Step 3

Identify known and unknown variables and write down the formula that relates these variables.

$I_{peak} = 48.08\text{ A}, I_{p-p} = ?$

$I_{p-p} = 2I_{peak}$

Step 4

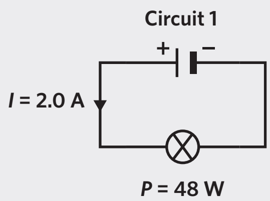
Substitute values into the formula and solve for the peak-to-peak current.

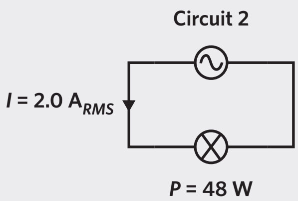
$I_{p-p} = 2 \times 48.08$

$I_{p-p} = 96.17 = 96.2\text{ A}$

WORKED EXAMPLE 2

Consider the two electrical circuits shown. In Circuit 1, a DC cell is producing 2.0 A which supplies 48 W to a light bulb. In Circuit 2, an AC source is producing 2.0 A_{RMS} which supplies 48 W to a light bulb.





a. Calculate the voltage delivered by the cell in Circuit 1.

Step 1

Identify known and unknown variables and write down the formula that relates these variables.

$P = 48\text{ W}, I = 2.0\text{ A}, V = ?$

$P = VI$

Step 2

Substitute values into the formula and solve for the voltage.

$48 = V \times 2.0$

$V = 24.0 = 24\text{ V}$

b. Calculate the peak voltage delivered in Circuit 2.

Step 1

Identify known and unknown variables and write down the formula that relates these variables.

$P = 48\text{ W}, I_{RMS} = 2.0\text{ A}, V_{RMS} = ?$

$P = V_{RMS} I_{RMS}$

Step 2

Substitute values into the formula and solve for the RMS voltage.

$48 = V_{RMS} \times 2.0$

$V_{RMS} = 24.0\text{ V}$

Step 3

Identify known and unknown variables and write down the formula that relates these variables.

$V_{RMS} = 24.0\text{ V}, V_{peak} = ?$

$V_{RMS} = \frac{1}{\sqrt{2}} V_{peak}$

Step 4

Substitute values into the formula and solve for the peak voltage.

$24.0 = \frac{1}{\sqrt{2}} V_{peak}$

$V_{peak} = 33.9 = 34\text{ V}$

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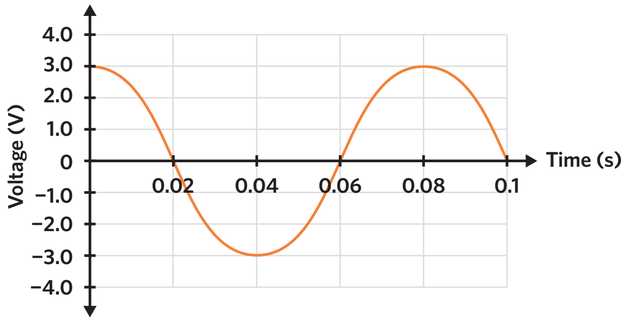
PROGRESS QUESTIONS

Use the following information to answer questions 1 and 2.

The output from an AC power source is shown.



Question 1

What is the peak voltage of the source?

A. 2.1 V **B.** 3.0 V **C.** 4.2 V **D.** 6.0 V

Question 2

What is the RMS voltage of the source?

A. 1.1 V **B.** 2.1 V **C.** 3.0 V **D.** 4.2 V

Question 3

A DC power source is being used to power a 10 V globe. What is the RMS voltage of an AC power source that would deliver the same average power to the globe?

A. 3.5 V **B.** 7.1 V **C.** 10 V **D.** 14 V

Question 4

The peak-to-peak current through a 15 Ω resistor is 4.0 A. What is the average power dissipated by the resistor?

A. 15 W **B.** 30 W **C.** 45 W **D.** 60 W

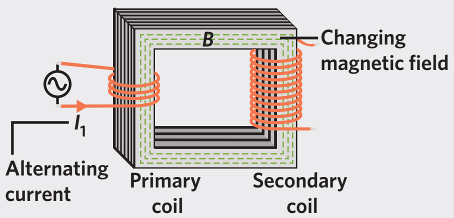
Transformers 3.3.7.1

Transformers are devices that transfer electric power between circuits, and are capable of increasing or decreasing the voltage or current. They operate using Faraday's principle of electromagnetic induction, which means that they require changing magnetic flux in the primary coil to operate effectively.

How does a transformer work?

A transformer consists of two coils of wire wrapped around the same iron core (Figure 3). Table 1 shows the operation of an ideal transformer.

Table 1 How a transformer operates

Description	Diagram
When an alternating current (AC) passes through one of the coils (known as the 'primary coil'), it produces a changing magnetic field.	

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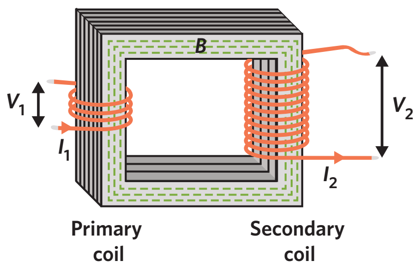
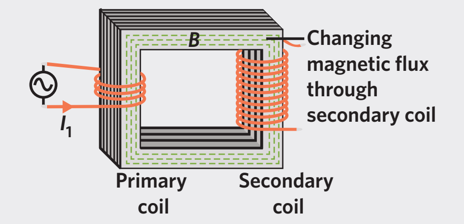
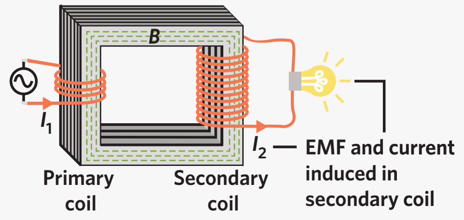


Figure 3 An electrical transformer

Table 1 Continued

Description	Diagram
The magnetic field produced by the primary coil is guided through the secondary coil by the iron core. As a result, there is a changing magnetic flux through the secondary coil.	
An EMF is induced in the secondary coil due to the changing magnetic flux through the coil, as described by Faraday's law ($EMF = -N\frac{\Delta\Phi_B}{\Delta t}$). A current will flow when this secondary coil forms a closed circuit.	

USEFUL TIP

If a DC power supply is connected to a transformer and turned on, there will initially be an EMF induced in the secondary coil as the flux changes when the supply turns on. After a short period of time, the flux through the secondary coil is no longer changing and so no continuous EMF is induced in the secondary coil. If the power supply is turned off, again there will be a brief EMF induced in the secondary coil.

It is important to recognise the role of the changing current in the primary coil of a transformer. If a constant DC supply were used, then the magnetic flux in the secondary coil would also be constant, meaning no EMF would be induced in the secondary coil (Figure 4).

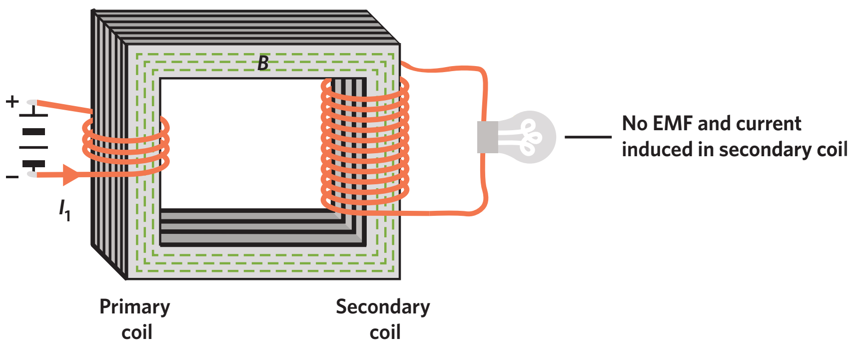


Figure 4 A DC power supply does not generate a consistent EMF in the secondary coil

KEEN TO INVESTIGATE?

2 **Where do the ideal transformer ratios come from?**
Search: Operation of ideal transformer

3 **Can transformers really be ideal?**
Search: Difference between ideal and real or practical transformer

The primary coil always refers to the coil on the power supply side of the circuit. The ratio of the voltage in the primary coil (V_1) to the voltage induced in the secondary coil (V_2) is equal to the ratio of the number of turns in the primary coil (N_1) to the number of turns in the secondary coil (N_2).[2]

$$\frac{V_1}{V_2} = \frac{N_1}{N_2}$$

In VCE Physics, we will model the transformer as ideal unless otherwise stated, which means that all of the power delivered to the primary coil is transferred to the secondary coil.[3]

$$P_1 = P_2 \Rightarrow V_1 I_1 = V_2 I_2$$

From this, we can relate the voltage, numbers of turns and current in the primary and secondary coil using the following ratios:

USEFUL TIP

A ratio may be given as a fraction, for example $\frac{N_1}{N_2}$, or as an explicit ratio, for example $N_1{:}N_2$.

FORMULA

$$\frac{V_1}{V_2} = \frac{N_1}{N_2} = \frac{I_2}{I_1}$$

N_1 = turns in the primary side (no units)
N_2 = turns in the secondary side (no units)
V_1 = primary voltage (V)
V_2 = secondary voltage (V)
I_2 = secondary current (A)
I_1 = primary current (A)

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It's important to note:

- If $N_2 > N_1$ then the transformer is a step-up transformer which will step-up the voltage but step-down the current.
- If $N_1 > N_2$ then the transformer is a step-down transformer which will step-down the voltage but step-up the current.

We can use RMS, peak, or peak-to-peak voltage and current values in calculations involving an ideal transformer, but we must consistently use the same type. For example, we will calculate an incorrect ratio if we use RMS voltage for the primary coil and the peak voltage for the secondary coil.

USEFUL TIP

The ideal transformer ratios can be broken down into three separate formulas: $\frac{V_1}{V_2} = \frac{N_1}{N_2}$, $\frac{V_1}{V_2} = \frac{I_2}{I_1}$ and $\frac{N_1}{N_2} = \frac{I_2}{I_1}$. These can each be used as individual formulas.

USEFUL TIP

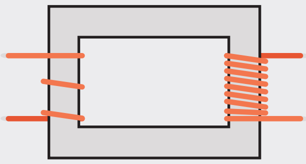
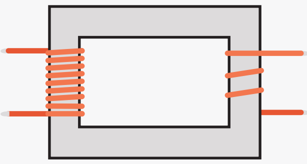
As the number of turns is a physical count of the number of turns of wire, it is stated as an integer without any decimal places, and does not contribute to the significant figures of a question.

USEFUL TIP

The AC power output from a transformer will have the same period and frequency as the AC power input to the transformer.

Table 2 outlines the differences between step-up and step-down transformers.

Table 2 Step-up vs. step-down transformer

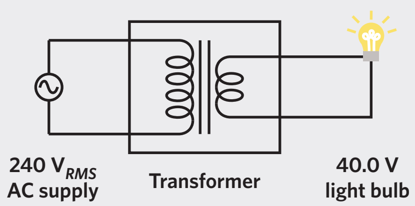
Type	Turns	Voltage	Current	Power	Diagram
Step-up	• More turns in the secondary coil than the primary coil • $N_1 < N_2$	• More voltage in the secondary coil than the primary coil • $V_1 < V_2$	• Less current in the secondary coil than the primary coil • $I_1 > I_2$	• Same power in both the secondary and primary coil • $P_1 = P_2$	
Step-down	• Less turns in the secondary coil than the primary coil • $N_1 > N_2$	• Less voltage in the secondary coil than the primary coil • $V_1 > V_2$	• More current in the secondary coil than the primary coil • $I_1 < I_2$	• Same power in both the secondary and primary coil • $P_1 = P_2$	

USEFUL TIP

A step-up transformer can be remembered as one that 'steps-up' in turns or voltage, and a step-down transformer can be remembered as one that 'steps-down' in turns or voltage.

WORKED EXAMPLE 3

Consider the electrical circuit shown, which consists of a 240 V_{RMS} AC power supply connected to a 40.0 V light bulb that is operating correctly. Assume that the connecting wires have negligible resistance.



a. Which type of transformer (step-up or step-down) is being used?

Breakdown	Answer
State the primary and secondary voltage.	The primary voltage, V_1, is 240 V and the secondary voltage, V_2, is 40.0 V.
Identify the type of transformer.	As the voltage in the secondary coil is less than in the primary coil, it is a step-down transformer.

Continues →

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b. The primary coil of the transformer has 600 turns in it. How many turns does the secondary coil have?

Step 1

Identify known and unknown variables and write down the formula that relates these variables.

Note that the ratio required is just the ratio between the number of turns and voltages, there is no need to state the ratio involving currents.

$N_1 = 600$, $V_1 = 240$ V, $V_2 = 40.0$ V, $N_2 = ?$

$$\frac{N_1}{N_2} = \frac{V_1}{V_2}$$

Step 2

Substitute values into the formula and solve for the number of turns in the secondary coil.

$$\frac{600}{N_2} = \frac{240}{40.0}$$

$N_2 = 100$

There are 100 turns in the secondary coil.

---

c. Considering the current in the primary coil is 12 A_{peak}, determine the RMS current in the secondary coil.

Step 1

Identify known and unknown variables and write down the formula that relates these variables.

Note that the primary current can either be converted to an RMS value before using the transformer ratio or after.

$N_1 = 600$, $N_2 = 100$, $I_1 = 12$ A_{peak}, $I_2 = ?$

$$\frac{N_1}{N_2} = \frac{I_2}{I_1}$$

Step 2

Substitute values into the formula and solve for the secondary RMS current.

$$\frac{600}{100} = \frac{I_2}{12}$$

$I_2 = 72.0$ A_{peak}

$$I_2 = \frac{1}{\sqrt{2}} \times 72.0 = 50.9 = 51\ A_{RMS}$$

PROGRESS QUESTIONS

Use the following information to answer questions 5 and 6.

An ideal transformer has $N_1 = 50$ turns in the primary coil and $N_2 = 100$ turns in the secondary coil. An AC power supply of 50 V_{RMS}, with an average power output of 150 W, is connected to the primary coil. The secondary coil is connected to a single resistor.

Question 5

What is the average power dissipated by the resistor?

A. 75.0 W **B.** 150 W **C.** 212 W **D.** 450 W

Question 6

What is the voltage drop across the resistor?

A. 25 V_{RMS} **B.** 50 V_{RMS} **C.** 75 V_{RMS} **D.** 100 V_{RMS}

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Theory summary

- RMS and peak values of voltage and current for AC electricity are related by:
  - $V_{RMS} = \frac{1}{\sqrt{2}}V_{peak}$ and $I_{RMS} = \frac{1}{\sqrt{2}}I_{peak}$
- For AC electricity, the values of RMS voltage and current indicate the values of a constant DC voltage and current that would deliver the same average power.
- Transformers operate through the principle of electromagnetic induction and are used to change the voltage and current.
  - They require a changing current in the primary coil to operate effectively.
  - Ideal transformers have the same power on the primary and secondary sides so that the primary and secondary coils are related by: $\frac{N_1}{N_2} = \frac{V_1}{V_2} = \frac{I_2}{I_1}$.

6B Questions

Mild 🌶 Medium 🌶🌶 Spicy 🌶🌶🌶

Deconstructed exam-style

Use the following information to answer questions 7–9.

A laptop computer requires a transformer to reduce the voltage to its rechargeable battery. The powerpoint supplies an RMS voltage of 240 V and delivers an RMS current of 0.35 A. The transformer converts the voltage to an RMS voltage of 8.0 V. Assume that the transformer is ideal.

Question 7 🌶 (1 MARK)

From the information provided, which ratio best solves for the current in the secondary coil?

A. $\frac{N_1}{N_2} = \frac{I_2}{I_1}$ **B.** $\frac{N_1}{N_2} = \frac{I_1}{I_2}$ **C.** $\frac{V_1}{V_2} = \frac{I_2}{I_1}$ **D.** $\frac{V_1}{V_2} = \frac{I_1}{I_2}$

Question 8 🌶 (1 MARK)

State the relationship between RMS current and peak current?

Question 9 🌶🌶 (3 MARKS)

Calculate the peak current in the secondary coil.

Adapted from VCAA 2022 NHT exam Short answer Q6b

Exam-style

Use the following information to answer questions 10 and 11.

A speaker that requires 15 V_{RMS} AC to operate correctly is supplied by a transformer connected to a 345 V_{RMS} power supply.

Question 10 🌶 (1 MARK)

What is the ratio of the turns in the transformer's primary to secondary coils, so that the speaker operates correctly?

A. 1:15

B. 15:1

C. 1:23

D. 23:1

Adapted from VCAA 2019 NHT exam Multiple choice Q5

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Question 11 (1 MARK)

The speaker is taken out of this circuit and is attached to a DC battery instead. The voltage of the battery required for the speaker to operate correctly is closest to

A. 11 V.

B. 15 V.

C. 21 V.

D. 23 V.

Adapted from VCAA 2019 NHT exam Multiple choice Q6

Question 12 (2 MARKS)

Alfie is working with a transformer that has 200 turns in the primary coil and 1200 turns in the secondary coil. The current in the secondary coil is 13.5 A_{RMS}.

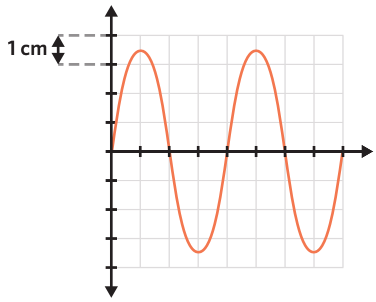
a. Calculate the peak-to-peak current in the secondary coil. 1 MARK

b. Calculate the RMS current in the primary coil. 1 MARK

Question 13 (1 MARK)

Key science skill

Alice is measuring the voltage from an AC signal generator using an oscilloscope, which produces the following output. The vertical scale is set to 3.0 V cm^{-1}.



Which of the following is closest to the RMS voltage of the AC signal generator?

A. 4.5 V

B. 7.4 V

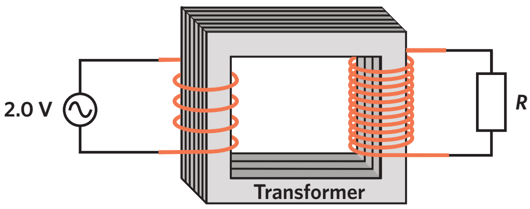
C. 11 V

D. 15 V

Adapted from VCAA 2010 Exam 1 Detailed Study 3 Q4

Question 14 (8 MARKS)

Ted is experimenting with an ideal transformer. The primary coil of the transformer has 500 turns and the secondary coil has 4000 turns. A 2.0 V_{peak} AC power supply is connected across the primary coil and there is a 1000 Ω resistor in the secondary circuit.



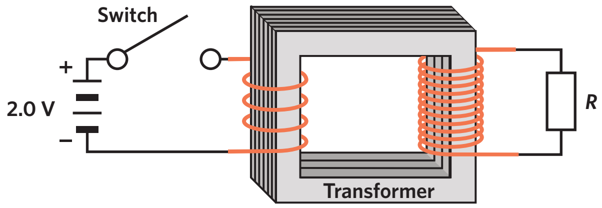
a. Calculate the average power dissipated in the resistor. 3 MARKS

b. ***Key science skill***

Draw a graph of one complete cycle of the voltage across the resistor vs. time. Values along the horizontal axis are not required. 2 MARKS

FROM LESSON 12D

c. Ted modifies the circuit and connects a 2.0 V DC battery and a switch in the primary circuit as shown. Initially there is no current through the resistor. As he closes the switch he measures a short pulse in current through the resistor before it returns to zero.



Explain why there is a short pulse of current as the switch is closed and why there is no current in the resistor as the switch remains closed. No numbers are required in your answer, but you should refer to the relevant law of physics. 3 MARKS

Adapted from VCAA 2013 exam Short answer Q15

Question 15 (4 MARKS)

Melanie is setting up a lamp for her desk. A variable AC power supply is connected to the primary side of a 15:1 transformer. The lamp is connected to the secondary side of the transformer. The voltage in the secondary coil is 20.0 V_{RMS}. Given that the resistance of the lamp in this situation is 10 Ω, calculate the peak-to-peak current in the primary coil.

Question 16 (1 MARK)

An ideal transformer has an input DC voltage of 240 V, 2000 turns in the primary coil and 80 turns in the secondary coil. The output voltage is closest to

A. 0 V.

B. 9.60 V.

C. 240 V.

D. 600 V.

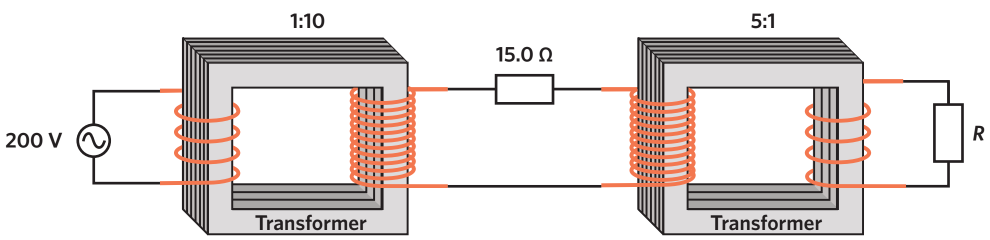
Adapted from VCAA 2020 exam Multiple choice Q7

Question 17 (3 MARKS)

Lily is setting up a 36 Ω amplifier that requires 144 W to operate correctly. It is connected to the secondary side of a transformer. The primary coil of the transformer has 500 turns and is connected to an AC power supply producing 18.5 V_{peak}. Given that the amplifier is working correctly, determine the number of turns in the secondary coil.

Question 18 (10 MARKS)

A power supply, supplying 400 W at 200 V_{RMS}, is connected to a step-up transformer with a ratio of 1:10. A 15.0 Ω resistor is connected between the secondary coil of the step-up transformer and the primary coil of a step-down transformer with a ratio of 5:1. The secondary coil of the step-down transformer is connected to an unknown resistor, *R*.



a. Calculate the power dissipated by the 15.0 Ω resistor. 4 MARKS

b. Calculate the resistance, *R*. 3 MARKS

c. Explain how the first transformer could be altered to increase the amount of power supplied to *R* can be increased. 3 MARKS

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Previous lessons

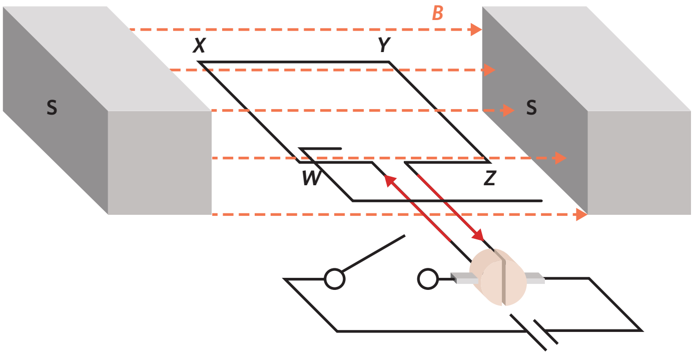
Question 19 (2 MARKS)

A string, of natural length 15 cm, is stretched to 20 cm. It has a spring constant of 15 N m^{-1}.
What is the strain potential energy stored in the string?

FROM LESSON 2D

Question 20 (2 MARKS)

A DC motor is set up using permanent magnets and a split ring commutator. Before the motor is switched on, the coil of the motor is stationary and horizontal (as in the diagram). Explain why the coil begins to rotate when the motor is turned on.



Adapted from VCAA 2014 exam Short answer Q17c

FROM LESSON 4D

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6C Transmission of power

STUDY DESIGN DOT POINT

- analyse the supply of power by considering transmission losses across transmission lines.

6A 6B 6C

3.3.8.1 Transmission of power

ESSENTIAL PRIOR KNOWLEDGE

6A Electrical circuit behaviour

6B Operation of transformers

See questions 62–63.

Why is power transmitted at high voltages?

When we transmit power over long distances, transformers are used to first step up the voltage at the generator and then step it back down for use in cities and towns. This lesson will explore the way that transformers are applied to increase the efficiency of power transmission systems.

FORMULAS

- Ohm's law
  $V = IR$
- power (electricity)
  $P = VI = I^2 R = \frac{V^2}{R}$
- RMS voltage
  $V_{RMS} = \frac{1}{\sqrt{2}} V_{peak}$
- RMS current
  $I_{RMS} = \frac{1}{\sqrt{2}} I_{peak}$
- ideal transformer ratio
  $\frac{V_1}{V_2} = \frac{N_1}{N_2} = \frac{I_2}{I_1}$

Transmission of power 3.3.8.1

Although the resistance of electrical wires is typically low, when power lines are run over long distances this resistance increases and results in a significant voltage drop and loss in power.

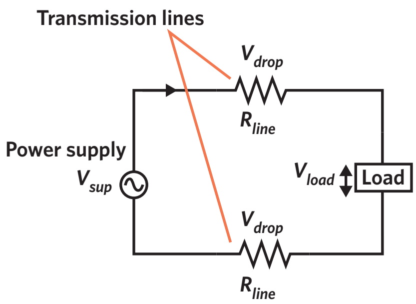
How can we analyse the transmission of power?

A simple power transmission system without transformers (Figure 1) consists of

- a power supply/generator
- transmission lines
- a load (this can be a single device, a house, or a whole town).

These transmission systems can be represented using a series circuit where the resistance of the transmission lines can be modelled:

- with two resistors (Figure 2a)
- or with a single resistor (Figure 2b).



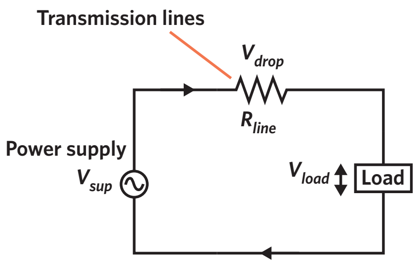


Figure 2 A circuit diagram for the transmission system from Figure 1, where the resistance of the transmission lines is modelled **(a)** as two resistors, and **(b)** as a single resistor.

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If the transmission lines are modelled using two resistors then the resistance of both wires need to be included in order to correctly calculate the voltage drop and power loss in the lines. Modelling the transmission lines as a single resistor simplifies the calculations involved with transmission lines.

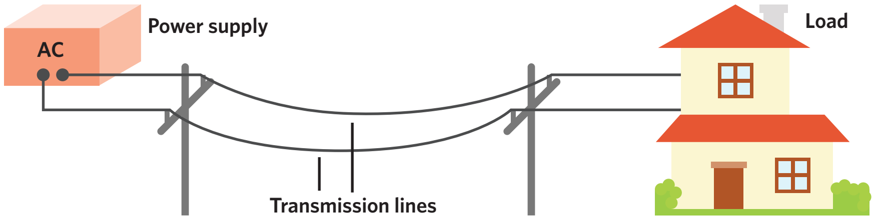


Figure 1 A simple power transmission system consists of the power supply, transmission lines, and a load.

The resistance of the transmission lines causes a voltage drop across the lines, which can be analysed using Ohm's law:

FORMULA

$$V_{drop} = I_{line} R_{line}$$

V_{drop} = voltage drop across the transmission lines (V)
I_{line} = current in the transmission lines (A)
R_{line} = resistance of the transmission lines (Ω)

In a simple transmission system without transformers, the voltage delivered to the load will be the difference between the voltage supply and the voltage drop:

$$V_{load} = V_{supply} - V_{drop}$$

The power loss due to the resistance in the transmission lines can be calculated using:

FORMULA

$$P_{loss} = V_{drop} I_{line} = I_{line}{}^2 R_{line}$$

P_{loss} = power loss in the transmission lines (W)
V_{drop} = voltage drop across the transmission lines (V)
I_{line} = current in the transmission lines (A)
R_{line} = resistance of the transmission lines (Ω)

The power delivered to the load will be the difference between the power supply and the power loss:

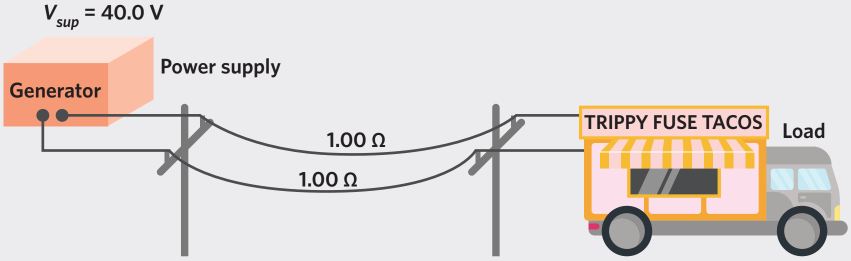
$$P_{load} = P_{supply} - P_{loss}$$

This relationship also applies when transformers are included in the transmission system.

WORKED EXAMPLE 1

A generator is producing 200 W at 40.0 V_{RMS} which is used to supply a food truck. The transmission lines have a resistance of 1.00 Ω each.

P_{sup} = 200 W
V_{sup} = 40.0 V



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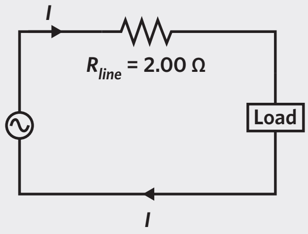
a. Draw a circuit diagram representing the transmission system to the food truck.

Breakdown

The generator is an AC power supply.

The transmission lines are shown with resistance in both lines, but this can be redrawn to model the resistance in the lines as a single resistor of 2.00 Ω.

Answer



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b. Calculate the voltage drop across the transmission lines.

Step 1

Identify known and unknown variables and write down the formula that relates these variables..

$P_{supply} = 200$ W, $V_{supply} = 40.0$ V, $I = ?$

$P_{supply} = V_{supply} I$

Step 2

Substitute values into the formula and solve for the current in the circuit.

$200 = 40.0 \times I$

$I = 5.00$ A

Step 3

Identify known and unknown variables and write down the formula that relates these variables.

Note that $I_{line} = I$ as the current in the series circuit is the same through each component.

$I_{line} = I = 5.00$ A, $R_{line} = 2.00$ Ω, $V_{drop} = ?$

$V_{drop} = I_{line} R_{line}$

Step 4

Substitute values into the formula and solve for the voltage drop.

$V_{drop} = 5.00 \times 2.00$

$V_{drop} = 10.0$ V

---

c. Calculate the power loss in the transmission lines.

Step 1

Identify known and unknown variables and write down the formula that relates these variables.

Note that $P_{loss} = V_{drop} I_{line}$ or $P_{loss} = \frac{V_{drop}{}^2}{R_{line}}$ can also be used to find the power loss in the lines.

$I_{line} = 5.00$ A, $R_{line} = 2.00$ Ω, $P_{loss} = ?$

$P_{loss} = I_{line}{}^2 R_{line}$

Step 2

Substitute values into the formula and solve for the power loss in the transmission lines.

$P_{loss} = 5.00^2 \times 2.00$

$P_{loss} = 50.0$ W

---

d. Calculate the power delivered to the food truck.

Step 1

Identify known and unknown variables and write down the formula that relates these variables.

$P_{supply} = 200$ W, $P_{loss} = 50.0$ W, $P_{load} = ?$

$P_{load} = P_{supply} - P_{loss}$

Step 2

Substitute values into the formula and solve for the power delivered to the food truck.

$P_{load} = 200 - 50.0$

$P_{load} = 150$ W

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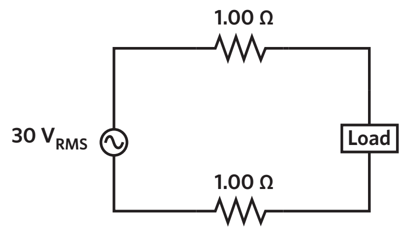
PROGRESS QUESTIONS

Use the following information to answer questions 1 and 2.

A 30 V_{RMS} power supply is used to deliver 300 W of power to a circuit. The resistance of each transmission wire is 1.00 Ω.



Question 1

What is the current in the transmission lines?

A. 10 A **B.** 14.1 A **C.** 30 A **D.** 300 A

Question 2

Which of the following is the correct V_{drop} and P_{loss} across the transmission lines, respectively?

A. 20 V_{RMS}, 20 W **B.** 20 V_{RMS}, 200 W **C.** 30 V_{RMS}, 20 W **D.** 30 V_{RMS}, 200 W

How can a transformer reduce power losses in transmission lines?

AC power has an advantage over DC power in the transmission of electricity because transformers can be used to reduce power loss in the lines.

By using a transformer:

- the current can be decreased in the transmission lines by stepping up the voltage
- this reduces the voltage drop across the lines, as $V_{drop} = I_{line} R_{line}$
- the power loss in the lines is significantly reduced, as $P_{loss} = I_{line}^2 R_{line}$
- this improves the overall efficiency of the power transmission system.

USEFUL TIP

Increasing the current in transmission lines by a factor of 2 increases the voltage drop in the lines by a factor 2, as $V_{drop} = I_{line} R_{line}$. However, it increases the power loss in transmission lines by a factor $2^2 = 4$, as $P_{loss} = I_{line}^2 R_{line}$.

Recall from Lesson 6B that the same amount of power can be transmitted using different combinations of current and voltage. When we step up the voltage, the current is reduced by the same factor, therefore the power transmitted remains the same. Using lower currents (and greater voltages) is preferred in long distance power transmission for the sake of reducing the voltage drop and the power loss in the transmission lines.

Transformers allow us to change the ratio of current and voltage to suit each stage of the transmission system (Figure 3):

- A step-up transformer between the power supply and the transmission lines allows voltage to be stepped up for transmission. This reduces the current and the power loss in the lines ($P_{loss} = I_{line}^2 R_{line}$).
- A step-down transformer between the transmission lines and the load allows voltage to be stepped-down to the required voltage for the load.

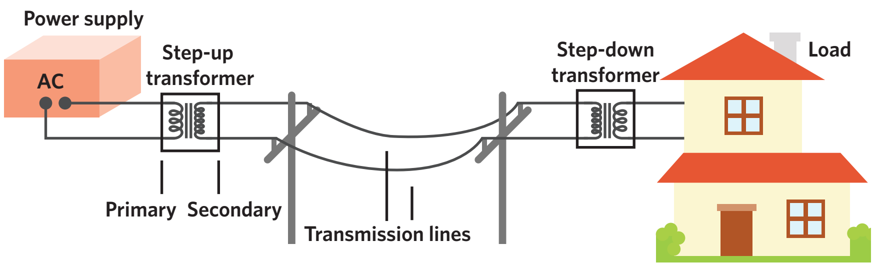


Figure 3 A power transmission diagram with a step-up transformer and a step-down transformer

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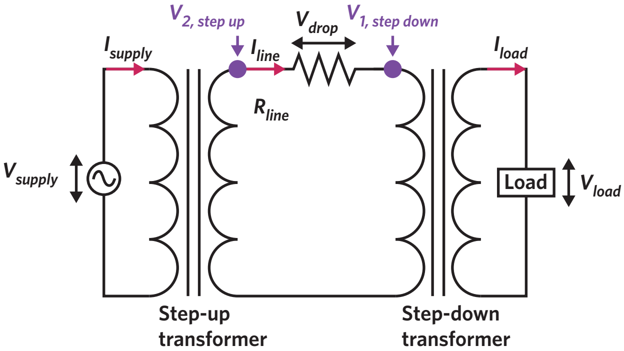

Figure 4 A circuit diagram for the transmission system shown in Figure 3.

To consider how current, voltage and power behave in the power transmission system, consider the electrical circuit diagram of the situation (Figure 4). Table 1 outlines the use of a step-up transformer installed at the generator.

USEFUL TIP

The formulas for power apply only to RMS values, so it is safest to do calculations using RMS and then convert to peak values if needed. Unless the question explicitly asks for a peak value, assume all answers are to be given as RMS values.

Table 1 Use of step-up transformer in power transmission

Step-up transformer	Current	Voltage	Power loss
Formulae	$\frac{N_1}{N_2} = \frac{I_{line}}{I_{supply}}$, where $N_1 < N_2$	$\frac{N_1}{N_2} = \frac{V_{supply}}{V_{2,\ step-up}}$, where $N_1 < N_2$	$P_{supply} = P_{2,\ step-up}$
Description	The current is decreased for transmission, $I_{supply} > I_{line}$.	The voltage is increased for transmission, $V_{supply} < V_{2,\ step-up}$.	Although the voltage is increased and the current is decreased, we assume that the transformer is ideal, so no power is lost across the transformer.

Using the output current from the step-up transformer, the voltage drop and power loss in the transmission lines can be calculated (Table 2).

Table 2 How current and voltage changes across transmission lines

Transmission lines	Current	Voltage	Power loss
Formulae	I_{line} is the output current from the step-up transformer.	$V_{drop} = I_{line} R_{line}$	$P_{loss} = I_{line}{}^2 R_{line} = V_{drop} I_{line}$
Description	The current through the transmission line remains the same regardless of power loss due to resistance in the line.	Resistance in the line results in voltage drop, V_{drop}, across the line.	Power loss can be calculated using the current through the line or the voltage drop across the line.

A step-down transformer can then be installed before the load (Table 3).

Table 3 Use of step-down transformer in power transmission

Step-down transformer	Current	Voltage	Power loss
Formulae	$\frac{N_1}{N_2} = \frac{I_{load}}{I_{line}}$, where $N_1 > N_2$	$V_{1,\ step-down} = V_{2,\ step-up} - V_{drop}$ $\frac{N_1}{N_2} = \frac{V_{1,\ step-down}}{V_{load}}$, where $N_1 > N_2$	$P_{1,\ step-down} = P_{2,\ step-up} - P_{loss}$ $P_{1,\ step-down} = P_{load}$
Description	The current into the step down transformer is the same as the current in the line, I_{line}, or the current out of the step up transformer. The current is then stepped up for use by the load, $I_{line} < I_{load}$.	The voltage into the step down transformer, $V_{1,\ step-down}$, can be calculated by subtracting the voltage drop in the line, V_{drop}, from the output voltage of the step up transformer, $V_{2,\ step-up}$. The voltage is then stepped down for use by the load, $V_{1,\ step-down} > V_{load}$.	Although the voltage is decreased and the current is increased, we assume that the transformer is ideal, so no power is lost across the transformer.

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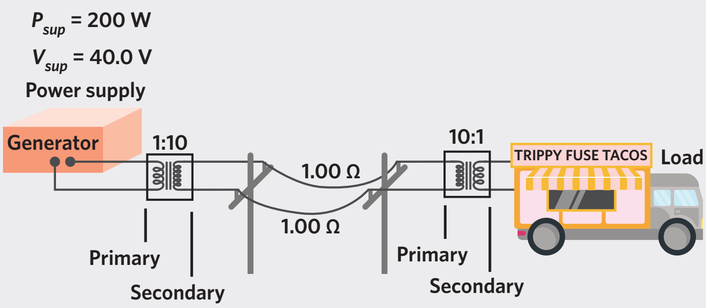
WORKED EXAMPLE 2

Consider the power transmission system used to supply the food truck from Worked Example 1. The same generator (200 W at 40.0 V_{RMS}) is used with the same transmission lines (1.00 Ω each). To reduce power losses, the owner installs a step-up transformer with a 1:10 turns ratio between the generator and the transmission lines, and a step-down transformer with a 10:1 turns ratio between the transmission lines and the truck.



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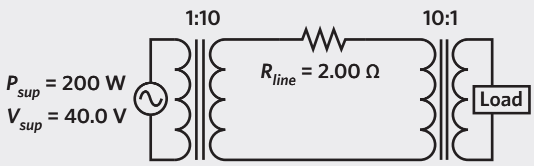
a. Model the electrical circuit shown in a circuit diagram.

Breakdown

The generator is an AC power supply.

The transmission lines can be modelled as a single resistor with 2.00 Ω resistance.

Answer



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b. Calculate the current in the transmission lines.

Step 1

Identify known and unknown variables and write down the formula that relates these variables.

$P_{supply} = 200$ W, $V_{supply} = 40.0$ V, $I_{supply} = ?$

$P_{supply} = V_{supply} I_{supply}$

Step 2

Substitute values into the formula and solve for the current in the circuit.

$200 = 40.0 \times I_{supply}$

$I_{supply} = 5.00$ A

Step 3

Identify known and unknown variables and write down the formula that relates these variables.

$I_{supply} = 5.00$ A, $N_{supply} = 1$, $N_{line} = 10$, $I_{line} = ?$

$$\frac{I_{supply}}{I_{line}} = \frac{N_{line}}{N_{supply}}$$

Step 4

Substitute values into the formula and solve for the current in the transmission lines.

$$\frac{5.00}{I_{line}} = \frac{10}{1}$$

$I_{line} = 0.500$ A

---

c. Calculate the power loss in the transmission lines.

Step 1

Identify known and unknown variables and write down the formula that relates these variables.

$I_{line} = 0.500$ A, $R_{line} = 2.00$ Ω, $P_{loss} = ?$

$P_{loss} = I_{line}{}^2 R_{line}$

Step 2

Substitute values into the formula and solve for the power loss in the transmission lines.

$P_{loss} = 0.500^2 \times 2.00$

$P_{loss} = 0.500$ W

Continues →

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d. Calculate the power delivered to the food truck

Step 1

Identify known and unknown variables and write down the formula that relates these variables.

$P_{supply} = 200$ W, $P_{loss} = 0.500$ W, $P_{load} = ?$

$P_{load} = P_{supply} - P_{loss}$

Step 2

Substitute values into the formula and solve for the power delivered to the food truck.

$P_{load} = 200 - 0.500$

$P_{load} = 199.5$ W

Table 4 compares the results from Worked Example 1 and Worked Example 2, to show how the use of transformers in transmitting electricity allows for higher efficiency transmission.

Table 4 shows that by using transformers, less power is lost in the transmission lines, resulting in more power being delivered to the food truck.

Table 4 Transmitting power with vs. without the use of transformers

	Voltage drop across transmission lines	Voltage drop across food truck	Power loss across transmission lines	Power dissipated by food truck	Power loss %
Without transformer	$V_{drop} = 10.0$ V	$V_{load} = 30.0$ V	$P_{loss} = 50.0$ W	$P_{load} = 150$ W	25%
With transformer	$V_{drop} = 1.00$ V	$V_{load} = 39.9$ V	$P_{loss} = 0.500$ W	$P_{load} = 199.5$ W	0.25%

PROGRESS QUESTIONS

Question 3

Which of the following best describes why AC power is preferred to constant DC power for long distance power transmission?

A. because AC power is faster to transmit that DC power.

B. because AC power is easier to generate than DC power.

C. because it's easier to build appliances that use AC power than DC power.

D. because AC power can be transmitted more efficiently than DC power with the use of transformers.

Question 4

Which of the following can be used to calculate the power loss in transmission lines? **(Select all that apply)**

A. $P_{loss} = V_{line} I_{line}$ **B.** $P_{loss} = V_{drop} I_{line}$ **C.** $P_{loss} = I_{line} R_{line}$ **D.** $P_{loss} = I_{line}{}^2 R_{line}$

Use the following information to answer questions 5 and 6.

In an AC power transmission system, a step-up transformer is installed between the power supply and the transmission lines. The transformer has a turns ratio of 1:4.

Question 5

By what factor will the voltage drop across the transmission lines decrease?

A. 2 **B.** 4 **C.** 8 **D.** 16

Question 6

By what factor will the power loss in the transmission lines decrease?

A. 2 **B.** 4 **C.** 8 **D.** 16

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Theory summary

- Simple power transmission systems consist of a power supply, transmission lines, and a load.
- Transmission lines over long distances have a significant resistance which can lead to a significant voltage drop and power loss.
- Transformers are used to step up the voltage for transmission, which reduces the current in the transmission lines and therefore voltage drop and power loss in the lines.
  - Power loss in the lines can be calculated using $P_{loss} = V_{drop} I_{line} = I_{line}{}^2 R_{line}$.
- As transformers require AC electricity to work properly, they are not effective in transmission systems which use constant DC electricity.

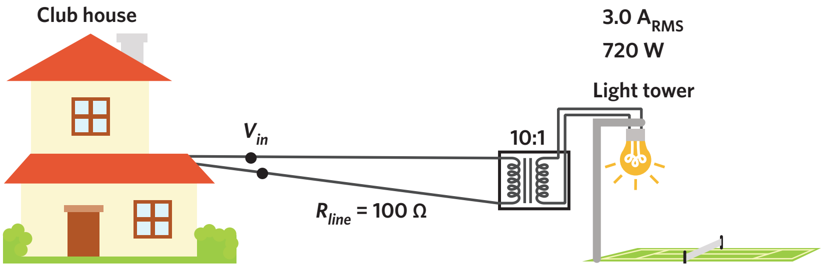
6C Questions

Mild 🌶 Medium 🌶🌶 Spicy 🌶🌶🌶

Deconstructed exam-style

Use the following information to answer questions 7–10.

A clubhouse power supply is used to power lights so that they operate at 3.0 A_{RMS} and 720 W. The connecting wires have a total resistance, R_{line}, of 100 Ω. To reduce the power loss in the connecting wires, an electrician installed a 10:1 step-down transformer near the light tower.



Question 7 🌶 (1 MARK)

Which of the following expressions about power in the transmission circuit is true?

A. $P_{supply} = P_{loss} = P_{light}$

B. $P_{supply} = P_{loss} + P_{light}$

C. $P_{supply} = P_{loss} - P_{light}$

D. $P_{supply} = P_{light} - P_{loss}$

Question 8 🌶 (1 MARK)

Calculate the current through the transmission lines.

Question 9 🌶 (1 MARK)

How can the power loss in the transmission lines be calculated?

A. $P_{loss} = I_{line} R_{line}$

B. $P_{loss} = V_{line} R_{line}$

C. $P_{loss} = I_{line}{}^2 R_{line}$

D. $P_{loss} = V_{line} I_{line} R_{line}$

Question 10 🌶🌶 (4 MARKS)

Calculate the power supplied by the clubhouse.

Adapted from VCAA 2019 NHT exam Short answer Q4c

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Exam-style

Question 11 (1 MARK)

Electrical power stations are often situated far from the cities. Which one of the following best describes the reason for the high-voltage transmission of electrical energy?

A. Transformers can be used to increase the voltage in the cities.

B. High voltages reduce the energy losses in the transmission lines.

C. High voltages provide the large currents needed for efficient transmission.

D. High voltages can reduce the overall total resistance in the transmission lines

Adapted from VCAA 2021 NHT exam Multiple choice Q7

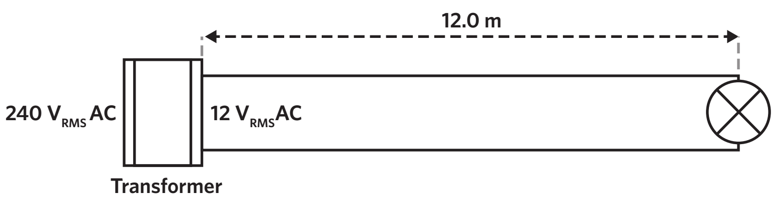
Question 12 (5 MARKS)

Angela and Janek are installing a low-voltage light in their outdoor garden. They have a 240 V_{RMS} AC transformer with an output voltage of 12 V_{RMS} AC. For the purposes of calculations, assume that the transformer is ideal.

a. Describe what is meant by an ideal transformer in terms of the input power and the output power. 1 MARK

b. Calculate the ratio of the number of turns of the primary coil to the number of turns of the secondary coil. 1 MARK

c. Angela and Janek now connect the light to the transformer using two wires, each 12.0 m long, as shown. Each wire has a resistance of 0.050 Ω m^{-1}. Calculate the RMS voltage across the light, when 3.0 A runs through the transmission lines. 3 MARKS



Adapted from VCAA 2021 NHT exam Short answer Q7

Question 13 (7 MARKS)

Key science skill

Students are investigating the effects of power loss. They attach an AC power supply to the primary coil of a step-up transformer, and a light globe to the secondary coil.

a. The students add a resistor in series with the AC power supply in the primary circuit to represent resistance in the transmission lines. Predict how the brightness of the light globe will change when the resistor is added. 2 MARKS

b. The students now move the resistor to the secondary circuit. Predict how the brightness of the light globe will change when the resistor is moved. 3 MARKS

c. The students now replace the AC power supply with a DC battery. Predict how the brightness of the light globe will change after the DC battery has been on for a short period of time. 2 MARKS

FROM LESSON 12A

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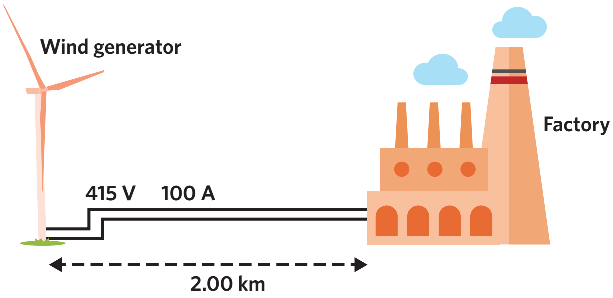
Question 14 (8 MARKS)

A wind generator provides power to a factory located 2.00 km away, as shown. When there is a moderate wind blowing steadily, the generator produces an RMS voltage of 415 V and an RMS current of 100 A. The total resistance of the transmission wires between the wind generator and the factory is 2.00 Ω.



a. Show that the power, in kilowatts, produced by the wind generator when there is a moderate wind blowing steadily is 41.5 kW. 1 MARK

b. To operate correctly, the factory's machinery requires a power supply of 40 kW. Determine whether the energy supply system, as shown, will be able to supply power to the factory when the moderate wind is blowing steadily. Justify your answer with calculations. 3 MARKS

c. The factory's owner decides to limit transmission power loss by installing two transformers: a step-up transformer with a turns ratio of 1:10 at the wind generator and a step-down transformer with a turns ratio of 10:1 at the factory. Each transformer can be considered ideal. With the installation of the transformers, determine the power, in kW, now supplied to the factory. 4 MARKS

Adapted from VCAA 2022 exam Short answer Q5

Question 15 (1 MARK)

Charlotte has installed a step-up transformer to transmit power from her AC generator to her house, but finds that 10 kW of power is being lost in the transmission lines. Her friend Ava suggests a new system with double the number of turns in the secondary coil. If Charlotte installs the new system, how much power will Charlotte lose in transmission?

A. $\frac{1}{4}$ of the original

B. same as the original

C. twice the original

D. four times the original

Question 16 (7 MARKS)

The generator of an electrical power plant delivers 500 MW to external transmission lines when operating at 25 kV. The generator's voltage is stepped up to 500 kV for transmission and stepped down to 240 V, 100 km away, for domestic use. The overhead transmission lines have a total resistance of 30.0 Ω. Assume that all transformers are ideal.

a. Calculate the current in the overhead transmission lines. 2 MARKS

b. Determine the maximum power available for domestic use at 240 V. 3 MARKS

c. Explain why the voltage is stepped up for transmission along the overhead transmission lines. 2 MARKS

Adapted from VCAA 2021 exam Short answer Q7

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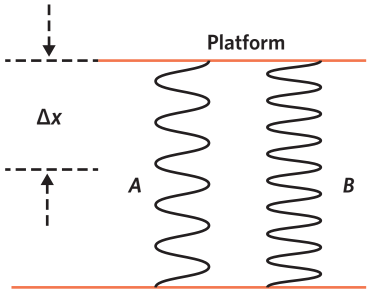
Previous lessons

Question 17 (4 MARKS)

Students are investigating a spring system consisting of two different springs, *A* and *B*. The two springs have the same unstretched length. A platform rests horizontally on both of the springs. Assume that the platform has negligible mass.



Spring *A* has a spring constant, k_A, of 3.00 N m^{-1}. The students place various masses on the platform and record the compression in the vertical direction, Δx. One of the measurements is shown.

Mass (g)	Vertical compression, Δx (cm)
60.0	5.88

a. When the 60.0 g mass rests on the platform, calculate the upward force exerted on the platform by spring *A*. 2 MARKS

b. When the 60.0 g mass rests on the platform, calculate the upward force exerted on the platform by spring B. 2 MARKS

FROM LESSON 2E

Adapted from VCAA 2019 exam Short answer Q19

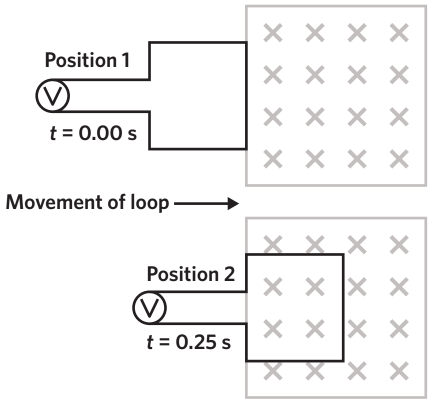
Question 18 (2 MARKS)

A square loop of 15 turns and a cross-sectional area of 4.0×10^{-3} m^2 passes into a magnetic field of magnitude 2.4×10^{-2} T at a constant speed. It takes 0.25 s for the loop to travel from position 1 to 2.

Calculate the magnitude of the average EMF induced in the loop as it moves from position 1 to 2.

Adapted from VCAA 2018 exam Short answer Q2a

FROM LESSON 5A



Chapter 6 review

Mild 🌶 Medium 🌶🌶 Spicy 🌶🌶🌶

These questions are typical of one hour's worth of questions on the VCE Physics Exam.

Total marks: 50

Section A

All questions in this section are worth one mark.

Unless otherwise indicated, the diagrams in this book are not drawn to scale.

Use the following information to answer questions 1 and 2.

In order to power an electric tool, a farmer must use a step-down transformer that has an input of 240 V_{RMS} AC and an output of 16 V_{RMS} AC. Assume the transformer is ideal.

Question 1 🌶

What is the ratio in the number of turns in the primary coil compared to the secondary coil (N_1:N_2)?

A. 20:1

B. 15:1

C. 1:20

D. 1:15

Adapted from 2017 VCAA Exam Section A Q4

Question 2 🌶🌶

If the primary coil delivers 80 W_{RMS}, what is the value of the peak current in the transformer's secondary coil?

A. 3.5 A_{RMS}

B. 5.0 A_{RMS}

C. 7.1 A_{RMS}

D. 11 A_{RMS}

Adapted from 2017 VCAA Exam Section A Q5

Question 3 🌶

The total resistance of a power line is known to be 2.0 Ω. If the power loss in the line is 2450 W, what is the current that flows through the power line?

A. 14 A_{RMS}

B. 25 A_{RMS}

C. 35 A_{RMS}

D. 70 A_{RMS}

Question 4

An ideal transformer has 180 turns on the primary coil and 2880 turns on the secondary coil. The input to the transformer is 60.0 V_{RMS} AC at 60.0 Hz. Which of the following identifies the frequency and peak voltage of the transformer's output?

	Frequency (Hz)	Output (V)
A.	60.0	9.60×10^2
B.	60.0	1.36×10^3
C.	9.60×10^2	6.79×10^2
D.	1.36×10^3	60.0

Question 5

Pendles uses an electrical transmission circuit with a step-up transformer before the transmission lines and a step-down transformer after the transmission lines. In order to decrease power loss, he proposes some modifications to the transmission lines and their existing transformers.

Which of the following options could be used by Pendles to decrease the power loss in the transmission lines?

A. add a transformer with $N_2 = N_1$

B. increase the resistance of the wires

C. increase the current in the transmission wire

D. decrease the number of primary turns in the step-up transformer

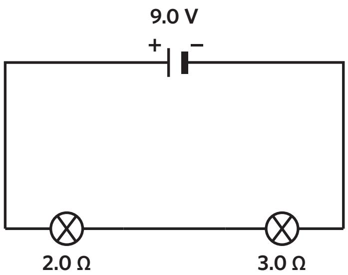
Section B

In questions where more than one mark is available, appropriate working must be shown.

Unless otherwise indicated, the diagrams in this book are not drawn to scale.

Question 6 (5 MARKS)

A 9.0 V cell is used to power two light globes in series arranged as shown.



a. What is the total resistance of the circuit? 1 MARK

b. What is the current in the circuit? 2 MARKS

c. Calculate the voltage drop across the 2.0 Ω resistor. 1 MARK

d. Calculate the power dissipated by the 3.0 Ω resistor. 1 MARK

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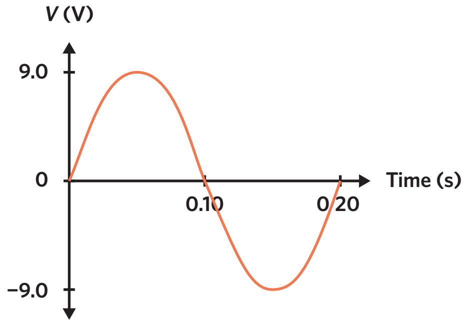
Question 7 (3 MARKS)

The graph shows the AC signal produced by an alternator.



a. *Key science skill*
Determine the peak voltage. 1 MARK

FROM LESSON 12D

b. *Key science skill*
Determine the peak-to-peak voltage. 1 MARK

FROM LESSON 12D

c. Calculate the root-mean-square voltage. 1 MARK

Question 8 (3 MARKS)

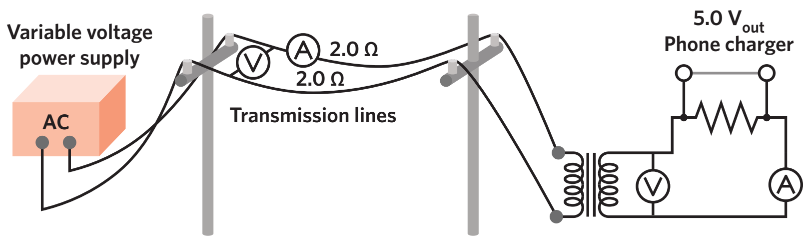
A power supply producing an AC voltage of 200 V_{RMS} is placed in series with a 100 Ω resistor.

a. Calculate the peak voltage of the power supply. 1 MARK

b. What is the equivalent DC voltage that will provide the same average power as the AC power supply? Justify your answer. 2 MARKS

Question 9 (13 MARKS)

Coco decides she will try to create her own power transmission system to recharge her phone. She connects two transmission wires, each with a resistance of 2.0 Ω, between an AC power supply and a variable ratio step-down transformer. The output of the transformer is connected to her phone charger. The variable ratio transformer is set to have a primary to secondary ratio of 3:1 and there is a current of 2.5 A_{RMS} in the transmission wires. With this setup the phone charger correctly operates at 5.0 V_{RMS}.



a. What is the total power loss in the transmission wires? 2 MARKS

b. Calculate the power delivered to the phone charger. 3 MARKS

c. What is the power output of the power supply? 2 MARKS

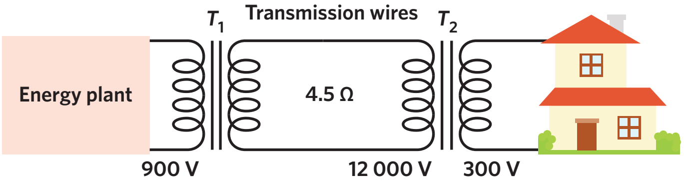
d. Coco changes the variable transformer so that it now has a ratio of 6:1 and adjusts the power supply so the phone charger operates correctly with 5.0 V_{RMS} across it. Calculate how much power will now be lost over the transmission lines. 3 MARKS

e. Explain why AC power is preferred for long-distance power transmission compared to a constant DC power supply. 3 MARKS

Adapted from VCAA 2018 exam Short answer Q5

Question 10 (7 MARKS)

Two transformers, T_1 and T_2, are used when transmitting power from a green energy plant that produces 900 V_{RMS} to a home which requires 300 V_{RMS}. The voltage input at the primary coil of T_2 is 12 000 V_{RMS}. The secondary coil of T_2 has 50 turns. The energy plant produces constant power. A diagram of the setup is shown.



a. How many turns are on the primary coil of T_2? 2 MARKS

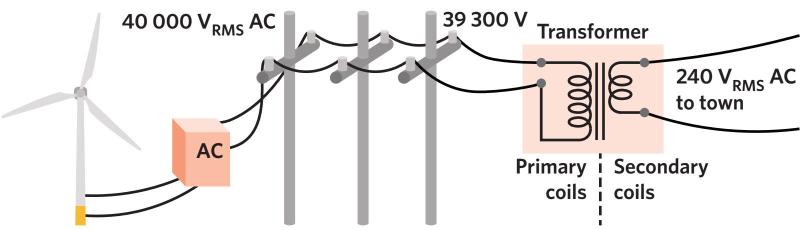
b. The ratio of secondary to primary coils in T_1 is doubled. Express the new power loss, $P_{new\ loss}$, as a proportion of the original power loss, $P_{old\ loss}$. Show your working. 2 MARKS

Adapted from VCAA 2017 exam Short answer Q6b

c. Explain why the transformers would be ineffective if the energy plant was replaced with a large DC battery. 3 MARKS

Question 11 (9 MARKS)

Jazzy is a young and aspiring electrical engineer with the selfless desire to power her town using Melbourne's Antarctic winds. She builds a wind turbine that produces 40 000 V_{RMS} AC and connects it to two 25 km transmission wires. The wires carry a current of 10.0 A_{RMS} to a transformer in her house where an input voltage of 39 300 V_{RMS} is converted to 240 V_{RMS}.



a. What power does the wind turbine supply to the transmission wires? 2 MARKS

Adapted from VCAA 2011 Exam 2 Area of Study 1 Section A Q13

b. 15% of the total power supplied is lost. What is the resistance per metre of the power lines? Give your answer in $\Omega\ km^{-1}$. 4 MARKS

c. Explain how the transformer induces an EMF in the secondary coil. 3 MARKS

Question 12 (5 MARKS)

Key science skill

Draw and label an electrical circuit that meets the following conditions:

- 10 000 W_{RMS} is generated at 500 V_{RMS} from an AC power supply
- resistance lines are used with a total resistance of 5.00 Ω to deliver power to a load
- the load requires 9980 W_{RMS} and a current of 50 A_{RMS} in order to work correctly

You must use two transformers and label the turns ratio of each. Calculations may be required.

Unit 3 AOS 3 review

Mild Medium Spicy

These questions are typical of one hour's worth of questions on the VCE Physics Exam.

Total marks: 50

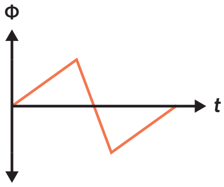
Section A

All questions in this section are worth one mark.

Unless otherwise indicated, the diagrams in this book are not drawn to scale.

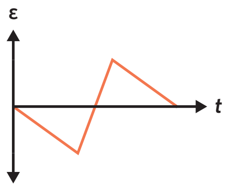
Question 1

The graph shows the magnetic flux passing through a coil of wire over time.

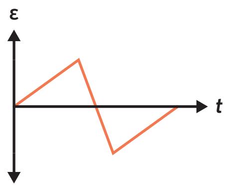


Which of the following graphs could be the resulting EMF induced within the coil of wire?

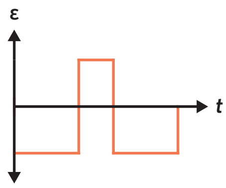
A.



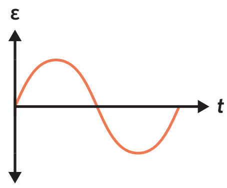
B.



C.



D.



Adapted from VCAA 2017 exam Multiple choice Q6

Use the following information to answer questions 2 and 3.

While creating a high voltage electric fence, Nikola uses a step-up transformer that converts 240 V_{RMS} to 6000 V_{RMS}. It is known that the transformer is ideal and that the primary coil delivers 75.0 W_{RMS} to the transformer.

Question 2

What is the ratio of turns in the primary coil to the secondary coil in the transformer?

A. 1:80

B. 1:25

C. 25:1

D. 80:1

Adapted from VCAA 2017 exam Multiple choice Q4

Question 3

What is the peak current in the secondary coil of the transformer?

A. 1.25×10^{-2} A

B. 1.77×10^{-2} A

C. 8.00×10^{1} A

D. 1.13×10^{2} A

Adapted from VCAA 2017 exam Multiple choice Q5

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Question 4

An AC generator is used to power a machine that requires a voltage of 7.5 V_{RMS}. The generator has 80 turns of wire which, in a quarter of rotation, experience a change in magnetic flux of 2.2 mWb.

For the correct functioning of the machine, what is the period of a quarter rotation of the generator?

A. 2.3×10^{-2} s

B. 3.3×10^{-2} s

C. 4.3×10^{-2} s

D. 2.3×10^{1} s

Question 5

In order to increase the output voltage of a DC generator, a manufacturer could

A. use slip rings.

B. use a weaker magnet.

C. reduce the area of the coils.

D. decrease the period of rotation.

Section B

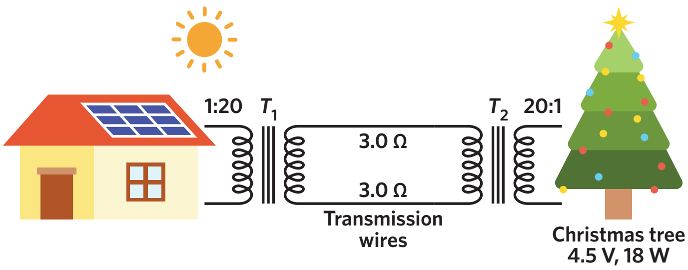
In questions where more than one mark is available, appropriate working must be shown.

Unless otherwise indicated, the diagrams in this book are not drawn to scale.

Question 6

(13 MARKS)

In order to power their Christmas tree lights, a family use their solar panels and an inverter to produce AC power. They position a step-up transformer, T_1, and a step-down transformer, T_2, with ratios of 1:20 and 20:1, respectively, between the solar panels and the Christmas tree. Their goal is to efficiently power the 4.5 V, 18 W Christmas tree lights via two transmission wires with a resistance of 3.0 Ω each.



a. If the lights are operating correctly, what is the current in the transmission wires? — 3 MARKS
Adapted from VCAA 2015 exam Section A Q16a

b. Determine the power loss in the transmission wires. — 2 MARKS
Adapted from VCAA 2015 exam Section A Q16c

c. Calculate the voltage input to the step-up transformer required for the lights to function correctly. — 4 MARKS

d. Explain why AC is favourable for long-distance power transmission compared to DC. — 3 MARKS
Adapted from VCAA 2015 exam Section A Q16f

e. Describe the purpose of an inverter in connecting solar panels to the existing electrical grid. — 1 MARK

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Question 7 (6 MARKS)

An alternator that produces 9.0 V_{RMS} and 3.5 A_{RMS} is used to transport power from a farmer's shed to a home 400 m away. Due to the distance, the farmer decides to install a step-up transformer with a turns ratio of 1:10 immediately after the generator.

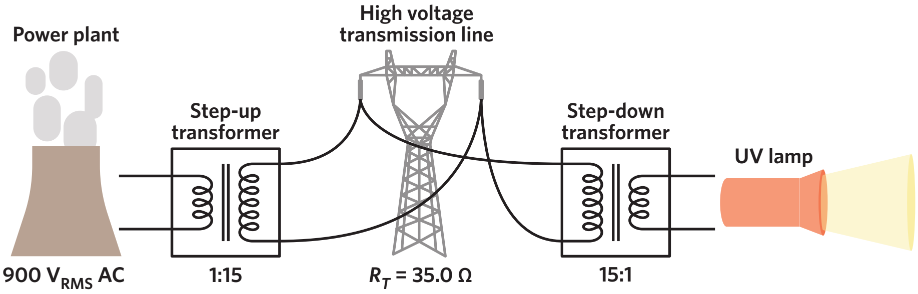
a. Explain the function of slip rings in an alternator and how they work. 2 MARKS

b. If the total resistance of the transmission lines carrying power from the transformer to the farmer's house is 3.5 Ω, what is the power loss in the lines? 2 MARKS

c. What change could the farmer make to his generator to produce DC electricity? Explain your answer. 2 MARKS

Question 8 (7 MARKS)

A sunbaking enthusiast decides to redirect the electricity from their city's transmission line into an experimental UV lamp. They utilise the existing ideal step-up and step-down transformers with ratios of 1:15 and 15:1 respectively. The lamp correctly operates with 890 V across it. The transmission line has a total resistance of 35.0 Ω and carries a current of 16.0 A. The city's power plant produces 900 V_{RMS} AC.



a. How much power is lost in the transmission lines? 2 MARKS

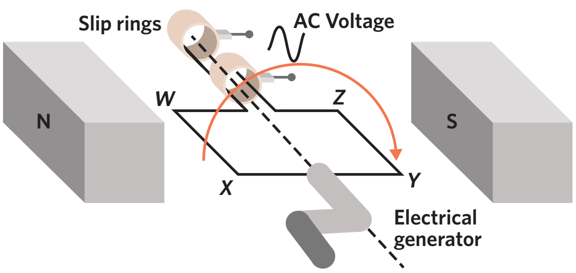
Adapted from VCAA 2018 exam Short answer Q5c

b. Determine the voltage across the UV lamp. 4 MARKS

c. The UV lamp does not operate correctly with this set up. State one change that could be made to the power system so that the lamp correctly operates. 1 MARK

Question 9 (10 MARKS)

Kayla constructs a simple alternator with 10 loops of wire measuring 7.5 cm × 12.5 cm, which she rotates 12 times per second. A magnetic flux of 7.5×10^{-3} Wb passes through the coil when its in the vertical position.



a. What is the strength of the magnetic field acting on the coil? 1 MARK

b. Find the average EMF induced in the coil over one quarter rotation. 3 MARKS

c. Would the induced current in the coil over the first quarter rotation be in the direction X to Y or Y to X? Explain your answer. 3 MARKS

d. Kayla gets tired and the rotation of the generator slows at a constant rate. Draw a graph showing how the EMF in the coil changes over time as the rotation slows. Values are not required. 3 MARKS

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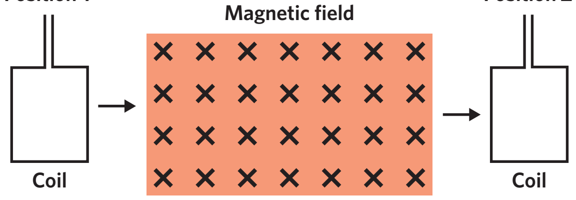
Question 10 (9 MARKS)

A rectangular coil of wire made of 25 loops, measuring 15 cm × 25 cm, is moved back and forth through a magnetic field of 0.500 T at a constant speed. The diagram shows the apparatus as viewed from the north pole of the magnet creating the field.



a. Draw a graph that shows the magnetic flux passing through the coil vs. time as it moves from position *Y* to position *Z*, and then back to position *Y*. You do not need to include any values. 2 MARKS

b. Draw a graph that shows the induced EMF versus time as the coil moves from position *Y* to position *Z*, and then back. You do not need to include any values. 2 MARKS

c. If the coil takes 0.10 s to move from completely outside the magnetic field to completely inside, what is the magnitude of the induced EMF in the coil? 2 MARKS

d. As viewed from the north pole of the magnet, determine the direction of the current in the coil as it enters the magnetic field. Justify your answer. 3 MARKS

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4

UNIT 4

How have creative ideas and investigation revolutionised thinking in physics?

A complex interplay exists between theory and experiment in generating models to explain natural phenomena. Ideas that attempt to explain how the Universe works have changed over time, with some experiments and ways of thinking having had significant impact on the understanding of the nature of light, matter and energy. Wave theory, classically used to explain light, has proved limited as quantum physics is utilised to explain particle-like properties of light revealed by experiments. Light and matter, which initially seem to be quite different, on very small scales have been observed as having similar properties. At speeds approaching the speed of light, matter is observed differently from different frames of reference. Matter and energy, once quite distinct, become almost synonymous.

In this unit, students explore some monumental changes in thinking in Physics that have changed the course of how physicists understand and investigate the Universe. They examine the limitations of the wave model in describing light behaviour and use a particle model to better explain some observations of light. Matter, that was once explained using a particle model, is re-imagined using a wave model. Students are challenged to think beyond how they experience the physical world of their everyday lives to thinking from a new perspective, as they imagine the relativistic world of length contraction and time dilation when motion approaches the speed of light. They are invited to wonder about how Einstein's revolutionary thinking allowed the development of modern-day devices such as the GPS.

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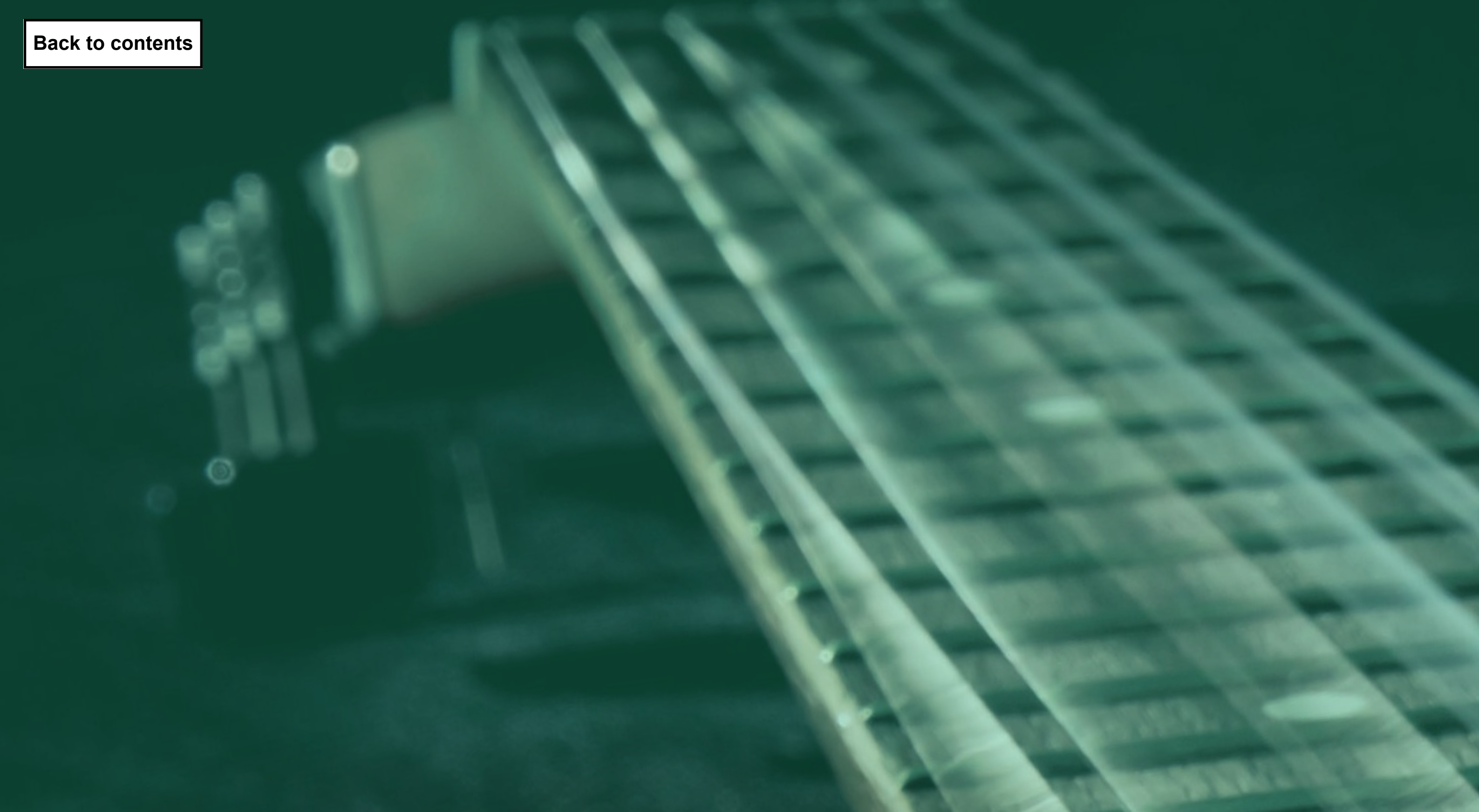

UNIT 4 AOS 1

How has understanding about the physical world changed?

In this area of study, students learn how understanding of light, matter and motion have changed over time. They explore how major experiments led to the development of theories to describe these fundamental aspects of the physical world.

When light and matter are probed, they appear to have remarkable similarities. Light, previously described as an electromagnetic wave, appears to exhibit both wave-like and particle-like properties. Findings that electrons behave in a wave-like manner challenged thinking about the relationship between light and matter.

Students consider the limitations of classical mechanics as they explore Einstein's view of the Universe. They consider postulates as distinct from theories and explore ideas related to objects moving at speeds approaching the speed of light. They use special relativity to explore length contraction and time dilation as observations are made by observers in different frames of reference, and the interrelationship between matter and energy.

Outcome 1

On completion of this unit the student should be able to analyse and apply models that explain the nature of light and matter, and use special relativity to explain observations made when objects are moving at speeds approaching the speed of light.

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7

CHAPTER 7

Properties of a mechanical wave

STUDY DESIGN DOT POINTS

- explain the formation of a standing wave resulting from the superposition of a travelling wave and its reflection
- analyse the formation of standing waves (only those with nodes at both ends is required)
- investigate and explain theoretically and practically diffraction as the directional spread of various frequencies with reference to different gap width or obstacle size, including the qualitative effect of changing the $\frac{\lambda}{w}$ ratio, and apply this to limitations of imaging using electromagnetic waves

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LESSONS

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7A Waves recap

STUDY DESIGN DOT POINT

- There are no study design dot points for this lesson.

7A 7B 7C 7D

1.1.2.1 Wave properties

1.1.3.1 & 1.1.4.1 The wave equation

ESSENTIAL PRIOR KNOWLEDGE

- Reading values off graphs

See question 64.

Image: Katerina_S/Shutterstock.com

What is a sonic boom?

If you've ever heard the crack of a whip or seen a supersonic jet then you will have heard a sonic boom – the sound made when an object travels faster than the speed of sound. But what is sound and why does its speed depend on the medium it's travelling through? In order to answer these questions we need to understand waves and their properties. This lesson covers identifying and calculating the properties of waves.

KEY TERMS AND DEFINITIONS

wave the transmission of energy via oscillations from one location to another without the net transfer of matter

transverse wave a wave in which the oscillations are perpendicular to the direction of wave travel and energy transmission

longitudinal wave a wave in which the oscillations are parallel to the direction of wave travel and energy transmission

amplitude (waves) the magnitude of an oscillation's maximum value from the neutral point within a wave

wavelength the distance covered by one complete wave cycle

period the time taken to complete one cycle

frequency the number of cycles completed per second

wave cycle the process of a wave completing one full oscillation, ending up in a final configuration identical to the initial configuration

wave speed the speed at which a wave travels through a medium

FORMULAS

- **frequency**
  $f = \frac{1}{T}$
- **wave equation**
  $v = f\lambda$

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Wave properties 1.1.2.1

A **wave** is the transmission of energy via oscillations from one location to another without the net (overall) transfer of matter. The direction a wave travels is defined by the direction of the energy transmission.

How do we identify the properties of waves?

All waves transfer energy without transferring matter with them and can either be classified as **transverse waves** or **longitudinal waves**.

Figure 1 shows ocean waves transferring energy across the water without taking the water or the ball with them. Even though the waves are moving to the left, the water and the ball oscillate up and down. This is an example of a transverse wave – a wave in which the oscillations are perpendicular to the direction the wave travels. The top of transverse waves are called crests and the bottom of transverse waves are called troughs.

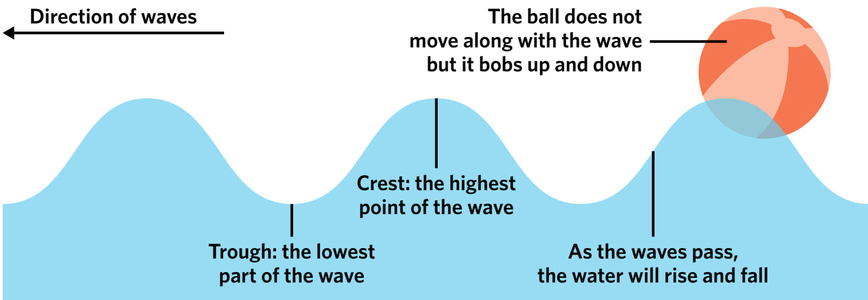

Figure 1 Properties of a transverse water wave

Figure 2 shows there is also no net transfer of matter within a longitudinal sound wave. Each air particle oscillates parallel to the direction of the wave (left and right) about their neutral position. This causes areas of:

- maximum pressure, called compressions, where the air particles are close together
- minimum pressure, called rarefactions, where the air particles are farthest apart

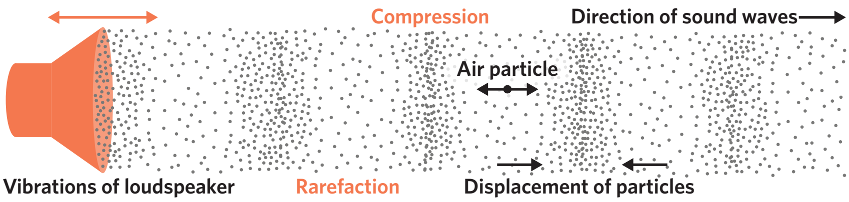

Figure 2 Properties of a longitudinal sound wave

Four important properties of waves include: **amplitude**, **wavelength**, **period**, and **frequency**. They are essential in describing the behaviour of all waves, whether longitudinal or transverse. Table 1 describes these properties and shows their symbols and units.[1]

KEEN TO INVESTIGATE?

[1] **What are the properties of a wave?**
Search YouTube: Wave motion

Table 1 Wave properties

Property	Description	Representation	SI Unit
Wavelength	The distance covered by one complete **wave cycle**.	λ	metres (m)
Frequency	The number of wavelengths that pass a particular point every second.	f	hertz (Hz) or s^{-1}
Period	The time it takes to complete one cycle of a wave.	T	seconds (s)
Amplitude	The maximum displacement of a particle from its neutral position.	A	metres (m)

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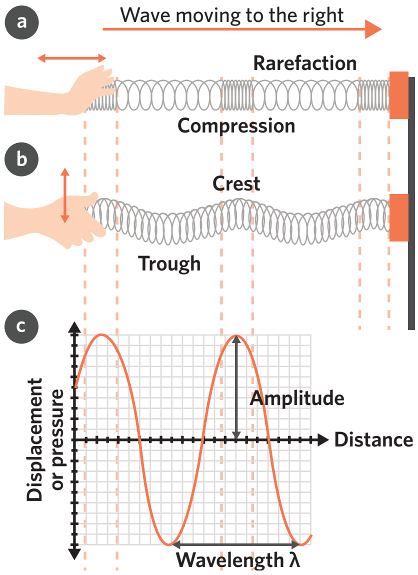

Figure 3 **(a)** A longitudinal wave and **(b)** an equivalent transverse wave **(c)** graphed as a displacement-distance graph.

KEEN TO INVESTIGATE?

[2] **How are transverse waves created?**
Search: Wave on a string simulation

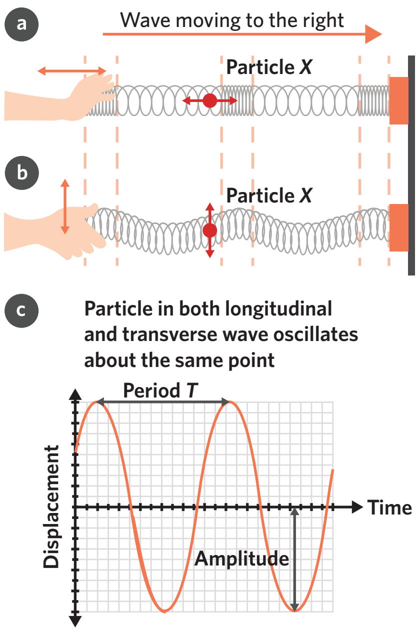

Figure 4 **(a)** A longitudinal wave and **(b)** an equivalent transverse wave **(c)** graphed as a displacement-time graph.

Period and frequency are mathematically related through the formula:

FORMULA

$$f = \frac{1}{T}$$

f = frequency (Hz or s^{-1})
T = period (s)

This shows that frequency and period are inversely proportional. With an inverse relationship, if the frequency doubles, then the period will halve and vice versa. Frequency is measured in Hz, which is the number of wavelengths that pass a point each second.

PROGRESS QUESTIONS

Question 1

Which of the following statements correctly describes the difference between longitudinal and transverse waves?

A. Longitudinal waves travel in a straight line, while transverse waves travel in a curved path.

B. Longitudinal waves have crests and troughs, while transverse waves have compressions and rarefactions.

C. Longitudinal waves require a medium to propagate, while all transverse waves can propagate through a vacuum.

D. Longitudinal waves oscillate parallel to the direction of wave propagation, while transverse waves oscillate perpendicular to the direction of wave propagation.

Question 2

If the frequency of a sound wave is 3.0 Hz, which of the following is closest to its period?

A. 0.33 s **B.** 0.50 s **C.** 0.66 s **D.** 3.0 s

How do we represent waves?

Waves can be represented using either displacement-distance or displacement-times graphs.[2]

To graph a wave on a displacement-distance graph, we can imagine freezing a longitudinal or transverse wave at a point in time and measuring its displacement (Figure 3).

- The amplitude of the wave is the distance from the horizontal axis to the top or bottom of the graph.
- The wavelength is the distance between consecutive crests or consecutive troughs on the graph.
  - For longitudinal waves, this is the distance between consecutive compressions or consecutive rarefactions.

To graph a wave on a displacement-time graph, we must consider the movement of a single particle within that wave over a period of time. The particle will oscillate about its neutral position as the wave travels through it (Figure 4).

- The amplitude is still the distance from the horizontal axis to the top or bottom of the graph.
- The period is the time between consecutive crests and consecutive troughs on the graph. For both longitudinal and transverse waves this is the time it takes one wave cycle to travel through the particle.

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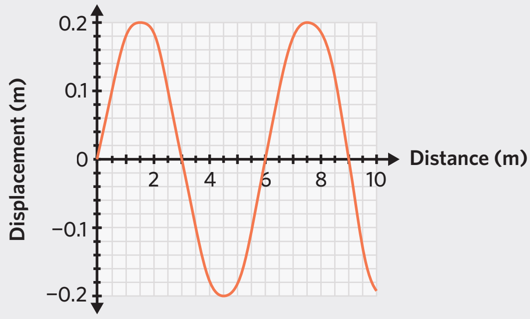
WORKED EXAMPLE 1

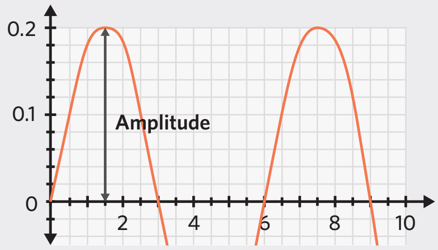
A wave is graphed at a single point in time.



a. Determine the amplitude. Make sure to use correct units in your answer.

Step 1

Use the graph to measure the distance between the horizontal axis and the maximum displacement of the particle.



Step 2

The unit of the final answer must be the unit represented on the vertical axis which is m.

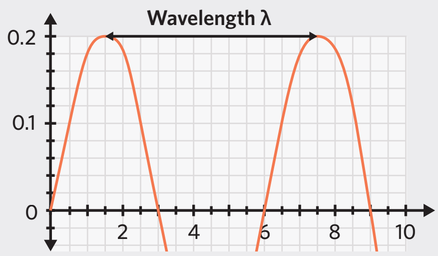
Amplitude is the maximum displacement of the particle.

$A = 0.2$ m

b. Determine the wavelength. Make sure to use correct units in your answer.

Step 1

Use the graph to measure the distance between crests to calculate the wavelength.



Step 2

The unit of the final answer must be the unit represented on the horizontal axis which is m.

Step 2

Wavelength is the distance between consecutive crests.

$\lambda = 7.5 - 1.5 = 6$ m

c. Can we calculate the frequency or period of the wave from this graph? Justify your answer.

Breakdown

Identify the limitation of a displacement distance graph.

Answer

The graph given has distance on its horizontal axis, therefore the period is unable to be found.

Justify your answer by connecting the period to the frequency.

Frequency is calculated from the period of the wave. As period can't be found, neither can frequency.

PROGRESS QUESTIONS

Question 3

In a longitudinal wave, wavelength is measured between

A. the first and second waves.
B. an adjacent crest and trough.
C. consecutive compressions or rarefactions.
D. Wavelength can't be measured for a longitudinal wave.

Question 4

Which of the following features can be read off a displacement–distance graph? **(Select all that apply)**

A. period **B.** frequency **C.** amplitude **D.** wavelength

Question 5

Which of the following features can be read off a displacement-time graph? **(Select all that apply)**

A. period **B.** frequency **C.** amplitude **D.** wavelength

The wave equation 1.1.3.1 & 1.1.4.1

The physical properties of the medium through which a wave travels determines its speed. The source of the wave determines its frequency. Wavelength is determined by its relationship to frequency and **wave speed** through the wave equation.

How are the speed and frequency of a wave determined?

Wave speed is the speed at which the wave transfers its energy through a medium from one place to another. It is determined by the physical properties of the medium in which it travels (e.g. state, stiffness, and temperature) (Table 2).

Table 2 Sound wave speed through different mediums

Medium	Speed of a sound wave
Air at sea level	340 m s^{-1}
Air at high altitude	303 m s^{-1}
Water	1482 m s^{-1}
Steel	5960 m s^{-1}

Wave frequency is determined by how fast the source of the wave is vibrating/oscillating. The faster the source is vibrating, the higher the frequency of a wave. Take sound for example; a speaker vibrating slower will produce a sound at a lower frequency.

MISCONCEPTION

'Sound travels faster in denser materials.'

Sound does not travel faster in denser materials! Sound actually travels slower in denser materials but travels faster in more rigid materials – gold is denser than glass, but sound travels faster in glass because glass is more rigid than gold.

MISCONCEPTION

'The speed of a wave is the speed of an individual particle on the wave.'

Wave speed is the speed at which the wave transfers its energy through a medium from one place to another. An individual particle within the wave can be moving, faster, slower or not at all without actually affecting the speed of the wave.

USEFUL TIP

Don't forget that frequency and period are linked through an inverse relationship. This means that the source will also determine the period of a wave. The faster the source vibrates the higher the frequency and the shorter the period will be.

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PROGRESS QUESTIONS

Question 6

A tap is dripping into water. Which of the following would change the speed of the resultant wave?

A. increase the amplitude of the waves

B. change the period of wave generation

C. change the frequency of wave generation

D. use a liquid with different physical properties

Question 7

The tap now drips faster. The resultant wave will have

A. the same frequency as before.

B. a lower frequency than before.

C. a higher frequency than before.

D. a higher amplitude than before.

How do the speed and frequency of a wave determine its wavelength?

The speed, frequency, and wavelength of a wave are related through the wave equation.

FORMULA

$$v = f\lambda$$

v = wave speed (m s^{-1})
f = frequency (Hz or s^{-1})
λ = wavelength (m)

Substituting $f = \frac{1}{T}$ into the wave equation gives:

FORMULA

$$v = \frac{\lambda}{T}$$

v = wave speed (m s^{-1})
λ = wavelength (m)
T = period (s)

WORKED EXAMPLE 2

A wave of frequency 48 Hz is travelling along a string at a speed of 24 m s^{-1}. What is its wavelength?

Step 1

Identify known and unknown variables and write down the formula that relates these variables.

$f = 48$ Hz, $v = 24$ m s^{-1}, $\lambda = ?$

$v = f\lambda$

Step 2

Substitute values into the formula and solve for the wavelength, λ.

$24 = 48 \times \lambda$

$\lambda = \frac{24}{48} = 0.50$ m

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PROGRESS QUESTIONS

Question 8

A loudspeaker emits a sound of frequency 60 Hz. Take the speed of sound in air to be 330 m s^{-1}. Which one of the following best gives the wavelength of the sound?

A. 60 m **B.** 11 m **C.** 5.5 m **D.** 0.18 m

Adapted from VCAA 2015 exam Detailed study 6 Q1

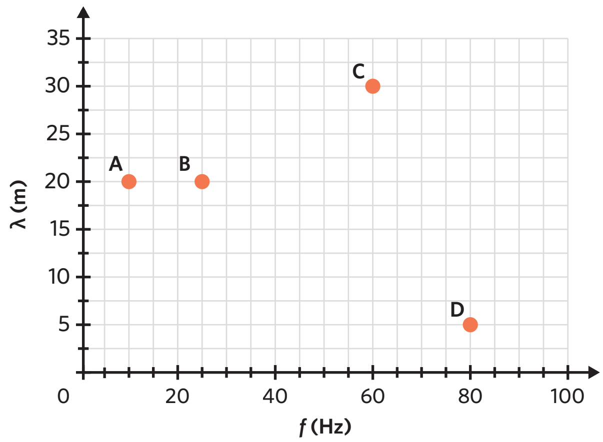
Question 9

Which of the following occurs when the wavelength of a wave is doubled? **(Select all that apply)**

A. the speed doubles
B. the period doubles
C. the frequency halves
D. the amplitude doubles

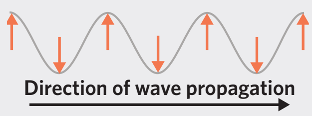
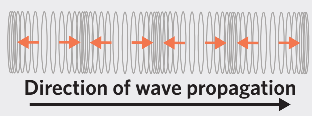
Question 10

The wavelength and frequency of four different waves is shown in the graph below. Which of the four waves has the lowest speed?



Theory summary

Table 3 Transverse vs. longitudinal waves

	Transverse wave	Longitudinal Wave
Visual representation		
Movement of oscillations	Perpendicular to the direction of wave propagation.	Parallel to the direction of wave propagation.
Common examples	Waves in strings, electromagnetic waves, and water waves.	Sound waves, waves in springs, or the primary (P) waves in an earthquake.[3]
Key features	Crests: Points on a wave with maximum positive displacement. Troughs: Points on the wave with maximum negative displacement.	Compressions: The points on a wave where particles are most closely grouped together (area of high pressure). Rarefactions: points where particles are most spread out (area of low pressure).

KEEN TO INVESTIGATE?

[3] **What sorts of waves make up an earthquake?**
Search YouTube: How earthquakes occur | seismic waves

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- The properties that waves have that determine their behaviour are:
  - frequency, period, wavelength, and amplitude.
- These properties can be found using displacement-distance or displacement-time graphs.

Table 4 Which property can be found from a graphed wave?

Graph type	Amplitude	Wavelength	Period	Frequency
Displacement-distance	✓	✓	✗	✗
Displacement–time	✓	✗	✓	✓ using $f = \frac{1}{T}$

- Wave speed is determined by the medium through which the wave travels.
- Wave frequency is determined by the source of the wave.
- $v = f\lambda$ relates frequency and wavelength to wave speed.
- $v = \frac{\lambda}{T}$ relates wavelength and period to wave speed.

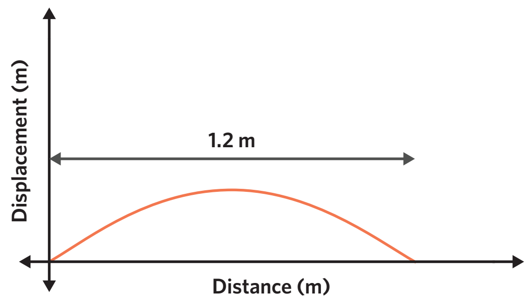
7A Questions

Mild 🌶 Medium 🌶🌶 Spicy 🌶🌶🌶

Deconstructed exam-style

Use the following information to answer questions 11–13.

A 1.2 m string is vibrating at a frequency of 300 Hz. The wave formed is shown in the diagram.



Question 11 🌶 (1 MARK)

Calculate the wavelength of the wave.

Question 12 🌶 (1 MARK)

Which of the following equations relates a wave's speed and frequency to its wavelength?

A. $f = \frac{1}{T}$

B. $v = \frac{\lambda}{T}$

C. $v = f\lambda$

D. $v = T\lambda$

Question 13 🌶🌶 (2 MARKS)

Calculate the speed of the wave on the string.

Adapted from VCAA 2020 exam Short answer Q13a

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Exam-style

Question 14 (1 MARK)

A set of speakers at a school assembly are driving sound waves at a frequency of 880 Hz. Calculate the resulting wavelength in m. Take the speed of sound in air to be 340 m s^{-1}.

Adapted from 2018 VCAA exam Short answer Q11a

Question 15 (1 MARK)

When a sound wave moves through a medium, such as air, there is a net transfer of

A. matter.

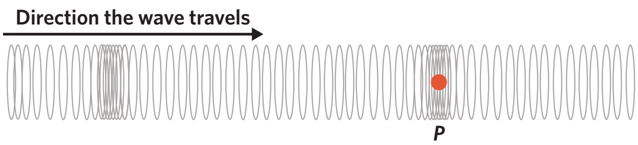
B. energy.

C. particles.

D. matter and energy.

Question 16 (2 MARKS)

A longitudinal wave is travelling along a slinky with a period of 8.0 s and speed of 0.40 m s^{-1}.



a. Determine the wavelength of the wave. 1 MARK

b. Draw an arrow(s) showing the direction(s) point *P* moves in as the wave travels through it. 1 MARK

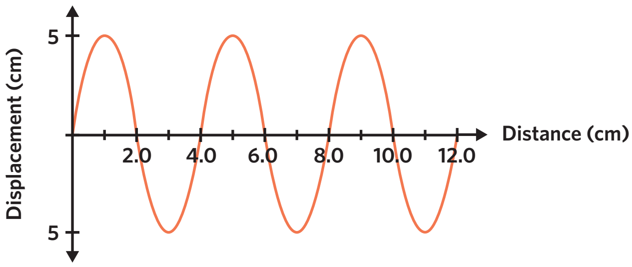
Question 17 (1 MARK)

The diagram shows part of a wave.

The wave propagates at 20 m s^{-1}.

Which of the following is closest to the amplitude and frequency of the wave?

	Amplitude	Frequency
A.	5 cm	5.0 Hz
B.	10 cm	5.0 Hz
C.	5 cm	500 Hz
D.	10 cm	500 Hz



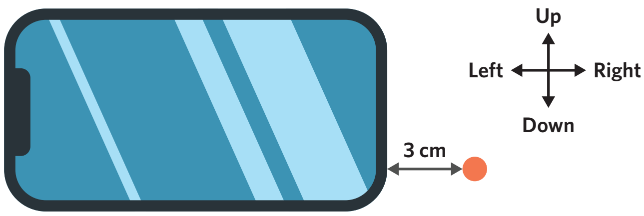
Adapted from VCAA 2021 exam Multiple choice Q13

Question 18 (2 MARKS)

A pair of headphones can emit sound waves between 85 Hz and 18 kHz. What is the longest possible wavelength produced by the headphones? Assume the speed of sound in air is 340 m s^{-1}.

Question 19 (2 MARKS)

Finn plays a 50 Hz sound from her phone. The air particle shown initially rests 3.00 cm away from the phone's speaker. Take the speed of sound in air to be 340 m s^{-1}. Describe how the frequency of the sound affects the air particles motion relative to its neutral position.



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Question 20 (2 MARKS)

A student is using waves to determine the identity of an unknown gas. Waves inside the 2.00 m tube of gas are measured to have a frequency of 534 Hz and a wavelength one quarter of the tube length. Using the table, identify which gas was in the tube.

Gas	Speed of sound ($m\ s^{-1}$)
Helium	1007
Krypton	221
Hydrogen	1270
Nitrogen	349
Oxygen	326
Carbon dioxide	267

Question 21 (2 MARKS)

Given the wave equation, $v = f\lambda$, explain why increasing wave frequency does not increase wave speed.

Question 22 (2 MARKS)

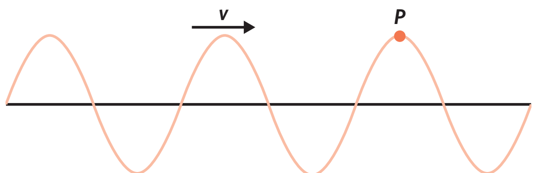
Dominique is singing a note with a period of 0.005 seconds. She finds that the note is flat (the frequency is too low). Explain whether she should make the period of the note longer or shorter to correct her pitch.

Question 23 (3 MARKS)

A wave is travelling along a stretched string with constant speed, v, as shown in the diagram. The time for point P on the string to move from maximum displacement to zero is 0.340 s and the wavelength is 1.80 m.

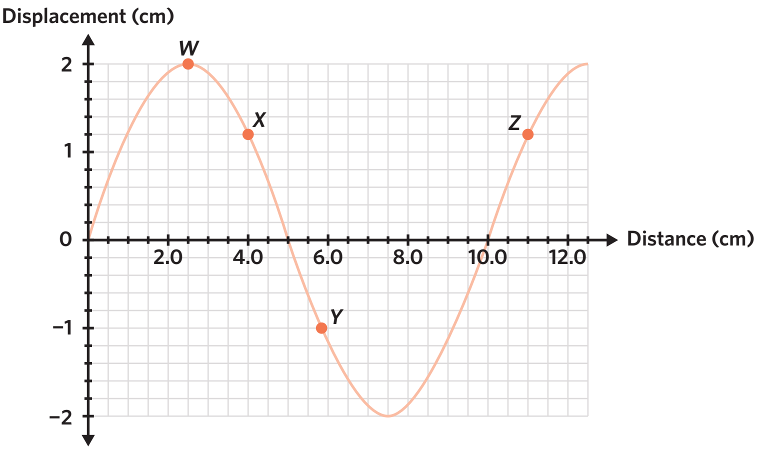
Calculate the speed of the wave, v. Show your working.

Adapted from VCAA 2019 exam Short answer Q12



Question 24 (9 MARKS)

The following graph relates to a transverse wave in a string that is moving to the right.



a. In what direction (up, down, left, right) are the particles located at positions W, X, Y and Z moving at the instant shown? If a particle is not moving, write 'not moving'. 4 MARKS

b. *Key science skill*

Identify whether the graph is linear or nonlinear. 1 MARK

c. *Key science skill*

Evaluate the effectiveness of representing a wave using a displacement-distance graph. Refer to both transverse and longitudinal waves in your answer. 4 MARKS

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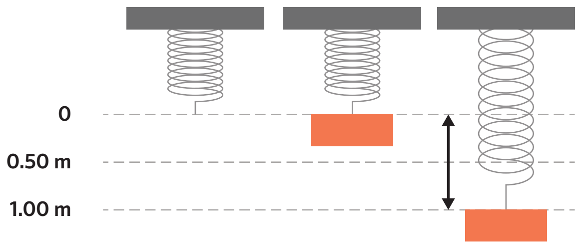
Previous lessons

Question 25 (9 MARKS)

A mass of 1.50 kg is attached to a spring which has a spring constant of 29.4 N m^{-1}. When the mass is released from the unstretched position of the spring, it falls a distance of 1.00 m where it briefly comes to rest. Consider the zero of gravitational potential energy to be at the mass' lowest point.



a. At its lowest point, calculate the spring potential energy. 🌶 2 MARKS

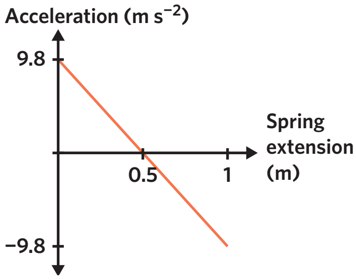
Adapted from 2015 VCAA Exam Section A Q6a

b. Calculate the maximum speed of the mass after it is released from the unstretched position. 🌶🌶 3 MARKS

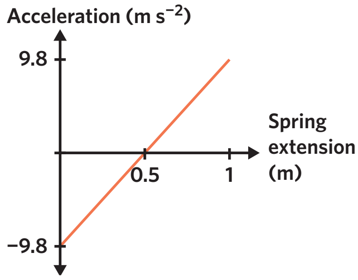
Adapted from 2015 VCAA Exam Section A Q6b

c. Which one of the following graphs (A–E) best displays the acceleration of the mass as it falls from its highest point to its lowest point? Take upwards acceleration to be positive. Explain your answer. 🌶🌶🌶 4 MARKS

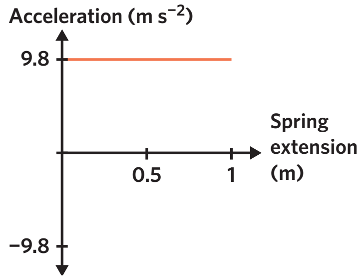
A.



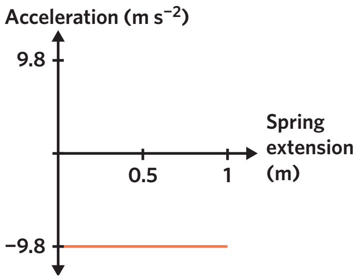
B.



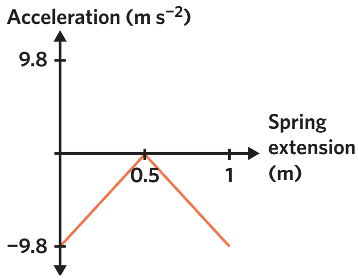
C.



D.



E.



Adapted from 2015 VCAA Exam Section A Q6d

FROM LESSON 2E

Question 26 🌶🌶 (2 MARKS)

Amy is choosing which kind of generator to use for her cabin. She can choose between an AC generator that has a peak voltage of 325 V or a DC supply of 250 V. With the AC supply, the total resistance of appliances in the cabin is 8.0 Ω. Using the DC supply, the total resistance is 9.0 Ω. Which option will provide the most power?

Adapted from 2012 VCAA Exam 2 Section A AoS 1 Q3

FROM LESSON 5C

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7B Wave interference and path difference

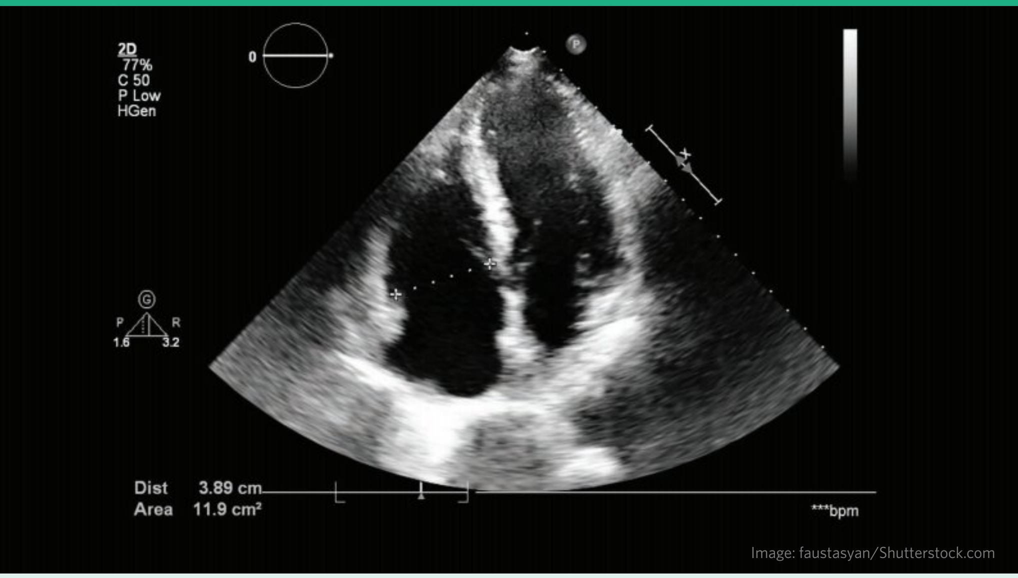


Image: faustasyan/Shutterstock.com

How do we use interference patterns in ultrasounds?

This lesson builds on fundamental wave properties to help us understand the interactions between multiple waves. The result of these interactions is known as an interference pattern. We can use interference in technologies relating to acoustics, antenna design, noise cancellation, physics experiments, and medical imaging like ultrasounds.

STUDY DESIGN DOT POINT

- explain the results of Young's double slit experiment with reference to:
  - evidence for the wave-like nature of light
  - constructive and destructive interference of coherent waves in terms of path differences: $n\lambda$ and $\left(n+\frac{1}{2}\right)\lambda$ respectively, where $n = 0, 1, 2, \ldots$
  - effect of wavelength, distance of screen and slit separation on interference patterns: $\Delta x = \frac{\lambda L}{d}$ when $L >> d$

7A 7B 7C 7D

4.1.6.2 Constructive and destructive interference

4.1.6.3 The wave equation

ESSENTIAL PRIOR KNOWLEDGE

7A Longitudinal wave fundamentals

7A Transverse wave fundamentals

7A The wave equation

See questions 65–67.

KEY TERMS AND DEFINITIONS

superposition the addition of overlapping waves in the same medium

interference superposition creating a larger (constructive) or smaller (destructive) resultant wave

coherent wave sources that create waves of the same frequency and constant phase difference in the same medium

path difference the difference in distance travelled by two waves from their sources to the same point

antinode a point where constructive interference consistently occurs

node a point where destructive interference consistently occurs

FORMULAS

- **wave equation**
  $v = f\lambda$
- **path difference for constructive interference**
  $p.d. = n\lambda$, where $n = 0, 1, 2, \ldots$
- **path difference for destructive interference**
  $p.d. = \left(n+\frac{1}{2}\right)\lambda$, where $n = 0, 1, 2, \ldots$

Constructive and destructive interference 4.1.6.2

When two waves meet they overlap. The resultant wave is the sum of each waves' amplitude at that point – this is called **superposition**. When two wave sources produce waves that continuously overlap, superposition of the waves creates regions where the waves add to form larger waves, and regions where the waves cancel – this is called **interference**.

How do waves interfere?

Interference is a product of the superposition of waves and can either be constructive or destructive. It's important to note that after the interference occurs, the waves continue unaffected along their original path.

In Figure 1, we can see constructive interference. This occurs when two waves of the same sign (both positive or both negative) interact. In this case the resultant wave is exactly double the amplitude of the individual pulses, since the individual pulses have the same amplitude. As the waves are adding their amplitude together, the resultant wave will be larger than the individual waves.

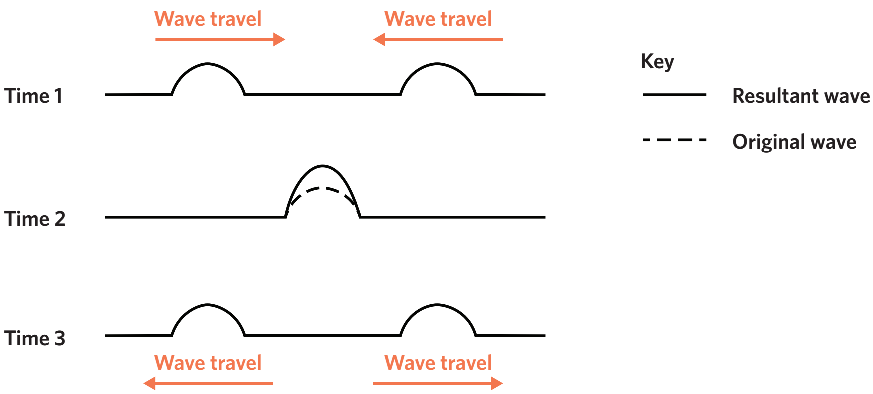


Figure 1 Constructive interference with identical waves in phase.

KEEN TO INVESTIGATE?

1 **How do we simulate superposition?**
Search: Wave pulse interference and superposition simulation

In Figure 2, we can see destructive interference. This occurs when one wave interacts with another wave of the opposite sign (one positive and one negative). In this case, the two wave pulses cancel each other since they have the same amplitude. As the waves have amplitudes with opposite signs, the resultant wave will be smaller than the individual waves.[1]

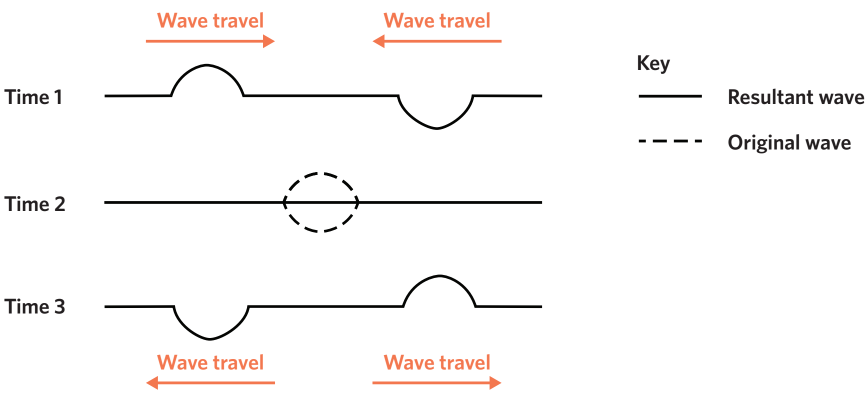


Figure 2 Destructive interference with identical waves out of phase by 180°.

In the case of sound, constructive interference means louder noise and destructive interference means quieter noise. Concert halls are designed to amplify particular frequencies by causing sound waves to bounce off walls and constructively interfere with themselves. Noise-cancelling headphones use destructive interference of sound waves to reduce ambient noise.

PROGRESS QUESTIONS

Question 1

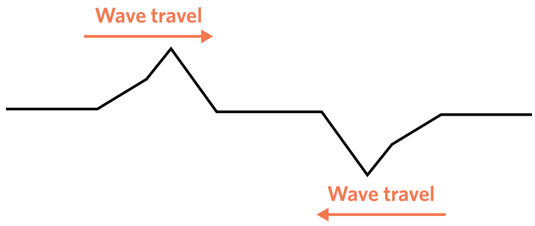
Two waves with the same amplitude, A, interact and constructive interference occurs. What will be the amplitude of the resultant wave?

A. 0
B. $\frac{A}{2}$
C. $2A$
D. $4A$

Question 2

According to the graph, what sort of interference will occur when the two waves meet?

A. negative
B. destructive
C. constructive
D. superposition



Interference patterns and path difference 4.1.6.3

When two **coherent** waves meet, the **path difference** at that point determines whether the waves interfere constructively or destructively.

How do we understand coherent interference patterns?

Coherent waves describe two waves with the same frequency and wavelength travelling in the same medium. Coherent waves create a constant interference pattern:

- Points of consistent constructive interference (e.g. crests meet crests or troughs meet troughs) are called **antinodes**.
- Points of consistent destructive interference (e.g. crests meet troughs) are called **nodes**.
- Points of constructive and destructive interference do not change.

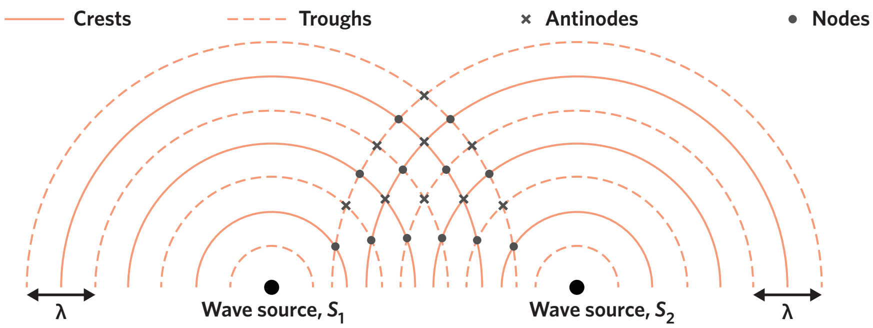


Figure 3 Interference pattern for two coherent waves

Figure 3 shows coherent waves propagating from two sources and the corresponding interference pattern. The waves could be ripples in water or sound waves, but in either case the interference pattern formed has similar properties:

- Solid lines represent the crests or compressions propagating from each source.
- Dashed lines represent troughs or rarefactions propagating from each source.
- Crosses represent antinodes – where consistent constructive interference occurs (solid lines meet solid lines and dashed lines meet dashed lines).
- Dots represent nodes – where consistent destructive interference occurs (solid lines meet dashed lines).

Although the crests and troughs continue to propagate away from the sources (the solid and dashed lines continue to travel outwards), the locations of the antinodes and nodes do not change (Figure 4).

Figure 4 Demonstration of an interference pattern in water[2]

KEEN TO INVESTIGATE?

[2] **How do we simulate interference patterns?**
Search: Surface Wave Interference in 3D simulation

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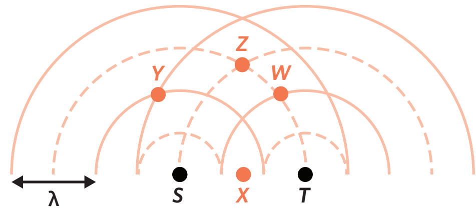
PROGRESS QUESTIONS

Question 3

Points W, X, Y, and Z all lie within the interference pattern caused by the coherent speakers at S and T. Point X is equidistant between speakers S and T. The solid lines represent compressions and the dotted lines represent rarefactions.



Which option correctly identifies the antinodes and nodes?

	W	X	Y	Z
A.	antinode	node	node	antinode
B.	node	antinode	antinode	node
C.	node	antinode	antinode	antinode
D.	antinode	node	node	node

Question 4

Two speakers are placed a particular distance from each other and are set to continuously play a sound. One speaker plays sound with a higher frequency than the other, so the waves are not coherent. Which of the following statements correctly describes the interactions between these two waves?

A. Interference does not occur.

B. Interference occurs but it is neither constructive nor destructive.

C. Constructive and destructive interference form consistent antinodes and nodes.

D. Constructive and destructive interference occurs but the positions of constructive and destructive interference change.

USEFUL TIP

Vertical lines around an expression, for example $|x|$, means to take the absolute value of that expression. This means we can ignore any negative signs in front of the number and take the positive value. Treat them like brackets for the purpose of order of operations.

- $|5| = 5$
- $|-5| = 5$

How do we use path difference to analyse interference patterns?

Path difference is the difference in length between paths from two different wave sources to the same endpoint (Figure 5):

$$p.d. = |S_1X - S_2X|$$

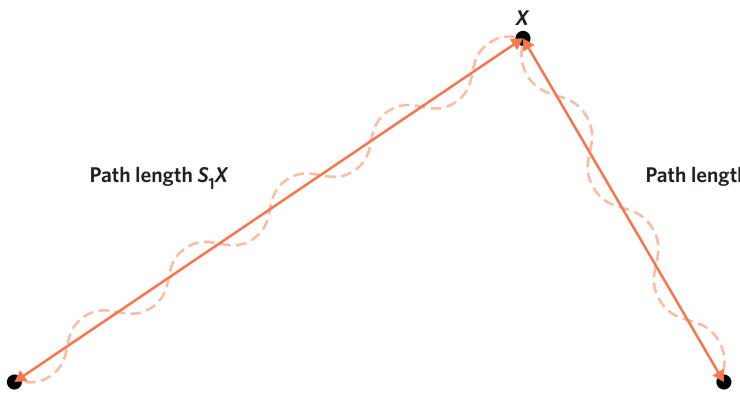


Figure 5 Path length from two sources to a point, X

Constructive interference

Path difference determines the type of interference that occurs at any given point in an interference pattern. Where the path difference is an integer multiple of the wavelength, the waves will be in phase – crests meet crests and troughs meet troughs, and so constructive interference occurs.

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Consider point A in Figure 6: $S_1A = 1.5\lambda$ and $S_2A = 3.5\lambda$ so $p.d. = |1.5\lambda - 3.5\lambda| = 2\lambda$. Therefore point A is an antinode.

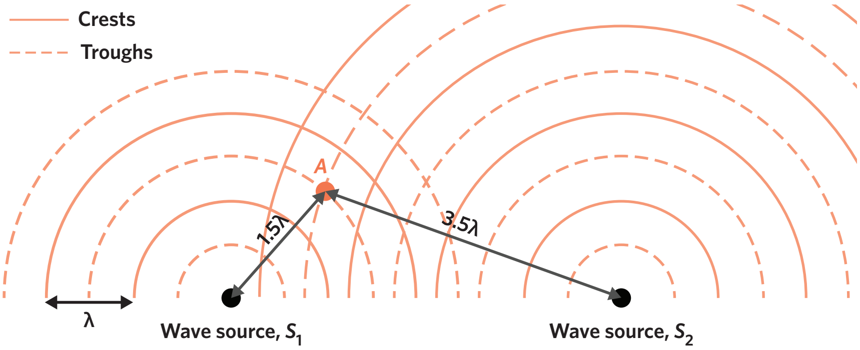

Figure 6 Antinodes occur when the path difference is an integer multiple of λ.

Constructive interference occurs where the path difference satisfies the following condition:

FORMULA

$$p.d. = |S_1X - S_2X| = n\lambda$$

$p.d.$ = path difference (m)
n = 0, 1, 2,...
λ = wavelength (m)

Destructive interference

Where the path difference is half a wavelength more than an integer multiple of the wavelength, the waves will be exactly out of phase – crests will meet troughs and so destructive interference occurs.

Consider point B in Figure 7: $S_1B = 3\lambda$ and $S_2B = 1.5\lambda$ so $p.d. = |3\lambda - 1.5\lambda| = 1.5\lambda$. Therefore point B is a node.

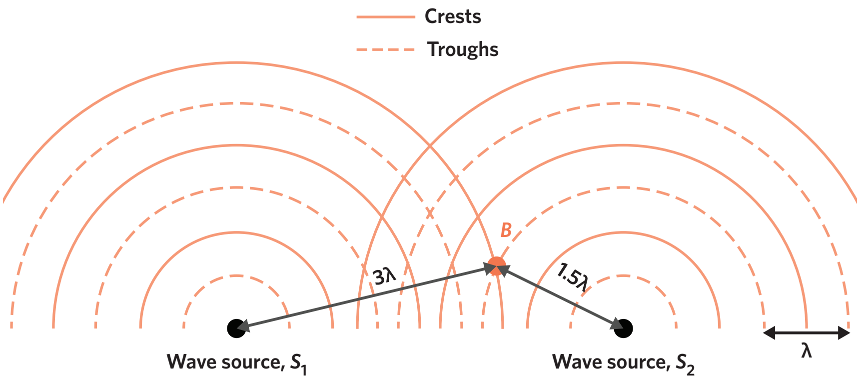

Figure 7 Nodes occur when the path difference is an odd multiple of $\frac{\lambda}{2}$

Destructive interference occurs when the path difference satisfies the following condition:

FORMULA

$$p.d. = |S_1X - S_2X| = \left(n + \frac{1}{2}\right)\lambda$$

$p\,d.$ = path difference (m)
n = 0, 1, 2,...
λ = wavelength (m)

USEFUL TIP

VCAA will often ask questions referring to numbered dark bands, light bands, quiet regions, or loud regions.

Light bands or loud regions refer to antinodes, or points of constructive interference whereas dark bands or quiet regions refer to nodes or points of destructive interference.

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It's important to note that for two sources in sync:

- the first antinode will occur when $n = 0$ and the path difference is 0λ
- the first node will occur when $n = 0$ and the path difference is 0.5λ.

Table 1 shows how the value of n corresponds to the path difference and number of the node or antinode.

Table 1 Nodes and their corresponding *n* values

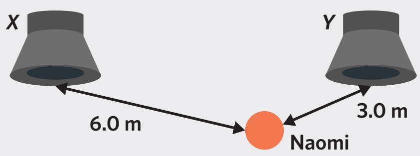
In text description	*n* value	Path difference to an antinode (constructive)	Path difference to a node (destructive)
First node or antinode	0	$p.d. = 0 \times \lambda$	$p.d. = 0.5 \times \lambda$
Second node or antinode	1	$p.d. = 1 \times \lambda$	$p.d. = 1.5 \times \lambda$
Third node or antinode	2	$p.d. = 2 \times \lambda$	$p.d. = 2.5 \times \lambda$
Fourth node or antinode	3	$p.d. = 3 \times \lambda$	$p.d. = 3.5 \times \lambda$

STRATEGY

To determine whether a point in an interference pattern is experiencing constructive or destructive interference, we can divide the path difference by the wavelength of light $\left(\frac{p.d.}{\lambda}\right)$. If the answer is a whole number e.g. 0, 1, 2, 3, then constructive interference is occurring. If the answer is an odd multiple of $\frac{1}{2}$ e.g. 0.5, 1.5, 2.5, then destructive interference is occurring.

WORKED EXAMPLE 1

Two speakers, located at point *X* and at point *Y*, are producing coherent waves with a wavelength of 1.50 m. Naomi is 6.00 m from speaker *X* and 3.00 m from speaker *Y*.



a. Determine what type of interference she is experiencing.

Step 1

Identify known and unknown variables and write down the formula that relates these variables.

$XN = 6.00$ m, $YN = 3.00$ m, $\lambda = 1.50$ m, $n = ?$

$p.d. = |S_1X - S_2X|$

Step 2

Calculate the path difference.

$p.d. = |S_1X - S_2X| = |XN - YN|$

$p.d. = |6.00 - 3.00| = 3.00$ m

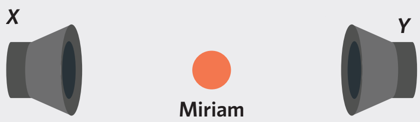
Step 3

Substitute values into the formula and determine whether constructive or destructive interference is taking place.

$\frac{p.d.}{\lambda} = \frac{3.00}{1.50} = 2$

As the path difference is an integer, *n*, we know that Naomi is experiencing constructive interference.

b. The speakers are now rotated, and Miriam stands in the middle between the two speakers. She walks in a straight line towards *Y* and stops at the third quiet region she experiences from the centre. She measures that she is 4.00 m away from speaker *X*. Calculate how far away she is from speaker *Y*.



Step 1

Identify known and unknown variables and write down the formula that relates these variables.

Note that quiet regions imply destructive interference is occurring. Therefore, the third quiet region implies $n = 2$.

$XM = 4.00$ m, $\lambda = 1.50$ m, $n = 2$, $YM = ?$

$p.d. = |S_1X - S_2X| = \left(n + \frac{1}{2}\right)\lambda.$

Continues →

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Step 2

Substitute values into the formula and solve the distance between Miriam and speaker Y.

Note that as Miriam is closer to speaker Y the path difference will be positive.

$$p.d. = |S_1X - S_2X| = |XM - YM| = \left(n + \frac{1}{2}\right)\lambda$$

$$|4.00 - YM| = \left(2 + \frac{1}{2}\right) \times 1.50$$

$$|4.00 - YM| = 3.75$$

$$YM = 0.25 \text{ m}$$

PROGRESS QUESTIONS

Question 5

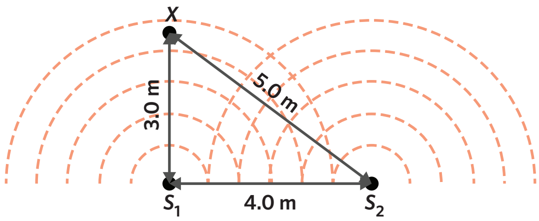
What is the path difference from the two wave sources, S_1 and S_2, to point X?

A. 2.0 m

B. 1.0 m

C. −1.0 m

D. −2.0 m



Question 6

The path difference from two coherent wave sources at point Y is 3.0 m. For which wavelength would Y be a node (consistent destructive interference)?

A. 3.0 m **B.** 2.0 m **C.** 1.5 m **D.** 1.0 m

Question 7

Katy finds the second region of constructive interference from the centre in an interference pattern. What is the path difference at this band?

A. 0 **B.** λ **C.** 2λ **D.** 3λ

Theory summary

- Interference can be either constructive or destructive.
  - Constructive interference occurs where waves superimpose to create a wave with twice the amplitude.
  - Destructive interference occurs where waves superimpose to create a wave with no amplitude.
- When waves from two coherent sources overlap an interference pattern is established. This pattern includes antinodes (constructive interference) and nodes (destructive interference) in fixed positions.
- The path difference to these points, as a multiple of the wavelength, can show whether the point is an antinode or a node.
  - Antinodes occur due to constructive interference, where the path difference is an integer multiple of λ. The path difference can be calculated using $p.d. = |S_1X - S_2X| = n\lambda$
  - Nodes occur due to destructive interference, where the path difference is an odd multiple of $\frac{\lambda}{2}$. The path difference can be calculated using $p.d. = |S_1X - S_2X| = \left(n + \frac{1}{2}\right)\lambda$

7B Questions

Mild 🌶 Medium 🌶🌶 Spicy 🌶🌶🌶

Deconstructed exam-style

Use the following information to answer questions 8-10.

In a shallow tray of water, two point sources, *P* and *Q*, are producing waves of the same wavelength, $\lambda = 5.00$ cm. The point *T* is the third node and is 15.0 cm from the nearer source, *Q*.

Question 8 🌶 (1 MARK)

What number, *n*, corresponds to the third node?

Question 9 🌶 (1 MARK)

Calculate the path difference from *P* and *Q* to the point *T*.

Question 10 🌶🌶 (3 MARKS)

Determine the distance from *P* to *T*.

Exam-style

Question 11 🌶 (1 MARK)

A boat is sitting within an interference pattern of two coherent wave sources. The boat's location has a path difference of 45 m and is on the fourth antinode. Which of the following is closest to the wave's wavelength?

A. 13 m

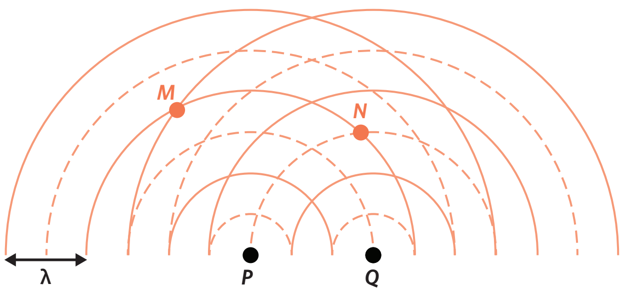
B. 15 m

C. 135 m

D. 180 m

Question 12 (4 MARKS)

The diagram shows a coherent wave pattern produced by two taps, *P* and *Q*, dripping into water. The point *M* is an antinode with a path difference of 4.0 cm from points *P* and *Q*.



a. Show that the wavelength, λ, equals 4.0 cm. 🌶 2 MARKS

b. Calculate the path difference to node *N* in centimetres. 🌶🌶 2 MARKS

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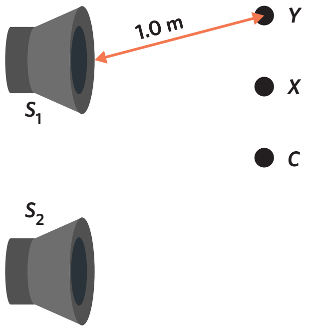
Question 13 (6 MARKS)

Two speakers are set up to play a coherent sound with a wavelength of 0.60 m. A student stands at point *C*, which is equidistant from both speakers, and then walks in a straight line recording positions where the sound is loudest (highest intensity). In addition to position *C*, the student records positions *X* and *Y*. Point *Y* is 1.0 m from speaker 1.



a. Calculate the distance, S_2Y, from speaker 2 to point *Y*. 3 MARKS

b. The student now changes the wavelength of the sound from both speakers to 0.80 m.
For this new sound, determine whether

i. point *C* will be a point of high or low intensity sound. 1 MARK

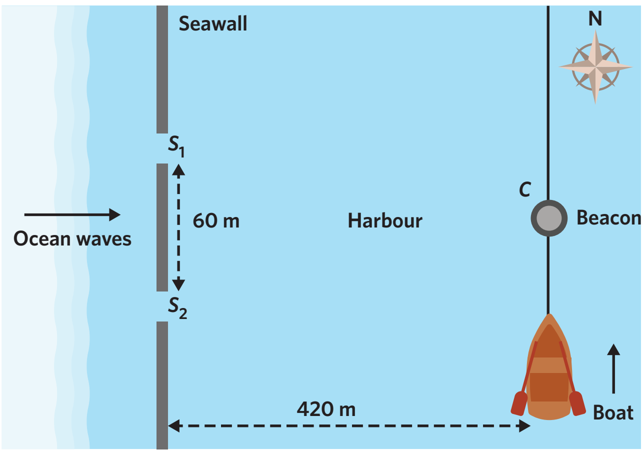
ii. point *Y* will be a point of high or low intensity sound. 2 MARKS

Question 14 (2 MARKS)

A seawall that is aligned north–south protects a harbour of constant depth from large ocean waves, as shown. The seawall has two small gaps, S_1 and S_2. At point *C* sits a beacon, equidistant from the two gaps in the seawall.

Will the beacon at point *C* be in calm water or large waves? Explain your answer.

Adapted from VCAA 2019 NHT exam Short answer Q13a



Question 15 (3 MARKS)

Two coherent speakers, S_1 and S_2, are set up a few metres apart on an oval. Megan walks away from the centre until she is at the third node. She is 4.50 m away from S_1 and 7.00 m away from S_2.

a. Calculate the wavelength of the sound. 2 MARKS

b. The speed of sound in air is 340 m s^{-1}. What frequency are the speakers producing? 1 MARK

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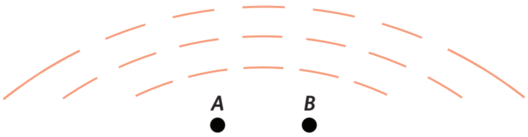
Question 16 (3 MARKS)

Two point sources, A and B, are creating ripples with a wavelength of 2.0 cm in a ripple tank. X is a point in the interference pattern 7.0 cm from A and 12.0 cm from B.

a. What sort of interference occurs at point X? 2 MARKS

b. Copy the diagram (which is not to scale) and indicate a possible location of X. 1 MARK



Question 17 (6 MARKS)

Mark stands half way between two speakers, A and B, producing a coherent sound of 680 Hz. As Mark walks towards speaker A, he notes alternating loud and quiet regions.

a. Explain why Mark experiences the alternating loud and quiet regions. 3 MARKS

b. At the third quiet region, Mark stops. Given the speed of sound in air $v = 340\text{m s}^{-1}$, how far did Mark travel? 3 MARKS

Adapted from VCAA 2018 exam Short answer Q11b

Question 18 (4 MARKS)

A pool of water has two taps suspended over it. Both taps are dripping simultaneously at 4.0 Hz, creating ripples. There is an antinode at point P which is 2.0 cm from one wave source and 5.0 cm from the other wave source. The wavelength of the ripples is 1.5 cm.

a. What is the speed of the ripples created by the dripping water? 1 MARK

b. If the first antinode appears in the centre, what number antinode is P? 3 MARKS

Question 19 (6 MARKS)

Beyoncé sets up two speakers to simultaneously play a sound of frequency 400 Hz. She notes the position, P, of the first antinode from the middle. She then changes the frequency in both speakers and point P becomes the second node from the middle.

a. Calculate the second frequency played. 3 MARKS

Beyoncé sets up the speakers to play a new, coherent, unknown frequency. In order to measure the wavelength of the sound, she listens for the first node and measures the distance from each of the speakers to this particular node. She then uses the equation $p.d. = \left(n + \frac{1}{2}\right)\lambda$ to find the wavelength.

b. *Key science skill*

Is the experimental process valid? 1 MARK

FROM LESSON 12A

c. *Key science skill*

Using your understanding of interference patterns, suggest one way to improve the accuracy of the results and explain how your suggestion would help. 2 MARKS

FROM LESSON 12C

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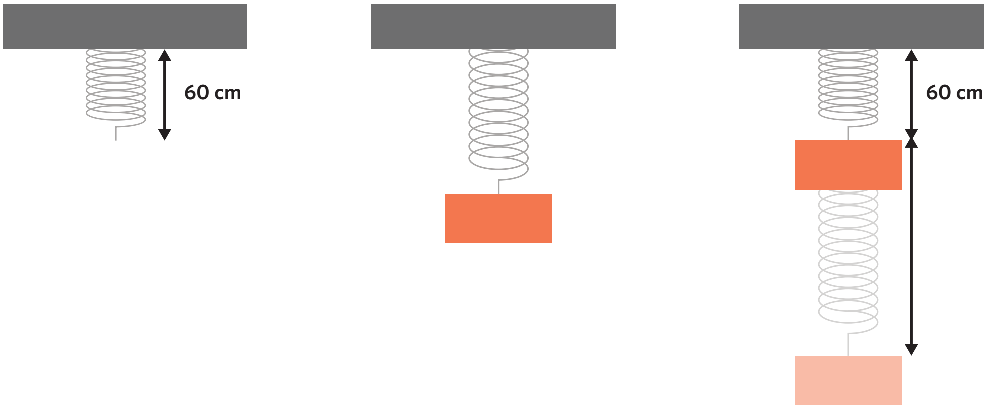
Previous lessons

Question 20 (5 MARKS)

Whilst trying to modify his toy gun, Kyle decides he will test the spring used to fire the rubber projectile. The spring has an unstretched length of 60 cm.



Kyle progressively adds 30 g masses to the end of the spring and measures its length when the mass is stationary. He records the included data

Number of 30 g masses on the spring	0	1	2	3
Length of the spring (cm)	60	65	70	75

a. Calculate the spring constant. 2 MARKS

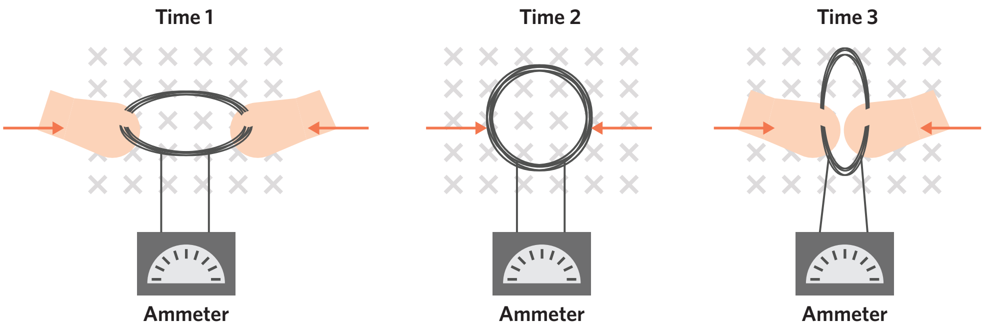
b. Kyle now attaches five 30 g masses to the end of the spring and releases it from its unstretched position, allowing the masses to oscillate. Find the maximum length of the spring. Ignore frictional losses. 3 MARKS

Adapted from VCAA 2014 exam Short answer Q2

FROM LESSON 2E

Question 21 (3 MARKS)

Two Physics students hold a coil of wire in a constant uniform magnetic field, as shown in the figure. The ends of the wire are connected to a sensitive ammeter. The students then change the shape of the coil by pushing each side of the coil in the horizontal direction. They notice a current register on the ammeter. Explain, using physics principles, why the ammeter registered a current in the coil and determine the direction of the induced current from time 1 through to time 3.



Adapted from VCAA 2020 exam Short answer Q6c

FROM LESSON 5B

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7C Standing waves

STUDY DESIGN DOT POINTS

- explain the formation of a standing wave resulting from the superposition of a travelling wave and its reflection
- analyse the formation of standing waves (only those with nodes at both ends is required)

7A 7B 7C 7D

4.1.3.1 Standing wave formation

4.1.4.1 Standing waves with two fixed ends

ESSENTIAL PRIOR KNOWLEDGE

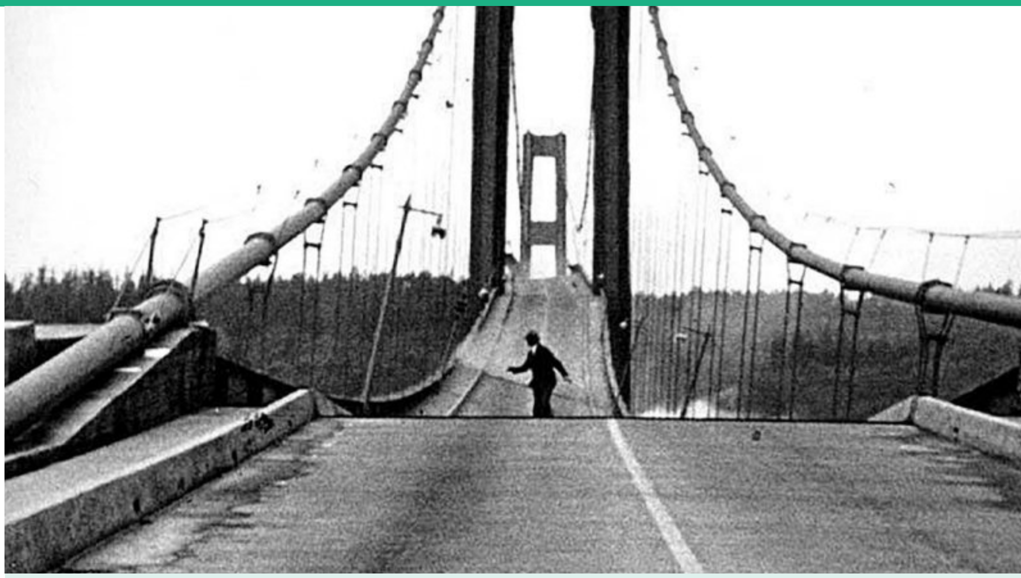
7B Constructive and destructive interference

7B Nodes and antinodes

See questions 68–69.

KEEN TO INVESTIGATE?

1 **How did standing waves break the Tacoma Narrows Bridge?**
Search YouTube: Tacoma Narrows Bridge collapse



How did wind destroy this bridge?

Even a bridge made out of steel can be brought down by the power of the wind, as proved by the 1940s Tacoma Narrows Bridge. Standing waves formed in the bridge, gradually increasing in intensity as the wind continued to blow, eventually breaking the bridge apart.[1] Standing waves have applications to musical instruments, engineering, and even subatomic physics and electron orbits.

KEY TERMS AND DEFINITIONS

standing wave two waves of the same frequency and amplitude travelling in opposite directions superimpose to create stationary regions of maximum and minimum displacement

travelling wave a wave that propagates through a medium, carrying energy from one location to another

fundamental frequency the lowest frequency of a standing wave that will form in a given medium

harmonic a standing wave with a frequency equal to an integer multiple of a fundamental frequency

FORMULAS

- **wave equation**
  $v = f\lambda$
- **standing wave wavelength**
  $\lambda = \frac{2L}{n}$
- **standing wave frequency**
  $f = \frac{nv}{2L}$

Standing wave formation 4.1.3.1

Standing waves are formed when **travelling waves** of certain frequencies interfere with their reflections travelling in the opposite direction in the same medium. The resultant wave looks like it is stationary – it appears to oscillate up and down rather than travel along the length of the medium.

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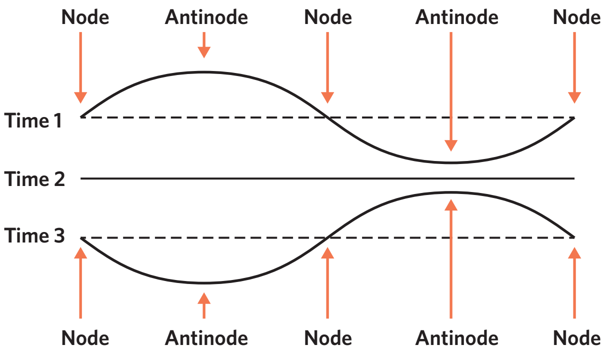
How does a reflected wave become a standing wave?

When a travelling wave reaches the end of its medium, the wave's energy is either transferred, transformed, or reflected. Consider a wave travelling along a string (Figure 1). When it reaches the end of the string and encounters a fixed end, most of the energy is reflected and so the wave is reflected back along the string but inverted 180°.

If a series of travelling waves with the same amplitude and frequency are sent along a string with two fixed ends, they will run into their inverted reflections. The superposition of the travelling waves can create an interference pattern that we call a standing wave (Figure 2). The standing wave does not appear to travel and is composed of:

- Nodes – positions of destructive interference where the amplitude is zero.
- Antinodes – positions of constructive interference where the amplitude oscillates between positive and negative maximum.



Although the standing wave appears to not travel along the string, it is composed of travelling waves interfering with their reflections. Standing waves can form from both transverse and longitudinal waves.[2,3]

Figure 2 The motion of a standing wave with two fixed ends at three time intervals

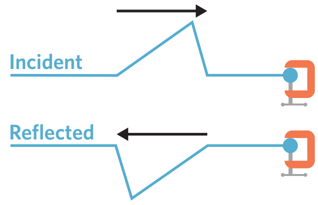


Figure 1 An incident wave and its reflection out of phase by 180°

MISCONCEPTION

'Regions of a standing wave where constructive interference occur, antinodes, are always at their maximum possible displacement from the mean position'

Antinodes are regions where the wave oscillates between positive maximum and negative maximum displacement. During this oscillation, the displacement of the antinode can have any displacement between its two maxima, including no displacement at all.

KEEN TO INVESTIGATE?

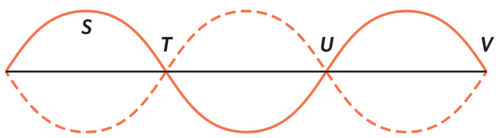
2 **How do we simulate the superposition of transverse waves?**
Search: Transverse standing wave oPhysics

3 **How do we simulate the superposition of longitudinal waves?**
Search: A longitudinal standing wave BU

PROGRESS QUESTIONS

Use the following information for questions 1 and 2.

A standing wave is formed on a string as shown.



Question 1

The standing wave shown is formed from

A. waves that do not travel.

B. a single wave travelling left to right.

C. interfering waves that travel up and down on the string.

D. interfering waves travelling left and right along the string.

Continues →

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Question 2

Identify which row in the table correctly identifies the nodes and antinodes in the standing wave shown.

	Node	Antinode
A.	*S*	*V*
B.	*T, U, V*	*S*
C.	*V*	*T*
D.	*S*	*T, U, V*

Standing waves with two fixed ends 4.1.4.1

Standing waves are commonly formed on mediums with two fixed ends – like two people holding a slinky or a string tied at both ends.

How can we analyse a standing wave with two fixed ends?

On a standing wave with two fixed ends, there will be nodes at both ends of the standing wave. The lowest frequency of wave in which a standing wave will form is called the **fundamental frequency**. This corresponds to the longest wavelength which meets the constraints that:

- there is a node at each end, and
- there is one antinode in the middle of the string, so the wavelength is double the length of the string (Figure 3).

USEFUL TIP

For diagrams showing standing waves, solid lines represent the wave at one position of maximum variation, and the dotted line represents the wave in the other position of maximum variation.

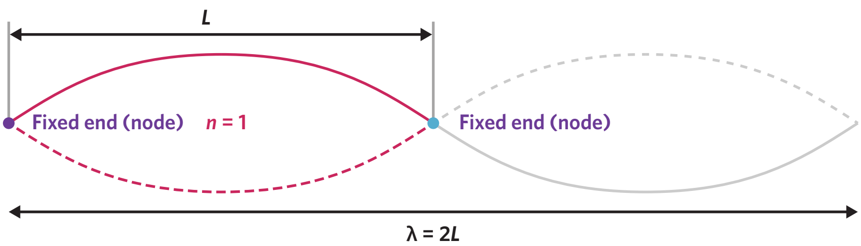

Figure 3 The fundamental frequency on a string with two fixed ends

STRATEGY

We can think of the harmonic number of a standing wave on a string with two fixed ends as the number of half-wavelengths that fit into the length of the string.

- Therefore, standing waves will only form if the length of the string is an integer multiple of half the wavelength ($L = n\frac{\lambda}{2}$).
- To determine whether a standing wave will form on a string fixed at both ends, we can rearrange the formula above to calculate how many half wavelengths fit into the length of the string. This can be done by calculating the ratio $L \div \frac{\lambda}{2}$, which simplifies to $\frac{2L}{\lambda}$:
  - If this ratio is equal to an integer (i.e. 0, 1, 2 ...), then a standing wave will form.
  - If this ratio is not equal to an integer, then a standing wave will not form.

Higher order standing waves will also form if the frequency of the travelling wave is an integer multiple of the fundamental frequency. The various frequencies that form standing waves are called **harmonics**, and are designated by an harmonic number n. The fundamental frequency is the first harmonic ($n = 1$). Higher order harmonics will have shorter wavelengths and higher frequencies.

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We can determine the harmonic number, n, by counting the number of antinodes in the standing wave (Figure 4).[4]

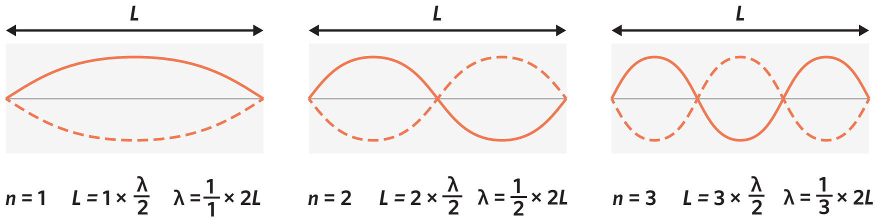


Figure 4 The first three harmonics for standing waves on strings with two fixed ends

For standing waves with two fixed ends, the wavelength and frequency can be calculated using the following formulas:

FORMULA

$$\lambda = \frac{2L}{n}$$

λ = wavelength (m)
n = harmonic number (1,2,3,...)
L = string length (m)

FORMULA

$$f = \frac{v}{\lambda} = \frac{nv}{2L}$$

f = frequency (Hz)
v = wave speed (m s^{-1})
λ = wavelength (m)
n = harmonic number (1,2,3,...)
L = string length (m)

KEEN TO INVESTIGATE?

[4] **How can we simulate standing waves on strings?**
Search YouTube: Standing waves on strings simulation

USEFUL TIP

If the period of oscillation is given then the frequency can be found using $f = \frac{1}{T}$.

WORKED EXAMPLE 1

A piece of string with a length of 4.50 m is secured at both ends. A series of waves are sent along the string such that a fourth harmonic standing wave is formed. Assume that the waves travel along the string at 300 m s^{-1}.

a. Calculate the wavelength of the fourth harmonic standing wave in the string.

Step 1

Identify known and unknown variables and write down the formula that relates these variables.

$L = 4.50$ m, $n = 4$, $\lambda = ?$

$\lambda = \frac{2L}{n}$

Step 2

Substitute values into the formula and solve for the wavelength.

$\lambda = \frac{2 \times 4.50}{4} = 2.25$ m

b. Calculate the frequency of the fourth harmonic standing wave in the string.

Step 1

Identify known and unknown variables and write down the formula that relates these variables.

$L = 4.50$ m, $v = 300$ m s^{-1}, $n = 4$, $f = ?$

$f = \frac{nv}{2L}$

OR

$\lambda = 2.25$ m, $v = 300$ m s^{-1}, $f = ?$

$v = f\lambda$

Continues →

Step 2

Substitute values into the formula and solve for the and solve for the frequency.

$f = \frac{4 \times 300}{2 \times 4.50}$

$f = 133.3 = 1.33 \times 10^2$ Hz

OR

$300 = f \times 2.25$

$f = 133.3 = 1.33 \times 10^2$ Hz

c. Waves with a wavelength of 0.5 m are now sent down the same string. Determine whether a standing wave will form.

Step 1

Calculate how many half-wavelengths fit into the length of the string.

Note that standing waves will only form if the ratio $\frac{2L}{\lambda}$ is an integer.

$\frac{2L}{\lambda} = \frac{2 \times 4.50}{0.5} = 18$

Step 2

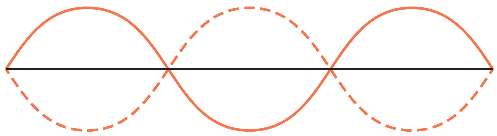
Identify that a standing wave will form in the string.

As the length of the string is an integer multiple of $\frac{\lambda}{2}$, a standing wave will form in the string.

PROGRESS QUESTIONS

Question 3

Which of the following is the correct harmonic number (n value) of the standing wave shown?



A. 1.5 **B.** 2 **C.** 3 **D.** 6

Question 4

What is the wavelength of the second harmonic that will form on a 16.0 m long string fixed at two ends?

A. 4.00 m **B.** 8.00 m **C.** 16.0 m **D.** 32.0 m

Theory summary

- Waves reaching a fixed end will reflect with the same frequency and wavelength but are inverted.
- When a travelling wave and its reflection are travelling in the same medium, they will interfere with each other. If the frequency of the travelling wave matches an integer multiple of the fundamental frequency of the medium, then a standing wave will form.
- Standing waves appear to be stationary but are in fact the result of a travelling wave and its reflection interfering. They are composed of:
  - nodes, which are areas of destructive interference
  - antinodes, which are areas of constructive interference.
- Standing waves can only form in a medium with two fixed ends when:
  - $\lambda = \frac{2L}{n}$
  - $f = \frac{nv}{2L}$

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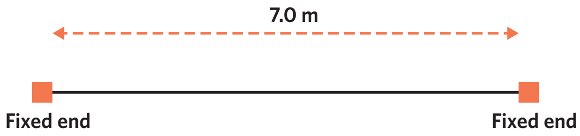
7C Questions

Mild 🌶 Medium 🌶🌶 Spicy 🌶🌶🌶

Deconstructed exam-style

Use the following information to answer questions 5–7.

In an experimental set-up used to investigate standing waves, a 7.0 m length of string is fixed at both ends. The string is under constant tension ensuring that the speed of the wave pulses is a constant 50 m s^{-1}.



A continuous transverse wave of frequency 8.0 Hz is generated on the string.

Question 5 🌶 (1 MARK)

Calculate the wavelength of the transverse wave along the string.

Adapted from VCAA 2019 exam Short answer Q13a

Question 6 🌶 (1 MARK)

How many half wavelengths fit along the length of the rope?

Question 7 🌶🌶🌶 (3 MARKS)

Will a standing wave form? Justify your answer using a calculation.

Adapted from VCAA 2019 exam Short answer Q13b

Exam-style

Question 8 (4 MARKS)

A 5.0 m tightrope is tied to a tree at both ends. Waves travel at 200 m s^{-1} along the rope.

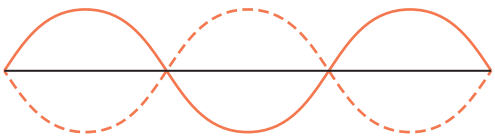
a. Show that the fundamental frequency of the rope is 20 Hz. 🌶 1 MARK

b. Calculate the wavelength of the fundamental frequency of the rope. 🌶 1 MARK

c. If waves with a frequency of 60 Hz are sent down the same rope, will a standing wave form? Justify your answer. 🌶🌶 2 MARKS

Question 9 🌶 (2 MARKS)

A series of waves with a wavelength of 3.0 m sets up the standing wave shown.



a. Determine the harmonic number of the standing wave. 🌶 1 MARK

b. Determine the length of the string. 🌶 1 MARK

Question 10 (2 MARKS)

The waves on a cello string have a speed of 330 m s^{-1}. The length of the string is 69.0 cm and both ends of the string are considered fixed.

a. Calculate the wavelength of the third harmonic of the string. 🌶 1 MARK

b. Calculate the frequency of the third harmonic of the string. 🌶 1 MARK

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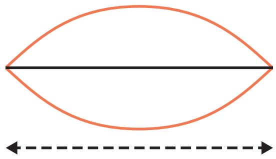
Question 11 (4 MARKS)

A 1.20 m long guitar string, fixed at both ends, is vibrating at a frequency of 82 Hz. The standing wave created by the guitar string is shown in the diagram.



a. Calculate the speed of the wave in the guitar string. 2 MARKS

b. The frequency of the vibration in the guitar string is tripled to 246 Hz. Draw the new shape of the standing wave now created. 2 MARKS

Adapted from VCAA 2020 exam Short answer Q13

Question 12 (1 MARK)

A travelling wave produced at point *A* is reflected at point *B* to produce a standing wave on a rope, as represented in the diagram.

The distance between points *A* and *B* is 3.6 m. The period of vibration of the standing wave is 2.4 s. The speed of the travelling wave along the rope is closest to

A. 0.75 m s^{-1}

B. 1.5 m s^{-1}

C. 4.3 m s^{-1}

D. 8.6 m s^{-1}

Adapted from VCAA 2022 exam Multiple choice Q13

Question 13 (4 MARKS)

Waves are sent down a string fixed at both ends, setting up a series of standing waves.

a. Draw a diagram of the 1st harmonic standing wave. 2 MARKS

b. Draw a diagram of the 3rd harmonic standing wave. 2 MARKS

Question 14 (2 MARKS)

Explain how standing waves are formed on a string.

Adapted from VCAA 2017 exam Short answer Q16c

Question 15 (4 MARKS)

The 'A' string on Zoe's violin has a length of 32.5 cm and a fundamental frequency of 440 Hz. It is fixed at both ends. Zoe presses her finger halfway down the 'A' string, effectively halving the length of the string, and plays a note.

a. Calculate the wavelength of the first harmonic that now forms on the string. 2 MARKS

b. Calculate the frequency of the resulting note Zoe plays. 2 MARKS

Question 16 (4 MARKS)

Peter attaches a device that causes the 'B' string of the cello to vibrate at a frequency of 520 Hz until it is turned off. Peter then reduces the effective length of the cello string in 1 cm increments to 27.5 cm and measures whether he sets up a standing wave or not.

a. ***Key science skill***
Identify the independent variable 1 MARK

FROM LESSON 12A

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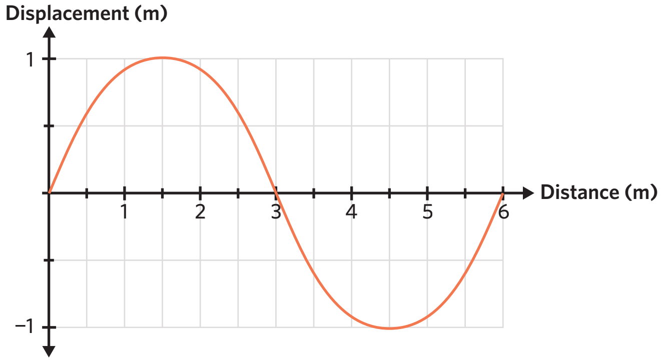
b. *Key science skill*
What type of data does Peter collect? 🌶 1 MARK

FROM LESSON 12A

c. Peter sets up a standing wave of the 5th harmonic on the string when its effective length is 27.5 cm. Calculate the speed of the wave 🌶🌶 2 MARKS

Question 17 (6 MARKS)

The graph shows the displacement-distance relationship for a second harmonic standing wave on a string at a particular moment. The period of the standing wave shown is 4.0 seconds.



a. *Key science skill*
Redraw the displacement-distance graph after 1.0 s has passed. 🌶🌶🌶 1 MARK

FROM LESSON 12D

b. *Key science skill*
Redraw the displacement-distance graph after 2.0 s has passed. 🌶🌶🌶 2 MARKS

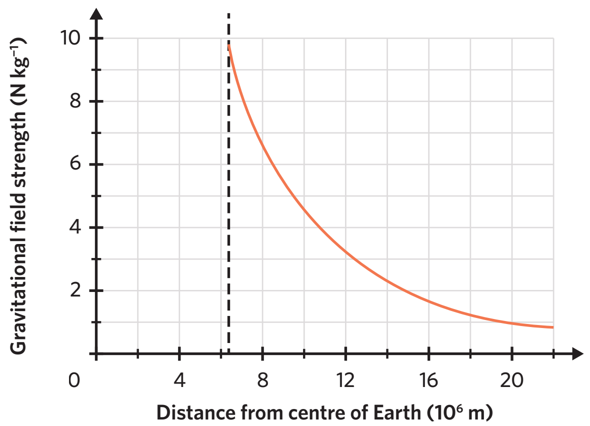
FROM LESSON 12D

c. Calculate the frequency of the fifth harmonic standing wave that would form on this string. 🌶🌶 3 MARKS

Previous lessons

Question 18 🌶🌶🌶 (2 MARKS)

An apple is dropped from an unknown height next to a scientist who is standing on the surface of Earth. The apple lands with 24 MJ of kinetic energy. Use the graph to determine the height from the centre of the Earth the apple fell from.



FROM LESSON 3B

Question 19 🌶🌶 (3 MARKS)

Mo is trying to connect their solar panels directly to their laptop charger but discovers that the laptop won't charge. Considering that the solar panels provide enough power to charge the laptop, provide a reason why connecting the laptop charger directly to the solar panel will not charge it and explain why.

FROM LESSON 5D

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7D Diffraction

STUDY DESIGN DOT POINT

- investigate and explain theoretically and practically diffraction as the directional spread of various frequencies with reference to different gap width or obstacle size, including the qualitative effect of changing the ratio $\frac{\lambda}{w}$, and apply this to limitations of imaging using electromagnetic waves

7A 7B 7C 7D

4.1.5.1 Diffraction

ESSENTIAL PRIOR KNOWLEDGE

7A Wave equation

See question 70.

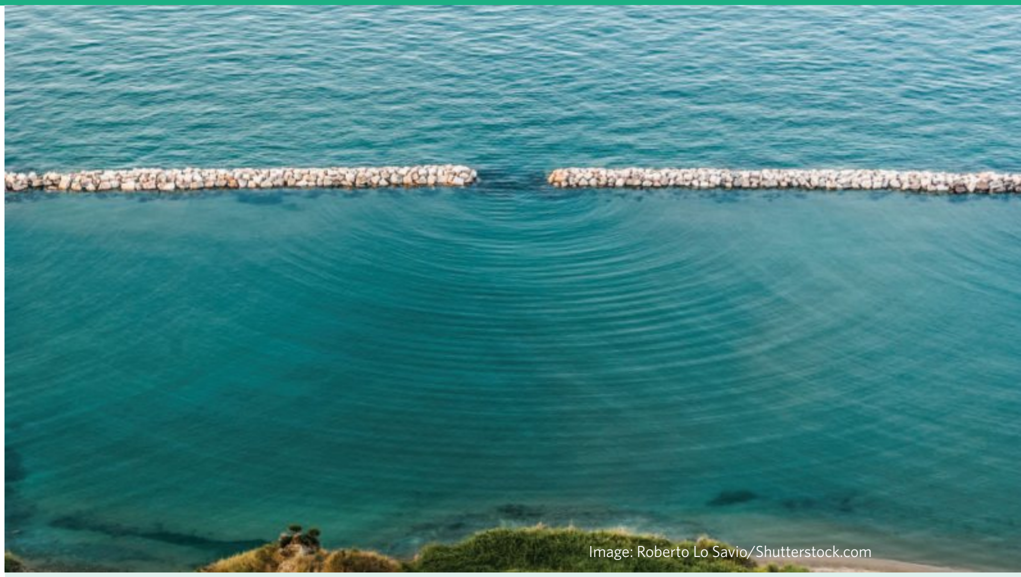

Image: Roberto Lo Savio/Shutterstock.com

Why do the waves bend as they pass through the gap in the breakwater?

You may have noticed that ocean waves bend and spread out as they pass through a relatively narrow gap in the breakwater or when they travel around a large rocky outcrop. However, when passing through a large gap, like the inlet of Port Phillip Bay, you don't notice this bending as much. This lesson will explore when diffraction occurs and develop our understanding of diffraction as a property of waves.

KEY TERMS AND DEFINITIONS

diffraction the spread of a wave around an obstacle or through an aperture

aperture a hole, gap, or slit through which a wave travels

FORMULAS

- **wave equation**
  $v = f\lambda$
- **diffraction ratio**
  $diffraction \propto \frac{\lambda}{w}$

Diffraction 4.1.5.1

Diffraction describes how waves spread around obstacles and through gaps.

How do we describe diffraction?

Diffraction occurs every time a wave interacts with the edge of an obstacle. Unlike particles, when a wave interacts with an obstacle the wave spreads around it rather than being blocked (Figure 1).

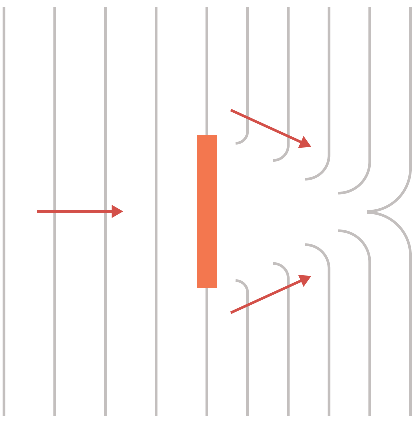

Figure 1 Diffraction around an object. Each line represents a wave front.

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An **aperture** or gap is the space between the edges of two obstacles. As a wave moves through the gap it spreads out, forming a curved wavefront (Figure 2)[1]. Diffraction is a property of all waves. It is responsible for sound waves spreading out as they pass through a doorway and also radio signals bending around mountains and buildings to give you reception in your car.

KEEN TO INVESTIGATE?

[1] **What principle governs diffraction?**
Search YouTube: Huygen's principle

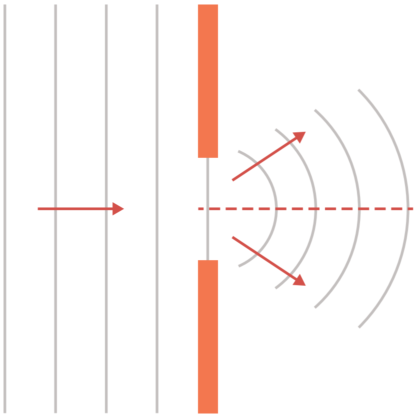


Figure 2 Diffraction through an aperture

PROGRESS QUESTIONS

Question 1

Diffraction is best defined as

A. the ratio of wavelength to width.

B. the pattern formed by two waves when they interact.

C. the spreading of waves around an obstacle or through a gap.

D. the change in the speed of a wave as it passes an obstacle or gap.

How do we analyse diffraction?

The extent (amount) of diffraction is proportional to the ratio of wavelength to obstacle/gap width.

FORMULA

$$diffraction \propto \frac{\lambda}{w}$$

diffraction = extent of diffraction (no units)
λ = wavelength (m)
w = obstacle/gap width (m)

Table 1 shows how the ratio $\frac{\lambda}{w}$ relates to the extent of diffraction occuring:

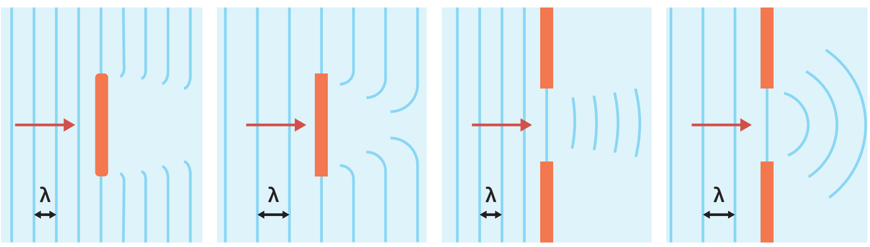
- If the wavelength is much smaller than the obstacle or aperture, then only limited diffraction will occur.
- If the wavelength is comparable to the width of the obstacle or aperture, then significant diffraction will occur.

Table 1 Interpretation of diffraction ratio

Diffraction ratio	Qualitative description
$\frac{\lambda}{w} \ll 1$	limited diffraction will occur
$\frac{\lambda}{w} \gtrsim 1$	significant diffraction will occur

If significant diffraction is occurring, that is $\frac{\lambda}{w} \gtrsim 1$:

- Increasing λ will result in more diffraction around the same object or aperture, as the ratio $\frac{\lambda}{w}$ increases (Figure 3).
- Increasing the width of the obstacle or aperture while keeping λ constant will result in less diffraction, as the ratio $\frac{\lambda}{w}$ decreases (Figure 4).



Shorter wavelength | Longer wavelength | Shorter wavelength | Longer wavelength

Figure 3 A longer wavelength diffracts more than a shorter wavelength around the same obstacle or aperture.

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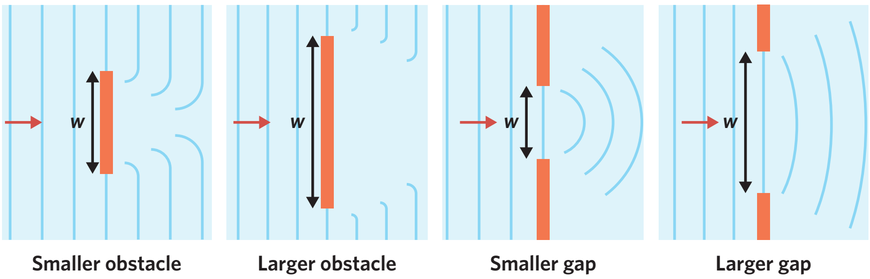


Figure 4 A smaller aperture will cause more diffraction than a larger aperture for the same wavelength.

If you've ever gone on a road trip you might have noticed that you lose mobile phone reception before you lose radio reception. This is because FM radio waves have a longer wavelength and diffract around large obstacles better (Figure 5).

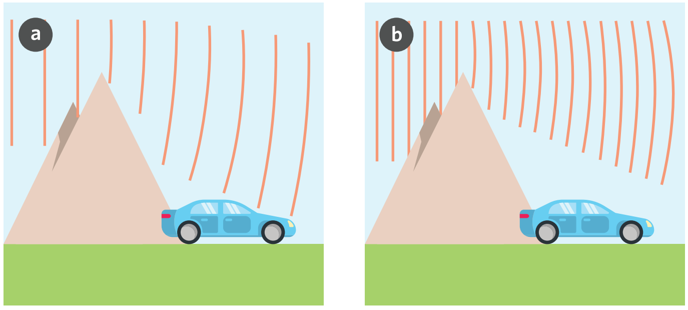


Figure 5 **(a)** Lower frequency FM radio waves diffract more than **(b)** higher frequency RF waves used by mobile phones.

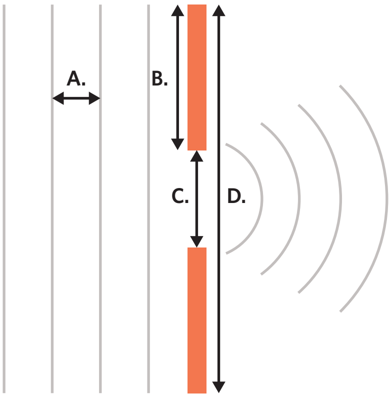
KEEN TO INVESTIGATE?

2 **How can we simulate diffraction?**
Search: Wave interference diffraction simulation

PROGRESS QUESTIONS

Question 2

Which of the following distances (*A*, *B*, *C*, or *D*) is the gap width in this scenario?



Question 3

For a given gap width and wave medium, which of the following frequencies will diffract the most?

A. 10 Hz **B.** 20 Hz **C.** 30 Hz **D.** 40 Hz

Question 4

For ripples of water passing through a gap, which of the following combinations of wavelength, λ, and gap width, w, will lead to the greatest extent of diffraction?

A. $\lambda = 1.0$ m, $w = 1.0$ m **B.** $\lambda = 2.0$ m, $w = 1.0$ m **C.** $\lambda = 1.0$ m, $w = 2.0$ m **D.** $\lambda = 2.0$ m, $w = 2.0$ m

Theory summary

- Diffraction is the phenomenon that describes how waves spread around obstacles and through gaps:
  - Limited diffraction occurs when $\frac{\lambda}{w} \ll 1$.
  - Significant diffraction occurs when $\frac{\lambda}{w} \gtrsim 1$.
- If $\frac{\lambda}{w} \gtrsim 1$, then increasing the value of the ratio $\frac{\lambda}{w}$ will result in a greater extent of diffraction.

7D Questions

Mild 🌶 Medium 🌶🌶 Spicy 🌶🌶🌶

Deconstructed exam-style

Use the following information to answer questions 5–7.

A trombonist plays two notes, one with a frequency of 100 Hz and one with a frequency of 400 Hz, through an opening 3.00 m wide. A scientist sits down the hall listening for the notes. Assume sound travels at 343 m s^{-1} in air.

Question 5 🌶 (1 MARK)

Calculate wavelength of the 100 Hz sound.

Question 6 🌶 (1 MARK)

Calculate wavelength of the 400 Hz sound.

Question 7 🌶 (3 MARKS)

Which note is the scientist more likely to hear? Justify your answer.

Exam-style

Question 8 🌶 (1 MARK)

In which of these situations is diffraction most likely to be responsible for the observation?

A. Light bending as it moves through a medium.

B. Wave crests travelling along a rope reach a wall and return as troughs.

C. A student notices regions of high intensity and low intensity sound while walking around a field with two coherent speakers.

D. The lower pitch sound of a siren on a stationary ambulance around a street corner is heard more clearly than the higher pitch sound.

Question 9 (4 MARKS)

The diagram shows waves in a ripple tank passing through a slit in a barrier.

The frequency of the incident waves is increased.

a. Copy the diagram with the original frequency (for comparison), and draw a new diagram showing the pattern for the higher frequency. 🌶 2 MARKS

b. Explain the change in the diffraction pattern. 🌶🌶 2 MARKS

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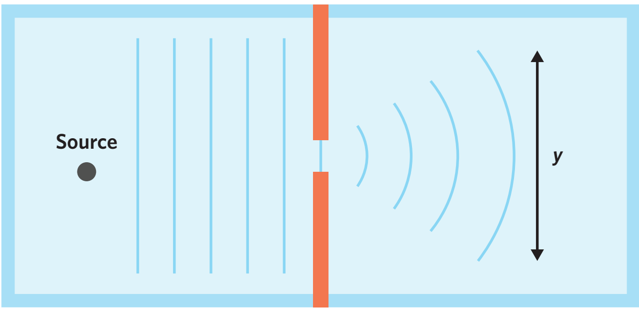
Question 10 (6 MARKS)

Michael is creating waves in a ripple tank. He inserts a wall with a gap to observe how the width of the diffraction pattern, y, is affected by the size of the gap, w.



a. Will increasing the intensity of the waves, produced by the source, have any impact on the width of the diffraction pattern? Explain your answer. 2 MARKS

b. *Key science skill*
Identify the independent, dependent, and controlled variables. 3 MARKS
FROM LESSON 12A

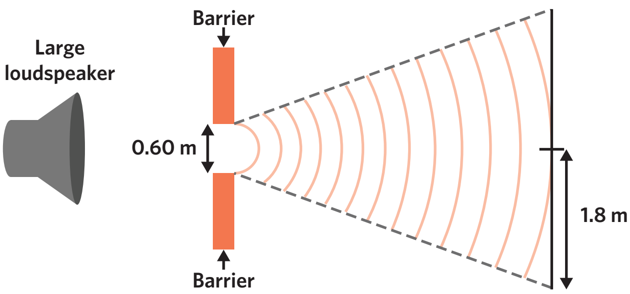
c. *Key science skill*
Nora follows the same method as Michael and records very similar results. What does this suggest about the experiment and its results? 1 MARK
FROM LESSON 12C

Question 11 (3 MARKS)

Two speakers are producing sound at the same intensity in a room. Speaker A is producing sound with a 1.0 m wavelength and speaker B is producing sound with a 3.0 m wavelength. Which speaker can be heard with greater intensity around the corner from a 2.0 m door? Justify your answer with supporting calculations.

Question 12 (1 MARK)

A group of students are conducting experiments to study the diffraction of sound. The first experiment is conducted on the school oval. The arrangement is shown in the diagram.



They play sound with a frequency of 1800 Hz through a gap 0.6 m wide. At some distance from the gap the students measure that the edge of the diffraction pattern is 1.8 m off the centre line.

The students increase the frequency to 3600 Hz. Which one of the following is most likely to be observed?

A. There will now be no edge of the pattern.
B. The edge of the pattern will be further out than 1.8 m.
C. The edge of the pattern will be closer to the centre line.
D. The edge of the pattern will still be approximately 1.8 m off the centre line.

Adapted from VCAA 2015 exam Detailed Study 6 Q10

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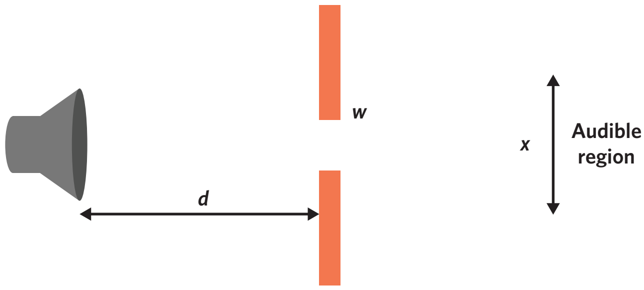
Question 13 (3 MARKS)

The diagram shows a speaker playing a single frequency, f, which is placed a distance, d, from a soundproof barrier which has a gap of width, w. Three students measure the width of the audible region on the other side of the barrier to be x. They want the audible region to be greater than x. To achieve this, Hannah suggests using a frequency of $\frac{f}{2}$. Ash suggests moving the speaker closer, making the distance, $\frac{d}{2}$. Shahan suggests using a gap width of $2w$.

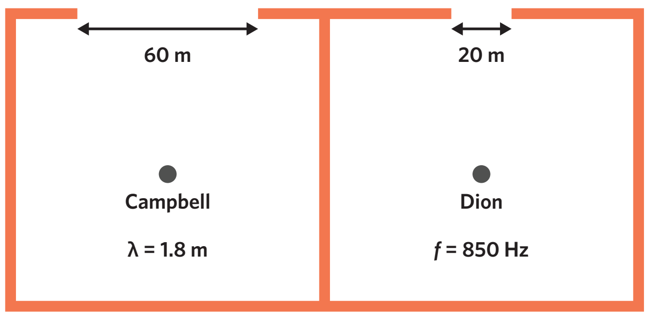


Evaluate these three suggestions.

Question 14 (3 MARKS)

Campbell is a large dog in a kennel with a 60 cm opening. His bark produces sound with a wavelength of 1.8 m. Dion is a small dog in a kennel with a 20 cm opening and his bark produces sound with a frequency of 850 Hz. Both dogs are barking with the same sound intensity.

Which of the dogs' barks will have a greater extent of diffraction? Use calculations to justify your answer. Assume the speed of sound in air is 340 m s^{-1}.



Previous lessons

Question 15 (2 MARKS)

Explain why, as a satellite moves a large distance from the surface of a planet, we cannot use $GPE = mg\Delta h$ to calculate its change in gravitational potential energy.

FROM LESSON 3B

Question 16 (3 MARKS)

Two identical resistors are placed in series. A power supply is connected, and set to 9.0 V. If the current in the circuit is measured to be 3.0 A, what is the resistance of the individual resistors?

FROM LESSON 6A

Chapter 7 review

Mild 🌶 Medium 🌶🌶 Spicy 🌶🌶🌶

These questions are typical of one hour's worth of questions on the VCE Physics Exam.

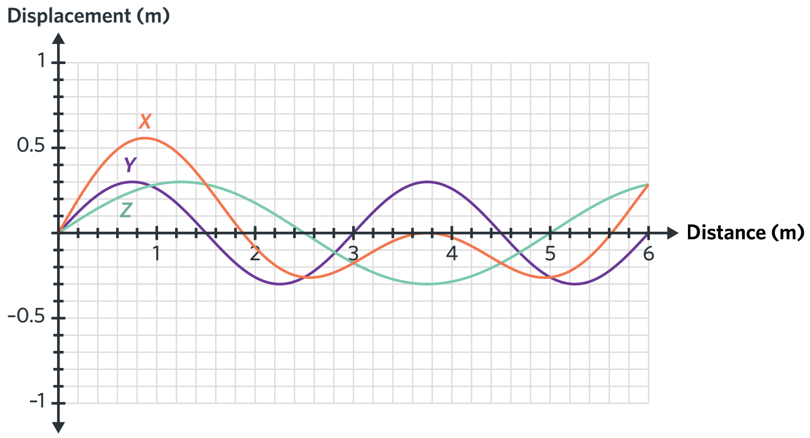
Total marks: 50

Section A

All questions in this section are worth one mark.

Unless otherwise indicated, the diagrams in this book are not drawn to scale.

Use the following graph to answer questions 1 and 2.



Question 1 🌶

Which wave could be the result of the superposition of the other two waves?

A. wave X **B.** wave Y **C.** wave Z **D.** none of the waves

Question 2 🌶

Which of the following correctly identifies the properties of wave Y?

A. Wavelength = 6 m, amplitude = 0.3 m, frequency = 3 Hz

B. Wavelength = 3 m, amplitude = 0.3 m, frequency = 0.33 Hz

C. Wavelength = 3 m, amplitude = 0.25 m, frequency = 3 Hz

D. Wavelength = 3 m, amplitude = 0.3 m, frequency unknown

Question 3 🌶🌶

A travelling wave produced at point Y is reflected at point Z to produce a standing wave on a rope, as represented in the diagram.

The distance between points Y and Z is 1.6 m. The period of vibration of the standing wave is 2.6 seconds. The speed of the travelling wave along the rope is closest to

A. 0.12 m s^{-1} **B.** 0.25 m s^{-1} **C.** 0.83 m s^{-1} **D.** 1.7 m s^{-1}

Adapted from VCAA 2022 exam Multiple choice Q13

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Question 4

For which of the following wavelengths would a given point that is 1.0 m from one wave source and 2.0 m from another coherent wave source correspond to a node?

A. 10 cm

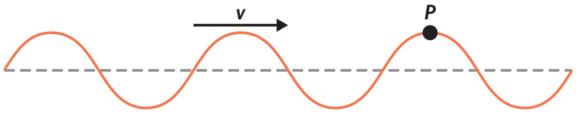
B. 20 cm

C. 30 cm

D. 40 cm

Question 5

A sinusoidal wave of wavelength 1.40 m is travelling along a rope with a constant speed *v*, as shown.



The time taken for point *P* on the string to move from maximum displacement to zero is 0.120 s. What is closest to the the speed of the wave, *v*?

A. 0.480 m s^{-1}

B. 0.672 m s^{-1}

C. 2.08 m s^{-1}

D. 2.92 m s^{-1}

Adapted from VCAA 2019 exam Short answer Q12

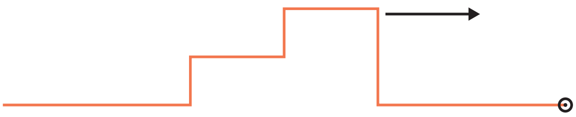
Section B

In questions where more than one mark is available, appropriate working must be shown.

Unless otherwise indicated, the diagrams in this book are not drawn to scale.

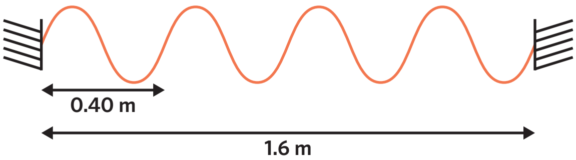
Question 6 (2 MARKS)

Draw the following wave pulse after its reflection from a fixed end.



Question 7 (2 MARKS)

A standing wave is formed in a string held firmly at both ends. The string is 1.6 m long and the wave has a wavelength of 0.40 m. Calculate the distance from the end on the left to the fourth node from left.



Question 8 (2 MARKS)

Evaluate the following statement: 'When a mechanical wave moves through a medium, there is a net transfer of mass and energy.'

Adapted from VCAA NHT 2019 Multiple choice Q13

Question 9 (2 MARKS)

Students set up a fourth harmonic standing wave on a 1.40 m string with a frequency of 250 Hz and an amplitude of 6 cm. Calculate the speed of the wave on the string.

Question 10 (3 MARKS)

Waves travel along a 5.0 m long string at 28 m s^{-1}. Both ends of the string are fixed.

a. Determine the longest wavelength that results in a standing wave forming on the string. 1 MARK

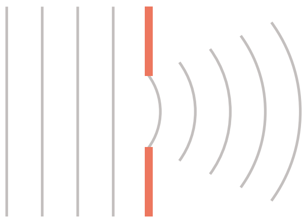
b. Calculate the third lowest frequency that results in a standing wave forming on the string. 2 MARKS

Question 11 (3 MARKS)

Andrew and Missy are studying a variety of wave phenomena using variable wave sources and a wave detector.

a. Two coherent sources emit waves in all directions. A wave detector is placed within range of the sources, however the detector does not register any incoming waves. Describe how this is possible. 1 MARK

b. Andrew and Missy now observe the diffraction pattern of waves from a single source passing through a gap.



Explain what will happen to the diffraction pattern as they decrease the frequency emitted by the source. 2 MARKS

Question 12 (4 MARKS)

Water waves are being created in a swimming pool. The waves have a period of 1.5 s and a wavelength of 9.00 m.

a. Calculate the speed of the waves. 1 MARK

b. Water waves with the same properties are now produced by two coherent sources, *X* and *Y*. Point *P* is located on the second node 12.0 m away from source *X*, in between source *X* and source *Y*. Calculate the distance from source *Y* to the point *P*. 3 MARKS

Question 13 (3 MARKS)

A string with two fixed ends forms a 3rd harmonic standing wave with a frequency of 30 Hz. The wave speed on the string is 6.0 m s^{-1}.

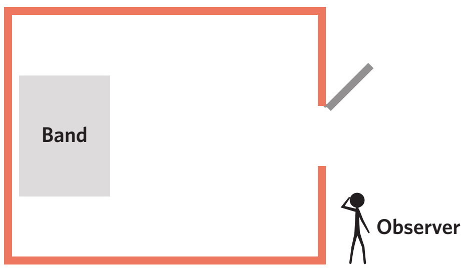
a. Draw a diagram of the standing wave. Values are not required. 1 MARK

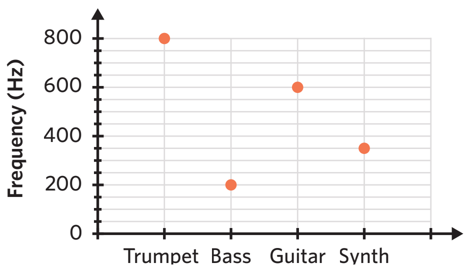
b. Calculate the length of the string. 2 MARKS

Question 14 (3 MARKS)

A rock band is playing in a soundproof room but with an open door. An observer stands outside the room with the wall in between her and the band.

The graph shows the mean frequency of sound produced by the four instruments in a rock band. Assume all instruments are producing the same volume.





a. Why is it possible for the observer to hear the instruments despite the soundproof wall between them and the band? 1 MARK

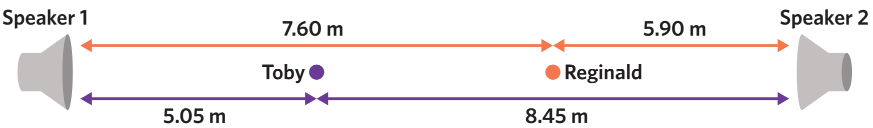
b. Which instrument will the observer be least likely to hear, assuming they all play at the same volume? Justify your answer. 2 MARKS

Question 15 (7 MARKS)

Two speakers are used at a school assembly. Take the speed of sound in air as 340 m s^{-1}.

a. Two humanities teachers setting up the assembly are discussing the effect of using two speakers rather than one. Mr Ridley suggests that all students in the hall will hear the sound twice as loud, while Ms Hawes believes the volume will depend on the students' position. Evaluate these opinions with reference to the relevant theory. 3 MARKS

b. Two troublesome friends have been separated for assembly. Toby sits 5.05 m from one speaker and 8.45 m from the other. Reginald sits 7.60 m from one speaker and 5.90 m from the other.

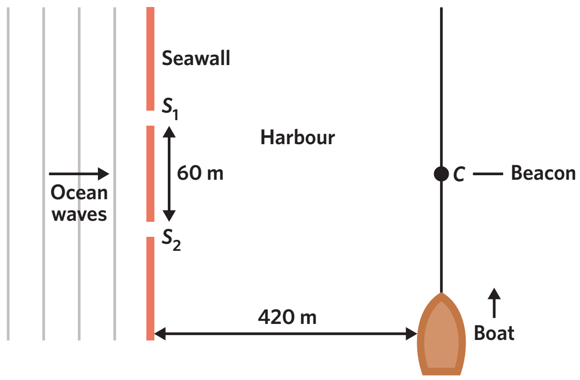


Use calculations to compare the sound heard by each student when both speakers emit a 100 Hz coherent sound. 4 MARKS

Question 16 (4 MARKS)

A seawall protects a harbour of constant depth from large ocean waves, as shown in the diagram.

The seawall has two small gaps, S_1 and S_2, which are 60 m apart. Inside the harbour, a small boat sails parallel to the seawall at a distance of 420 m from the seawall. At point C sits a beacon, at an equal distance from the two gaps in the seawall. The boat's captain notices that every 42 m there is calm water, while there are large waves between those calm points.



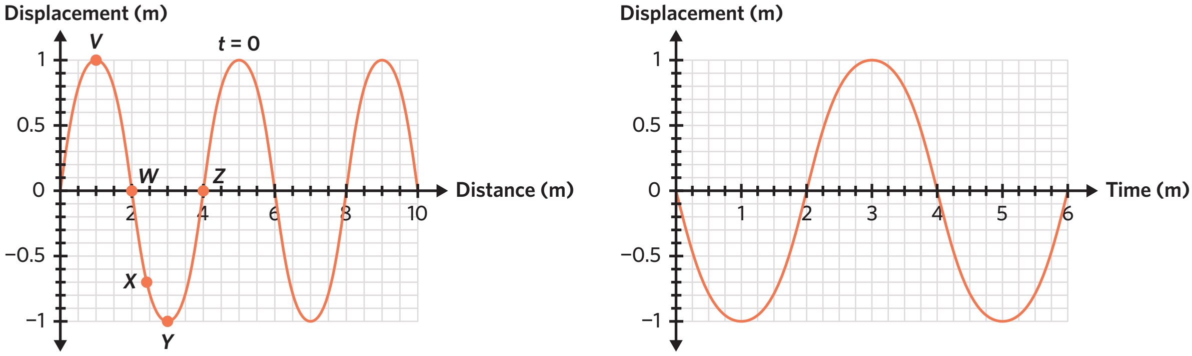
a. The relationship between the spacing of the consecutive calm water, Δx, the distance between the boat and the seawall, L, the wavelength of the wave, λ, and the spacing between the two gaps, d, is given by $\Delta x = \frac{\lambda L}{d}$. Calculate the wavelength of the ocean waves. Show your working. 2 MARKS

b. After the boat reaches the beacon at point C, it turns and travels in a straight line directly towards a point halfway between S_1 and S_2. Describe the waves (calm waves or large waves) that the boat experiences as it travels towards the seawall. 2 MARKS

Adapted from VCAA NHT 2019 Short Answer Q13b

Question 17 (10 MARKS)

The two graphs represent the characteristics of the same transverse wave travelling left to right along a rope. The displacement-distance graph depicts the rope at $t = 0$ s. The displacement-time graph represents a single particle on the rope.



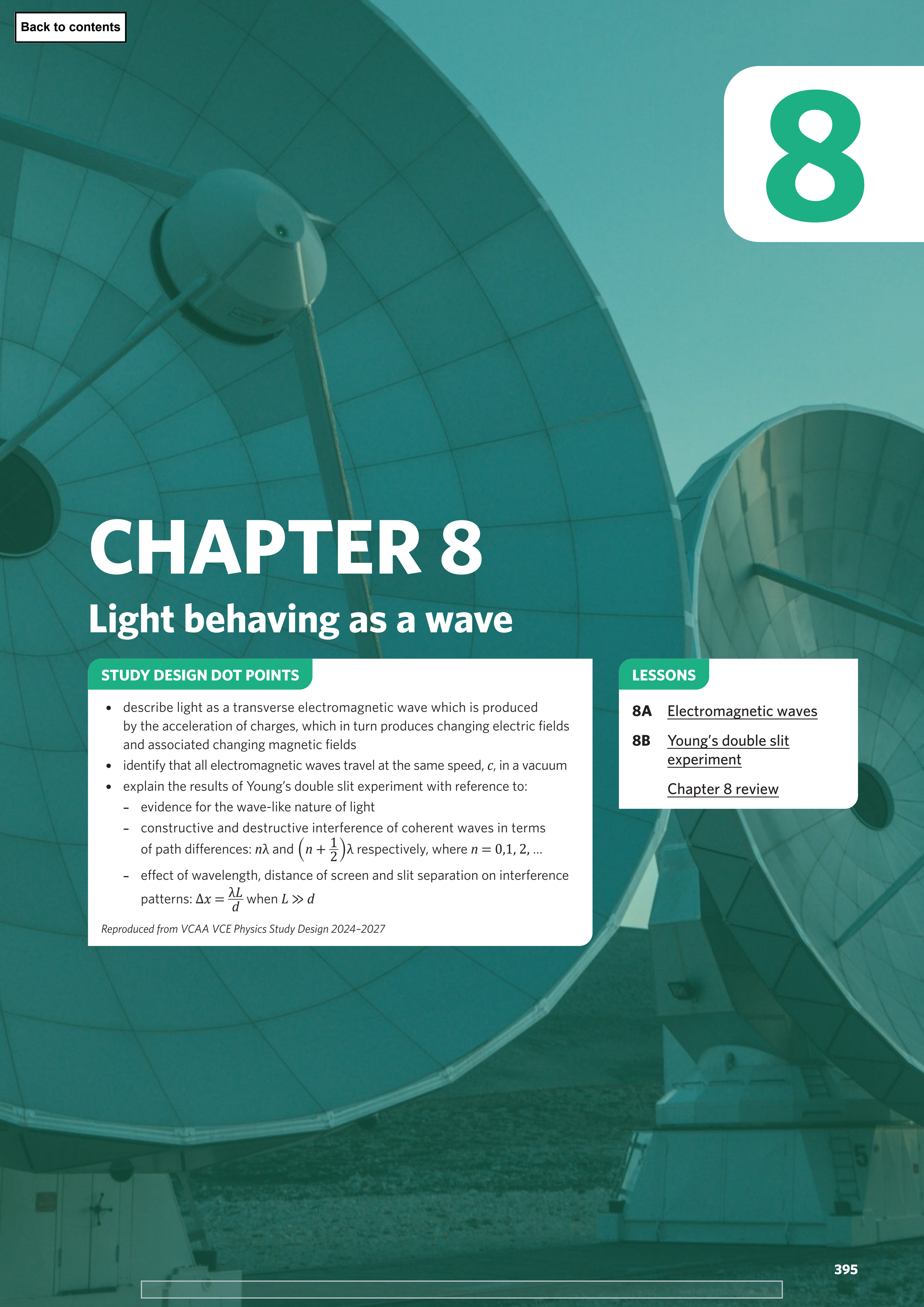
a. Calculate the speed of the wave. 2 MARKS

b. In which direction (up, down, left, or right) is particle X moving at $t = 0$ s? 1 MARK

c. Which particle (V, W, X, Y or Z) could the displacement-time graph represent? 1 MARK

d. Draw the displacement-distance graph at $t = 1.0$ s. 3 MARKS

e. Draw the displacement-time graph for particle V between $t = 0$ and $t = 6.0$ s. 3 MARKS



8

CHAPTER 8

Light behaving as a wave

STUDY DESIGN DOT POINTS

- describe light as a transverse electromagnetic wave which is produced by the acceleration of charges, which in turn produces changing electric fields and associated changing magnetic fields
- identify that all electromagnetic waves travel at the same speed, *c*, in a vacuum
- explain the results of Young's double slit experiment with reference to:
  - evidence for the wave-like nature of light
  - constructive and destructive interference of coherent waves in terms of path differences: $n\lambda$ and $\left(n + \frac{1}{2}\right)\lambda$ respectively, where $n = 0, 1, 2, \ldots$
  - effect of wavelength, distance of screen and slit separation on interference patterns: $\Delta x = \frac{\lambda L}{d}$ when $L \gg d$

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LESSONS

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8A Electromagnetic waves

Image: Satakorn/Shutterstock.com

Is radiation bad for you?

Radiation can be used to see broken bones, send emails, and even turn fictional humans into superheroes, but is it bad for you? Despite radiation having a special place in the superhero universe, it often just refers to electromagnetic waves. This lesson explores the properties of electromagnetic waves and how they make up the electromagnetic spectrum.

STUDY DESIGN DOT POINTS

- describe light as a transverse electromagnetic wave which is produced by the acceleration of charges, which in turn produces changing electric fields and associated changing magnetic fields
- identify that all electromagnetic waves travel at the same speed, *c*, in a vacuum

8A 8B

4.1.1.1 & 4.1.2.1 Light as an electromagnetic wave

ESSENTIAL PRIOR KNOWLEDGE

7A Waves recap

See question 71.

KEY TERMS AND DEFINITIONS

electromagnetic wave a transverse wave composed of a changing electric field perpendicular to a changing magnetic field

electromagnetic spectrum the range of all electromagnetic waves ordered by frequency and wavelength

FORMULAS

- **wave equation**
  $v = f\lambda$

Light as an electromagnetic wave 4.1.1.1 & 4.1.2.1

Light can be modelled as an **electromagnetic wave** composed of a changing electric field perpendicular to a changing magnetic field. These fields are produced by the acceleration of charged particles. The **electromagnetic spectrum** is made up of all the different frequencies of electromagnetic waves, which all travel at the speed of light in a vacuum.

USEFUL TIP

Electromagnetic radiation and light are just different words for electromagnetic waves.

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How can light be modelled as a wave?

A stationary charged particle has a constant electric field around it. When the particle accelerates, this electric field changes:

- A changing electric field produces a changing magnetic field perpendicular to it.
- This changing magnetic field produces a changing electric field.
- The electric and magnetic fields self-propagate, creating what is known as an electromagnetic wave or electromagnetic radiation (Figure 1).
- As a result, an accelerating charged particle will emit electromagnetic waves.

It is important to recognise that, unlike mechanical waves, electromagnetic waves do not require a medium to travel through. Whereas mechanical waves exist as the transfer of energy through matter, electromagnetic waves exist as the transfer of energy through the propagation of electric and magnetic fields.

Electromagnetic waves have no mass and all travel at the speed of light, c, in a vacuum, regardless of their frequency and wavelength. Substituting c into the wave equation, $v = f\lambda$, gives the speed of an electromagnetic wave in a vacuum as:

$$c = f\lambda$$

Where $c = 3.0 \times 10^8$ m s^{-1}, in a vacuum.

If a charged particle is oscillating, the frequency of the electromagnetic wave it produces will be equal to the frequency of the oscillation. The frequencies that make up visible light are just a small range in a spectrum of electromagnetic waves.

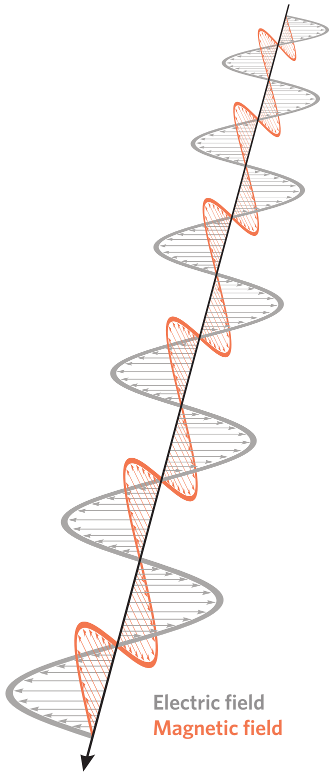

Image: Fouad A. Saad/Shutterstock.com

Figure 1 Electromagnetic waves consist of changing electric and magnetic fields.

PROGRESS QUESTIONS

Question 1

Light can be modelled as

A. a travelling electron that creates a changing electric field.

B. static electric and magnetic fields around a charged particle.

C. changing electric and magnetic fields perpendicular to each other.

D. changing gravitational and electric fields perpendicular to each other.

Question 2

Which of the following is not true of electromagnetic waves?

A. They have a frequency and wavelength.

B. They require a medium to travel through.

C. They travel at the speed of light in a vacuum.

D. They are created from accelerating charged particles.

Question 3

Calculate the frequency of red light with a wavelength of 710 nm.

A. 2.1×10^2 Hz

B. 4.2×10^6 Hz

C. 2.1×10^{14} Hz

D. 4.2×10^{14} Hz

USEFUL TIP

The speed of light is $c = 3.0 \times 10^8$ m s^{-1}, in a vacuum. When light travels through denser mediums, like air and water, it slows down. However the wave equation can still be used as the speed of all electromagnetic waves is constant in the medium they travel through. Therefore, the frequency, f, and wavelength, λ, are inversely proportional to each other. If the frequency of a wave doubles, its wavelength will half.

MISCONCEPTION

'Any absorption of radiation is dangerous'

We are surrounded by radiation (electromagnetic waves) everyday, most of which are completely harmless to humans. Only ultraviolet, X-rays, and gamma rays have enough energy to eject electrons from an atom and damage human cells.

What is the electromagnetic spectrum?

The electromagnetic spectrum is made up of all the possible frequencies and wavelengths of electromagnetic waves. It is divided into regions defined by their frequency and wavelength (Figure 2). Visible light is a small region of this spectrum, with wavelengths from 380–750 nm, that human eyes have evolved to see.[1]

KEEN TO INVESTIGATE?

[1] **What makes visible light special?**
Search Youtube: Kurzgesagt light

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Table 1 shows the different regions of the electromagnetic spectrum, along with their properties and uses.

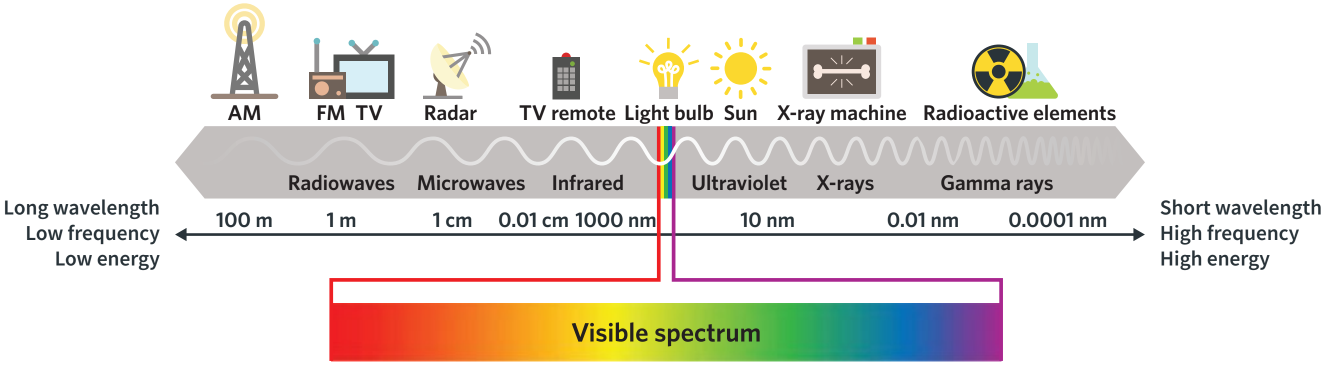

Image: VectorMine/Shutterstock.com

Figure 2 The electromagnetic spectrum

Table 1 Types of electromagnetic waves and their properties and uses

Type of electromagnetic wave	Properties and uses
Radiowaves  Image: muse studio/Shutterstock.com	• Their long wavelength allows them to diffract around obstacles like buildings and mountains, and can reflect off the ionosphere to travel long distances • Mostly used in radio and television communications, where they are emitted by radio towers and picked up by antennae on devices such as car radios
Microwaves  Image: TimeImage Production/Shutterstock.com	• Used to heat and cook food in microwave ovens by matching the resonant frequency of water molecules and causing them to vibrate • Used for mobile phone signals, Wi-Fi and radar systems • Cosmic microwave background (CMB) radiation are microwaves which were created in the early stages of the universe and provide strong evidence for the Big Bang Theory
Infrared  Image: OSORIOartist/Shutterstock.com	• All objects emit electromagnetic radiation due to the thermal vibration of charged particles. At room temperature the peak wavelength emitted is infrared • When infrared radiation hits an object, it causes the particles in that object to vibrate so the object heats up. Radiator heaters and heating lamps use this principle • It is also used in some forms of signal transmission such as TV remote controls
Visible light  Image: rukawajung/Shutterstock.com	• Composed of the colours of the rainbow (ROYGBIV) – with red light having the lowest frequency and violet light having the highest frequency • The only type of electromagnetic wave that human eyes can detect • One of the main types of electromagnetic radiation, along with infrared and ultraviolet, emitted by the Sun

Continues →

Table 1 Continued

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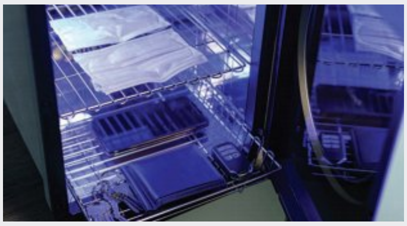
Type of electromagnetic wave	Properties and uses
Ultraviolet (UV)  Image: MBLifestyle/Shutterstock.com	• Often used to sterilise medical equipment and water • Used in black lights (UV light bulbs) for forensic analysis as it causes other substances, including bodily fluids, to fluoresce (emit visible light) • Can be dangerous to humans when absorbed, with symptoms ranging from mild sunburn to cancer
X-rays  Image: Lena Si/Shutterstock.com	• High energy and highly penetrating • Easily pass through soft tissue, so are useful for imaging bone structures • Produced by astrophysical objects and used by astronomers to study those objects • Can damage the DNA in cells or even kill cells in significant doses
Gamma rays  Image: Egoreichenkov Evgeniii/Shutterstock.com	• Higher energy, more penetrating, and more damaging than X-rays • Produced by nuclear reactions • Used in medicine to target and kill tumour cells but care must be taken to minimise damage to other cells • Produced by some astrophysical objects and used by astronomers to study those objects[2]

PROGRESS QUESTIONS

Question 4

The electromagnetic spectrum consists of

A. only radiation that human eyes can see grouped by colour.

B. all possible elementary particles ordered by increasing energy.

C. all possible electromagnetic waves divided into regions and ordered by how useful they are.

D. all possible electromagnetic waves divided into regions and ordered by increasing frequency.

Question 5

Which of the following is true of the waves in the electromagnetic spectrum?

A. Only the waves which are useful to humans are included.

B. They are all dangerous to humans and should be avoided.

C. Each wave is a different type of wave created by different particles.

D. They are all electromagnetic waves with different frequency and wavelengths.

KEEN TO INVESTIGATE?

[2] **Where do we find gamma rays in space?**
Search Google: What is gamma ray burst?

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Theory summary

- Light is a self-propagating electromagnetic wave consisting of perpendicular electric and magnetic fields produced by the acceleration of charged particles.
- The speed of all electromagnetic waves in a vacuum is a constant: 3.0×10^8 m s^{-1}.
- For an electromagnetic wave travelling in a vacuum, $c = f\lambda$, where c is the speed of light in a vacuum.
- The regions of the electromagnetic spectrum ordered from lowest frequency to highest frequency are: radiowaves, microwaves, infrared, visible light, ultraviolet, X-rays, and gamma rays.

8A Questions

Mild 🌶 Medium 🌶🌶 Spicy 🌶🌶🌶

Deconstructed exam-style

Question 6 🌶 (1 MARK)

An accelerating charge produces a

A. gravitational field.

B. static electric field.

C. static magnetic field.

D. changing electric field.

Question 7 🌶 (1 MARK)

A changing electric field creates

A. a gravitational field.

B. a static magnetic field.

C. a changing magnetic field.

D. an accelerating charged particle.

Question 8 🌶🌶 (3 MARKS)

Explain how an accelerating charged particle produces a self-propagating electromagnetic wave.

Exam-style

Question 9 🌶 (1 MARK)

Which of the following best describes electromagnetic waves?

A. They are a form of visible light.

B. They all have the same frequency.

C. They all travel at the same speed, c, in a vacuum.

D. They all travel at the same speed, c, in all mediums.

Adapted from VCAA 2018 NHT exam Multiple choice Q14

Question 10 🌶 (1 MARK)

Calculate the frequency of a microwave with a wavelength of 3 cm travelling at 3.0×10^8 m s^{-1}.

Adapted from VCAA 2018 NHT exam Short answer Q11a

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Question 11 (1 MARK)

Order the following regions of the electromagnetic spectrum from longest wavelength to shortest wavelength: X-rays, microwaves, radio, ultraviolet, infrared.

Adapted from VCAA 2018 NHT exam Multiple choice Q15

Question 12 (1 MARK)

Which of the following statements about electromagnetic radiation is correct?

A. Electromagnetic radiation is always produced by moving charges.

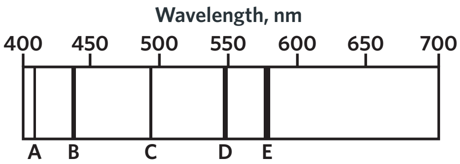
B. Electromagnetic radiation can be produced by accelerating charges.

C. Electromagnetic radiation is only produced by electrons accelerating between energy levels.

D. Electromagnetic radiation cannot be produced by electrons accelerating between energy levels.

Adapted from VCAA 2019 NHT exam Multiple choice Q12

Question 13 (4 MARKS)



The vertical lines in the diagram show the wavelengths of light which a mercury atom can emit. The following list gives the five visible colours that are emitted by the mercury atom.

Yellow Green Blue-green Blue Violet

a. Identify which band (A, B, C, D or E) represents the green emission. Justify your answer. 2 MARKS

Adapted from VCAA 2018 exam Short answer Q19a

b. ***Key science skill***

A student looking at these results concludes that because gold has one less electron than mercury it must emit one less wavelength. Explain one limitation in the student's conclusion and suggest an experiment the students could conduct to develop their idea. 2 MARKS

FROM LESSON 12D

Question 14 (4 MARKS)

During the Apollo 11 mission when NASA was communicating with astronauts on the Moon, which is 384 400 km from Earth, there was a time delay in the process of sending radio messages.

a. Show that the time it takes for a radio signal to travel from Earth to the Moon is 1.3 s. 1 MARK

b. Mission control found that the actual delay in the process of sending radio messages was 1.34 s. Use relevant physics to explain why the delay was longer than calculated time to send a signal to the Moon. 3 MARKS

Question 15 (5 MARKS)

Several students are taking measurements of the wavelength of a laser as it travels through an unknown gas. The wavelength of the laser is cited as 532.0 ± 0.1 nm. The wavelengths they measure are: 532.3 nm, 532.5 nm, 532.1 nm, 531.9 nm and 532.7 nm.

a. ***Key science skill***

Calculate the average value with an appropriate uncertainty. 2 MARKS

b. The students decide to increase the frequency of the laser by one third of its original frequency. Explain how this change in frequency affects the wavelength and speed of the laser. No calculations are required. 3 MARKS

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Previous lessons

Question 16 (1 MARK)

A satellite orbits Earth at a constant speed. Which of the following statements is true?

A. The satellite is not accelerating.

B. The satellite is travelling with a constant velocity.

C. The satellite must have an engine force keeping it in orbit.

D. The acceleration of the satellite is equal to the strength of Earth's gravitational field at the satellite's location.

FROM LESSON 3C

Question 17 (1 MARK)

An ideal transformer has 25 turns in its primary coil and 150 turns in its secondary coil. Which of the following correctly gives the ratio of the current in the primary coil to the current in the secondary coil?

A. 1:6

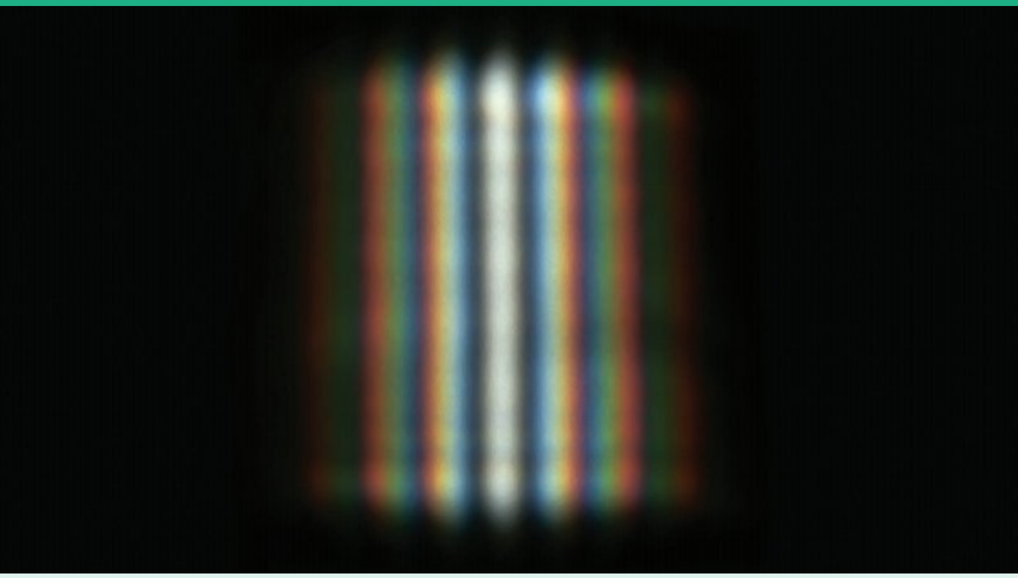
B. 6:1

C. 1:25

D. 1:150

FROM LESSON 6B

8B Young's double slit experiment



Can light cancel itself out?

Lesson 7B introduced the concept of waves constructively and destructively interfering with each other to produce regions of maximum and minimum amplitude. Lesson 8A introduced the model of light as an electromagnetic wave. Therefore, modelling light as a wave, two waves of light should be able to interfere destructively and cancel each other out. This lesson explores Young's double slit experiment, which challenged the particle model of light, and provided one of the key pieces of evidence for the wave model of light.

STUDY DESIGN DOT POINT

- explain the results of Young's double slit experiment with reference to:
  - evidence for the wave-like nature of light
  - constructive and destructive interference of coherent waves in terms of path differences: $n\lambda$ and $\left(n + \frac{1}{2}\right)\lambda$ respectively, where $n = 0, 1, 2, \ldots$
  - effect of wavelength, distance of screen and slit separation on interference patterns: $\Delta x = \frac{\lambda L}{d}$ when $L >> d$

8A — 8B

4.1.6.1 Evidence for the wave-like nature of light

4.1.6.4 Fringe spacing

ESSENTIAL PRIOR KNOWLEDGE

7A Wave equation

7B Wave interference and path difference

See questions 72–73.

KEY TERMS AND DEFINITIONS

path difference the difference in distance travelled by two waves from their sources to the same point

coherent wave sources that create waves of the same frequency and constant phase difference in the same medium

fringe spacing the distance between adjacent bright or dark bands in an interference pattern

FORMULAS

- **path difference for constructive interference**
  $p.d. = n\lambda$, where $n = 0, 1, 2, \ldots$
- **fringe spacing**
  $\Delta x = \frac{\lambda L}{d}$
- **path difference for destructive interference**
  $p.d. = \left(n + \frac{1}{2}\right)\lambda$, where $n = 0, 1, 2, \ldots$

Evidence for the wave-like nature of light 4.1.6.1

Young's double slit experiment shows light exhibiting the wave property of interference. This experiment challenged the particle nature of light and provided evidence for a wave model of light.

How does Young's double slit experiment support the wave model of light?

In 1665, Francesco Grimaldo discovered that light diffracts. Through this, he argued that light must be a wave. During this time scientists like Grimaldo and Huygen conducted experiments and argued for a wave model of light, while other scientists, most notably Isaac Newton, argued for a particle model of light.

In 1801, a physicist called Thomas Young performed an experiment in which he shone a thin beam of light through two slits onto a screen.

- According to the particle model of light, light particles passing through the two slits should result in two vertical bright bands appearing on the screen (Figure 1a).
- According to the wave model of light, light waves passing through the two slits should interfere with each other, creating an interference pattern on the screen (Figure 1b).

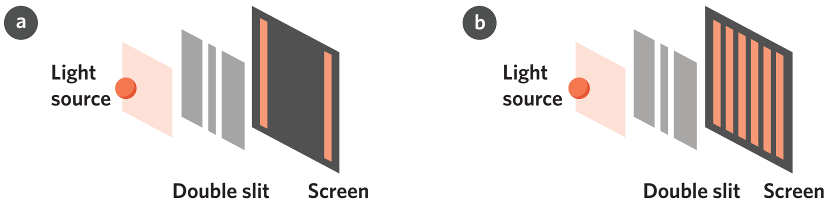


Figure 1 The expected outcome of the double slit experiment according to the **(a)** particle model of light and **(b)** the wave model of light

USEFUL TIP

The amount of diffraction depend on the ratio of the wavelength to the slit width, $\frac{\lambda}{w}$:

- If $\frac{\lambda}{w} << 1$ then limited diffraction occurs
- If $\frac{\lambda}{w} \gtrsim 1$ then significant diffraction occurs

Young observed an interference pattern, consisting of alternating regions of bright and dark bands, which could only be explained using the wave model of light (Figure 2):

- When light passes through the two narrow slits, diffraction occurs, causing the light to spread out.
- This allows the slits to be treated as two sources of light.
- The superposition of diffracted light from the two slits results in an interference pattern on the screen:
  - bright bands are the results of constructive interference occurring, where the **path difference** is an integer multiple of the wavelength:

$$p.d. = |S_1X - S_2X| = n\lambda$$

  - dark bands are the result of destructive interference occurring, where the path difference is half a wavelength more than an integer multiple of the wavelength:

$$p.d. = |S_1X - S_2X| = \left(n + \frac{1}{2}\right)\lambda$$

- The diffracted light from these slits is **coherent**, as the diffracted light originates from the same source.
- As the path difference at the centre is zero ($p.d. = 0 = 0 \times \lambda$), there is a bright band at the centre of the interference pattern, often referred to as the central maximum.

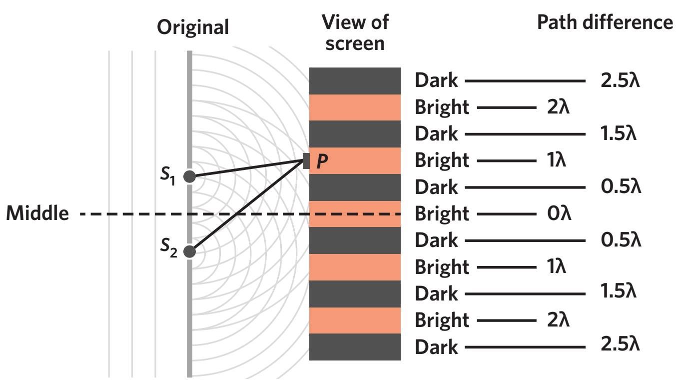


Figure 2 Interference pattern formed from Young's double slit experiment

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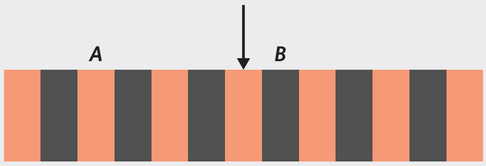
WORKED EXAMPLE 1

The diagram represents the pattern observed in a double slit experiment. The arrow indicates the central bright band. The path difference to the bright band A is 1.2×10^{-6} m.



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a. Calculate the wavelength of the light.

Step 1

Identify known and unknown variables and write down the formula that relates these variables.

Note that A is the third bright band and so has an n value of 2 and a path difference equal to the distance from A to the centre.

$p.d. = 1.2 \times 10^{-6}$ m, $n = 2$, $\lambda = ?$

$p.d. = n\lambda$

Step 2

Substitute values into the formula and solve for the wavelength.

$1.2 \times 10^{-6} = 2 \times \lambda$

$\lambda = 6.0 \times 10^{-7}$ m

---

b. Determine the path difference to the dark band B.

Step 1

Identify known and unknown variables and write down the formula that relates these variables.

Note that B is the dark band adjacent to the central maximum so $n = 0$.

$n = 0$, $\lambda = 6.0 \times 10^{-7}$ m, $p.d. = ?$

$p.d. = \left(n + \frac{1}{2}\right)\lambda$

Step 2

Substitute values into the formula and solve for the path difference.

$p.d. = \left(0 + \frac{1}{2}\right) \times 6.0 \times 10^{-7}$

$p.d. = 3.0 \times 10^{-7}$ m

OR

B is one quarter of the distance between A and the central maximum.

$p.d = \frac{1.2 \times 10^{-6}}{4} = 3.0 \times 10^{-7}$

How Young's double slit experiment supports the wave model of light

- Young's double slit experiment results in an interference pattern created by light.
- An interference pattern is a wave phenomena.
- This means light exhibits wave properties, which provides evidence for the wave-like nature of light.

PROGRESS QUESTIONS

Question 1

Which of the following best describes the predicted results of Young's double slit experiment according to the particle model of light?

A. two vertical bright bands

B. a single bright band appearing in the centre

C. an interference pattern consisting of bright and dark regions

D. an interference pattern consisting of two vertical bright bands

Continues →

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Question 2

Which of the following best describes how Young's double slit experiment supports the wave model of light?

A. The results show an interference pattern, which is a particle phenomenon.

B. The results show multiple bright bands, which is the result of a moving light source.

C. The results show a central maximum, which indicates the sources of light are coherent.

D. The results show an interference pattern, which indicates that light exhibits wave properties.

Fringe spacing 4.1.6.4

The **fringe spacing** is the distance between adjacent bright or dark bands in an interference pattern. It depends on the slit separation, the distance between the slits and the screen, and the wavelength.

How can we change the fringe spacing of an interference pattern?

The fringe spacing is the distance between the centre of adjacent bright bands or adjacent dark bands (Figure 3). The fringe spacing can be calculated using the following relationship:

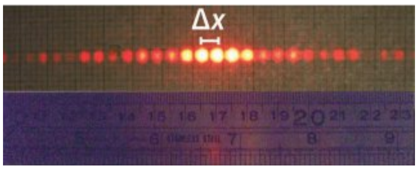

Figure 3 Measuring the fringe spacing for red laser light using a ruler

FORMULA

$$\Delta x = \frac{\lambda L}{d}$$

Δx = fringe spacing (m)
λ = wavelength (m)
L = distance from slits to screen (m)
d = slit separation (m)

KEEN TO INVESTIGATE?

1 **How does changing the variables in the fringe spacing formula affect the fringe spacing?**
Search Google: oPhysics 'Double slit diffraction and interference' simulation

MISCONCEPTION

'Slit separation, *d*, represents the width of the slits'

Slit separation, *d*, is the distance between the two slits, not the width of the individual slits.

Figure 4 shows how the variables in the fringe spacing equation relate to the experimental set up in Young's double slit experiment, while Table 1 shows the effect changing each variable has on the fringe spacing.[1]

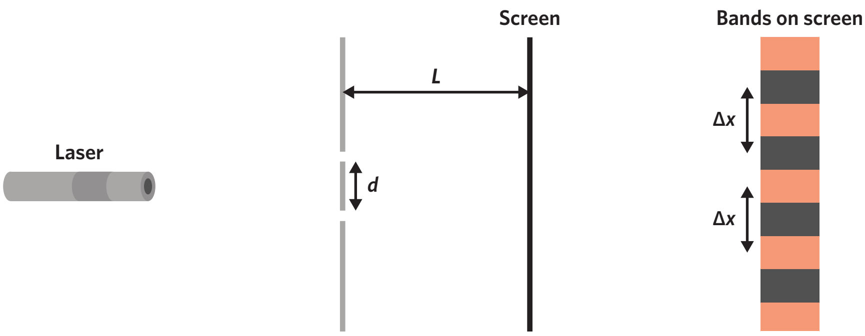

Figure 4 The variables in fringe spacing formula and how they apply to Young's double slit experiment

Table 1 The effect changing each variable has on the fringe spacing

Variable	Change	Effect on fringe spacing
Wavelength, λ	Increase	Increase
Distance from slits to screen, *L*	Increase	Increase
Slit separation, *d*	Increase	Decrease

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WORKED EXAMPLE 2

A laser with wavelength 600 nm is incident on two slits 3.00×10^{-5} m apart. The interference pattern is visible on a screen 1.00 m behind the slits.

a. Calculate the distance between adjacent bright bands.

Step 1

Identify known and unknown variables and write down the formula that relates these variables.

$\lambda = 6.00 \times 10^{-7}$ nm, $L = 1.00$ m, $d = 3.00 \times 10^{-5}$ m, $\Delta x = ?$

$$\Delta x = \frac{\lambda L}{d}$$

Step 2

Substitute values into the formula and solve for the fringe spacing.

$$\Delta x = \frac{6.00 \times 10^{-7} \times 1.00}{3.00 \times 10^{-5}}$$

$$\Delta x = 2.00 \times 10^{-2} \text{ m}$$

b. Calculate the distance between the central bright band and the dark band immediately to its right.

Step 1

Identify the formula that relates the fringe spacing to the distance between adjacent bright and dark bands.

Note that the distance between a bright band and the next dark band is half the distance between adjacent bright bands.

$\Delta x = 2.00 \times 10^{-2}$ m, $distance = ?$

$$distance = \frac{\Delta x}{2}$$

Step 2

Calculate the distance between the central bright band and the dark band to its right.

$$distance = \frac{2.00 \times 10^{-2}}{2} = 1.00 \times 10^{-2}$$

$$distance = 1.00 \times 10^{-2} \text{ m}$$

PROGRESS QUESTIONS

Question 3

Fringe spacing is

A. the distance between the two slits.

B. the distance from the slits to the screen.

C. the length of the entire interference pattern.

D. the distance between the centres of adjacent bright or dark bands.

Use the following information to answer questions 4 and 5.

A laser of wavelength 450 nm is incident on double slits 3.00×10^{-5} m apart. The interference pattern is visible on a screen 2.00 m behind the slits.

Question 4

What is the distance between adjacent bright bands?

A. 0.030 cm **B.** 0.030 m **C.** 0.30 cm **D.** 0.30 m

Question 5

If the distance from the two slits to the screen is halved, the fringe spacing will

A. halve. **B.** double. **C.** increase. **D.** remain the same.

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Theory summary

- Young's double slit experiment supports the wave model of light.
- It shows that light exhibits the wave property of interference.
- Constructive interference leads to bright bands and destructive interference leads to dark bands. These can be predicted by path difference equations by treating the slits as light sources.
- The fringe spacing, $\Delta x = \frac{\lambda L}{d}$, calculates the distance between the centre of adjacent bright fringes or dark fringes.

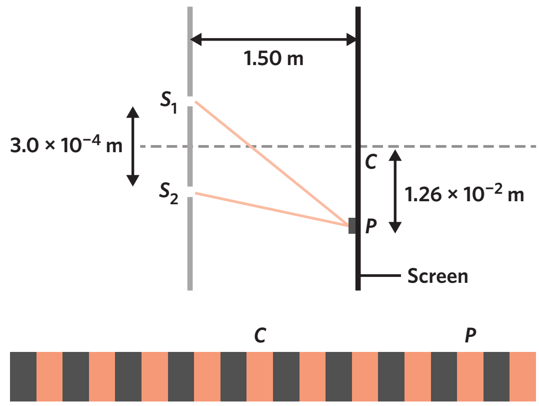
8B Questions

Mild Medium Spicy

Deconstructed exam-style

Use the following information to answer questions 6–8.

In a Young's double-slit experiment, laser light is incident on two slits, S_1 and S_2, that are 3.0×10^{-4} m apart, as shown in the diagram. Rays from the slits meet on a screen 1.50 m away to produce the interference pattern shown. The point C is a bright band in the centre of the pattern. The distance from the central bright fringe at point C to the bright fringe at point P is 1.26×10^{-2} m.



Question 6 (1 MARK)

Which of the following could be used to calculate the fringe spacing?

A. $\Delta x = \frac{1.26 \times 10^{-2}}{4}$

B. $\Delta x = \frac{1.26 \times 10^{-2}}{1.5}$

C. $\Delta x = \frac{1.26 \times 10^{-2}}{3.0 \times 10^{-4}}$

D. $\Delta x = \frac{1.26 \times 10^{-2} \times 1.5}{3.0 \times 10^{-4}}$

Question 7 (1 MARK)

Which of the following correctly identifies the variables L and d?

A. $L = 3.0 \times 10^{-4}$ m, $d = 1.50$ m

B. $L = 1.50$ m, $d = 3.0 \times 10^{-4}$ m

C. $L = 1.50$ m, $d = 1.26 \times 10^{-2}$ m

D. $L = 1.26 \times 10^{-2}$ m, $d = 3.0 \times 10^{-4}$ m

Question 8 (3 MARKS)

Calculate the wavelength of the laser light. Show your working.

Adapted from VCAA 2020 exam Short answer Q12b

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Exam-style

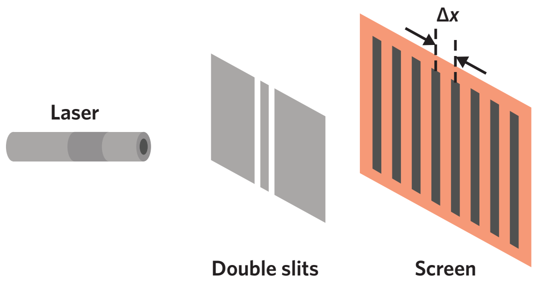
Question 9 (1 MARK)

Which of the following options correctly describes Young's double slit experiment?

	Observed result on the screen	Explanation of observed result	Model of light supported
A.	Two bright spots	Light travels in straight lines	Wave
B.	Alternating bright and dark regions	Interference	Particle
C.	Alternating bright and dark regions	Interference	Wave
D.	Alternating bright and dark regions	Light travels in straight lines	Particle

Question 10 (1 MARK)

A teacher set up an apparatus to demonstrate Young's double-slit experiment. A pattern of bright and dark bands is observed on the screen as shown.



Which one of the following actions will increase the distance, Δx, between the adjacent dark bands in this interference pattern?

A. decrease the slit width

B. decrease the slit separation

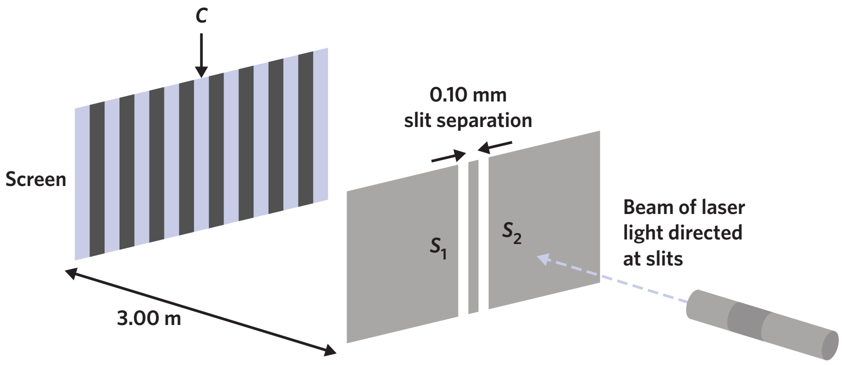
C. decrease the wavelength of light

D. decrease the distance between the slits and the screen

Adapted from VCAA 2018 exam Multiple choice Q12

Question 11 (6 MARKS)

Two students conduct an experiment using laser light, two narrow slits, and screen as shown.



Point C is a bright band at the centre of the pattern of light and dark bands on the screen. The slit separation is 0.10 mm and the screen is 3.00 m away from the two slits.

a. This experiment is often described as Young's double slit experiment. Explain how this experiment gave support for those who argued light has wave-like properties. 2 MARKS

b. The frequency of the laser light is 6.50×10^{14} Hz. Calculate the spacing of the dark bands on the screen. Show your working. 2 MARKS

c. Explain why point C is a bright band and why there is a dark band to the left of the centre. 2 MARKS

Adapted from VCAA 2022 exam Short answer Q12

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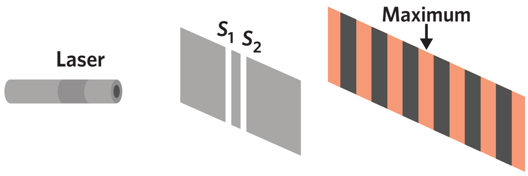
Question 12 (8 MARKS)

Two students are conducting Young's double slit experiment using two slits, S_1 and S_2, which are 1.0 mm apart. The students fire a laser through the two slits and calculate the distance between adjacent dark bands that appear on a screen 1.5 m away.



a. If a laser with a wavelength of 650 nm travels through the two slits, what is the distance between two successive dark bands? Show your working. 2 MARKS

Adapted from VCAA 2021 exam Short answer Q13a

b. ***Key science skill***

The students move the screen in 10 cm increments back from the slits and measure the distance between adjacent dark bands. Identify the independent variable, the dependent variable, and one control variable in this experiment. 3 MARKS

FROM LESSON 12A

c. ***Key science skill***

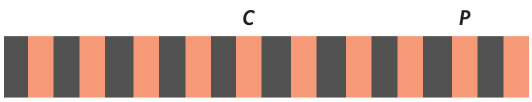
The students decide to safely immerse the entire apparatus in a liquid. The students know that light travels slower in the liquid than in air but don't know the exact speed. They place the screen 1.5 m from the slits, and using the same laser, they notice that the spacing of the bands changes. Describe the change observed in the spacing and explain why this change occurred. 3 MARKS

Adapted from VCAA 2022 exam Short answer Q12d

FROM LESSON 12A

Question 13 (2 MARKS)

In Young's double slit experiment laser light is incident on two slits. Light from the slits meet on a screen and form the interference pattern shown. Point *C* is the centre of the pattern and point *P* is a bright fringe.

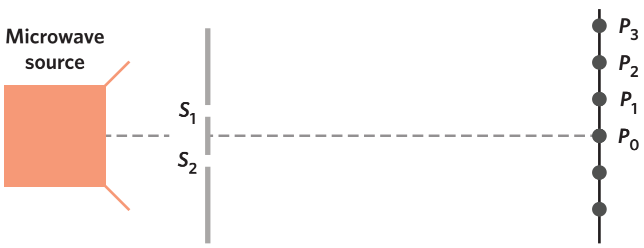


Explain how the bright fringe at point *P* is formed.

Adapted from VCAA 2020 exam Short answer Q12a

Question 14 (4 MARKS)

Students have set up a double-slit experiment using microwaves. The microwaves pass through a metal barrier with two slits, shown as S_1 and S_2. The students measure the intensity of the resulting beam at points along the line shown. They determine the positions of maximum intensity to be at the points labelled P_0, P_1, P_2 and P_3. Take the speed of electromagnetic radiation to be 3.00×10^8 m s^{-1}. A diagram of the setup is shown.



The distance from S_1 to P_3 is 73.5 cm and the distance from S_2 to P_3 is 81.6 cm.

a. What is the frequency of the microwaves transmitted through the slits? Show your working. 2 MARKS

b. The signal strength is at a minimum approximately midway between points P_0 and P_1. Explain the reason why the signal would be minimum at this location. 2 MARKS

Adapted from VCAA 2019 exam Short answer Q14

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Previous lessons

Question 15 (2 MARKS)

A satellite is in orbit around Earth and experiences a force due to gravity of 230 N. The satellite is orbiting at a distance of 9.00×10^6 m from the centre of the Earth, the mass of Earth is 5.98×10^{24} kg, and $G = 6.67 \times 10^{-11}$ N m^2 kg^{-2}. Calculate the mass of the satellite.

FROM LESSON 3C

Question 16 (1 MARK)

Which of the following would decrease the amount of power lost in transmission lines?

A. stepping the current up before transmission

B. installing higher resistance transmission lines

C. stepping the current down before transmission

D. stepping the voltage down before transmission

FROM LESSON 6C

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Chapter 8 review

Mild 🌶 Medium 🌶🌶 Spicy 🌶🌶🌶

These questions are typical of one hour's worth of questions on the VCE Physics Exam.

Total marks: 50

Section A

All questions in this section are worth one mark.

Unless otherwise indicated, the diagrams in this book are not drawn to scale.

Question 1 🌶

Which of the following gives the order of light from lowest to highest energy?

A. Infrared, radio, red, green, blue

B. Red, green, blue, infrared, radio

C. Radio waves, infrared, red, green, blue

D. Radio waves, infrared, blue, green, red

Question 2 🌶

Which of the following is true?

A. Young's double slit experiment proved that the wave model of light is correct.

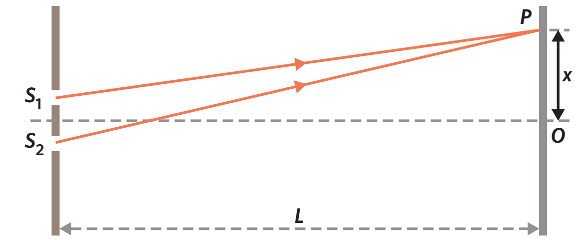
B. Young's double slit experiment proved that the particle model of light was correct.

C. Young's double slit experiment only creates interference patterns with white light.

D. Young's double slit experiment provided evidence that light demonstrates wave-like properties.

Question 3 🌶🌶

The double-slit arrangement shown was used to estimate the wavelength of a monochromatic light source.



- The path difference between points S_1 and S_2 to point P is known.
- Point P occurs at a bright band of light.

Which other measurement is required to find the wavelength of the monochromatic light?

A. L

B. x

C. the distance between S_1 and S_2

D. the number of bright bands from O to P

Question 4

An electromagnetic wave is produced, with a frequency of 1.2×10^{10} Hz. What is its wavelength? Assume that it travels at the speed of light in a vacuum.

A. 9.0×10^{-7} m

B. 5.5×10^{-3} m

C. 2.5×10^{-2} m

D. 7.4×10^{1} m

Question 5

In a double slit experiment, a student establishes an interference pattern. He then halves the distance from the double slits to the screen and doubles the wavelength. Determine the change to the interference pattern.

A. There would be no change to the pattern.

B. The fringes would be spaced twice as far apart.

C. The fringes would be spaced four times as far apart.

D. We can not determine the change as the student changed two variables.

Section B

In questions where more than one mark is available, appropriate working must be shown.

Unless otherwise indicated, the diagrams in this book are not drawn to scale.

Question 6 (4 MARKS)

A double slit experiment is set up and an interference pattern of alternating bright and dark bands is obtained.

a. Explain the conditions where bright bands are formed. 2 MARKS

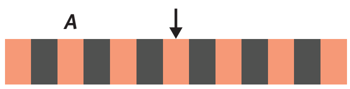
b. Explain the conditions where dark bands are formed. 2 MARKS

Question 7 (2 MARKS)

A household microwave operates at a frequency of 2.45 GHz. Show that the wavelength of the microwave emission is 12 cm.

Question 8 (2 MARKS)

In a double slit experiment, the bright band A is 1.50×10^{-6} m closer to one slit than the other. The diagram of the interference pattern is shown with the arrow representing the central maximum. Calculate the wavelength of the light, in nanometres.



Adapted from VCAA 2019 exam Short answer Q14a

Question 9 (2 MARKS)

Michael argues that regardless of the medium, light will always travel at 3.0×10^{8} m s^{-1}. Evaluate Michael's argument.

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Question 10 (8 MARKS)

Key science skill

Students attempted Young's double slit experiment. They wanted to determine the relationship between the distance from the slits to the screen, L, and the fringe spacing of the resulting interference pattern, Δx. To test this, they measured the fringe spacing, Δx, with an uncertainty of $\pm 0.05 \times 10^{-5}$ m, for multiple values of L. The following results were recorded.

L (m)	Δx ($\times 10^{-5}$ m)
0.23	1.1
0.27	1.3
0.31	1.5
0.32	1.6
0.45	2.3

a. Identify the independent and dependent variables in this experiment. 2 MARKS

b. Use the data to plot a graph of Δx on the vertical axis against L on the horizontal axis. Be sure to include: 5 MARKS

- axis labels and units
- an appropriate scale
- error bars for Δx the values
- a straight line of best fit

c. Describe how the graph from part **b** would change if the uncertainty in Δx doubled to $\pm 0.1 \times 10^{-5}$ m. 1 MARK

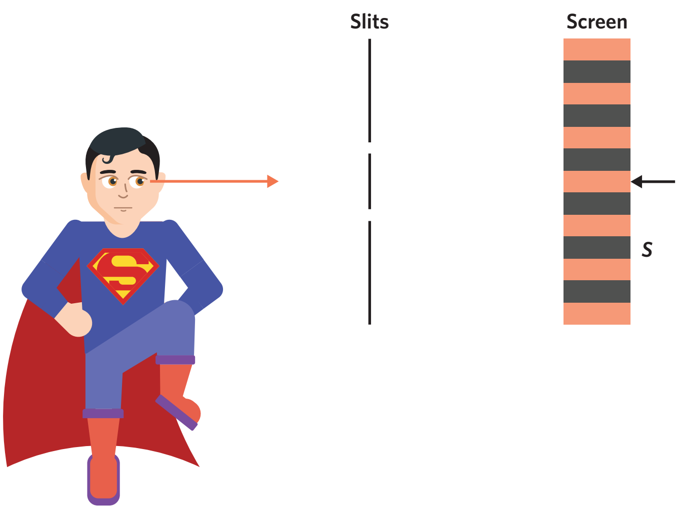
FROM LESSON 12D

Question 11 (3 MARKS)

Describe how light is produced when an electron is accelerated.

Question 12 (6 MARKS)

Superman keeps his super clean super suits in an airless locked room. The only way to unlock the room is by creating a particular interference pattern as shown, in which the path difference to the dark band S is 1.60×10^{-6} m. The arrow represents the central maximum.



a. Superman shines a laser from his eye, which has a wavelength of 640 nm, into the lock. Use calculations to determine whether the lock opens. 3 MARKS

b. Superman now decides to use his super strength to move the screen closer or further away from the slits. Will he be able to unlock the door this way? Justify your answer. 3 MARKS

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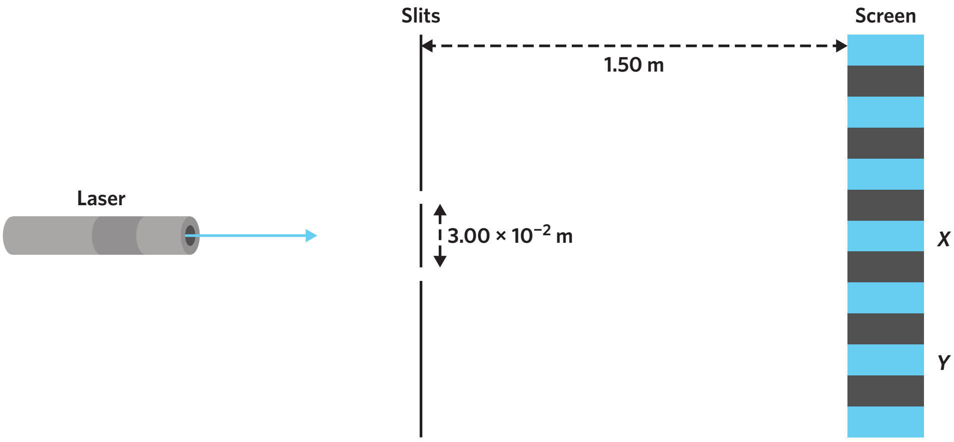
Question 13 (8 MARKS)

In a double slit experiment, the slits are separated by a distance of 3.00×10^{-2} m, the screen is 1.50 m away from the slits, and the laser produces light with a wavelength of 480 nm. A diagram of the experimental set up and resulting interference pattern is shown, where *X* is a bright band at the centre of the pattern.



a. Calculate the path difference to bright band *Y*. Give your answer in m. 2 MARKS

Adapted from VCAA 2010 exam Short answer Q4

b. Calculate the fringe spacing. 2 MARKS

c. Describe how the spread of the interference pattern would change if a laser producing a shorter wavelength of light is used instead. 1 MARK

d. After changing the wavelength of light to 350 nm, would band *X* be a node or antinode? Explain your answer. 3 MARKS

Question 14 (4 MARKS)

Explain how Young's double slit experiment provided evidence for a wave model of light and contradicted a particle model of light.

Adapted from VCAA 2010 exam Short answer Q1

Question 15 (3 MARKS)

The ratio of the speed of light in a vacuum, c, and the speed of light in a given medium, v, is given by $n = \frac{c}{v}$.

The wavelength of light in a medium with $n = 1.80$ is 880 nm. Calculate the frequency of this wave.

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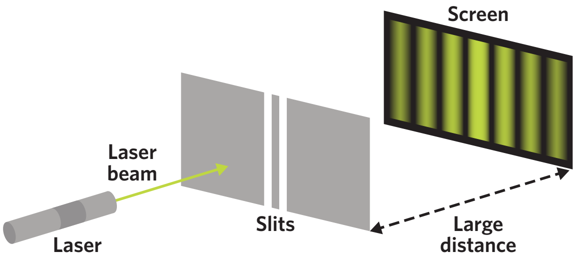
Question 16 (3 MARKS)

A group of students are undertaking Young's double slit experiment. They shine monochromatic light onto a double slit card, which is placed far away from the screen. The interference pattern produced on the screen is a pattern of bright and dark bands of light.



The students then change the monochromatic light source to white light. All students agree that there will be bands of colour on the screen, but have different opinions about the centre band. Dom predicts a predominantly white band in the centre with some colour on the edges, while Julia believes a completely coloured band will be observed in the centre.

Who is correct? Justify your answer.

Adapted from VCAA 2002 exam Short answer Q5

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9

CHAPTER 9

Light behaving as a particle

STUDY DESIGN DOT POINTS

- apply the quantised energy of photons: $E = hf = \frac{hc}{\lambda}$
- analyse the photoelectric effect with reference to:
  - evidence for the particle-like nature of light
  - experimental data in the form of graphs of photocurrent versus electrode potential, and of kinetic energy of electrons versus frequency
  - kinetic energy of emitted photoelectrons: $E_{k\,max} = hf - \phi$, using energy units of joule and electron-volt
  - effects of intensity of incident irradiation on the emission of photoelectrons
- describe the limitation of the wave model of light in explaining experimental results related to the photoelectric effect

Reproduced from VCAA VCE Physics Study Design 2024–2027

LESSONS

Image: Chepe Nicoli/Shutterstock.com

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9A Experimental design of the photoelectric effect

STUDY DESIGN DOT POINT

- analyse the photoelectric effect with reference to:
  - evidence for the particle-like nature of light
  - experimental data in the form of graphs of photocurrent versus electrode potential and of kinetic energy of electrons versus frequency
  - kinetic energy of emitted photoelectrons: $E_{k\,max} = hf - \phi$, using energy units of joule and electron-volt
  - effects of intensity of incident irradiation on the emission of photoelectrons

9A 9B 9C 9D

4.1.8.1 The electron-volt

4.1.8.2 Understanding the photoelectric effect experiment

4.1.8.3 Work function

4.1.8.5 Stopping voltage as a way to determine the maximum kinetic energy of electrons

4.1.8.4 Dependent and independent variables of the photoelectric effect experiment

ESSENTIAL PRIOR KNOWLEDGE

2D Conservation of energy
4A Work done by an electric field
6A Constructing electrical circuits
12A Understanding variable types
See questions 74–77.

How can we use the emission of photoelectrons to see at night?

When light with enough energy hits a metal surface, it results in the emission of photoelectrons. This phenomena, known as the photoelectric effect, has many applications, including in night vision goggles which help us see in low light conditions. This lesson introduces the key ideas of the electron-volt, work function, and stopping voltage, to be expanded upon in future lessons. It was for his work in explaining the photoelectric effect that Albert Einstein won his first Nobel prize in physics in 1921.

KEY TERMS AND DEFINITIONS

electron-volt a measure of energy equal to 1.6×10^{-19} J

photoelectrons electrons emitted in the photoelectric effect

photocurrent the electrical current produced by photoelectrons in the photoelectric effect

variable voltage source a voltage source that can provide a range of voltage levels in different directions to a circuit

work function the minimum energy of light required to release the most loosely bound electron from a metal surface

stopping voltage the voltage required to stop electrons with the highest kinetic energy and hence reduce photocurrent to zero

cut-off potential see stopping voltage

FORMULAS

- **work in an electric field**
  $W = qV$

The electron-volt 4.1.8.1

The **electron-volt**, or eV, is a measure of energy useful for describing very small quantities. In Unit 4, electron-volts will be used alongside joules to describe the energy of light and **photoelectrons**.

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How can we measure energy on small scales?

When a charged particle moves parallel to an electric field, the energy gained or lost by the particle can be calculated using $W = qV$. If we consider an electron, with a charge of 1.6×10^{-19} C, moving across a potential difference of 1 V, the amount of energy lost or gained can determined using:

$$W = qV = 1.6 \times 10^{-19} \times 1 = 1.6 \times 10^{-19}\ \text{J}$$

This defines the value of an electron-volt:

$$1\ \text{eV} = 1.6 \times 10^{-19}\ \text{J}.$$

The unit eV can be used to describe the energy of anything, it is not confined to just electrons. However, electron-volts are more conveniently used for quantities on very small scales. The conversion between electron-volts and joules is shown in Figure 1.

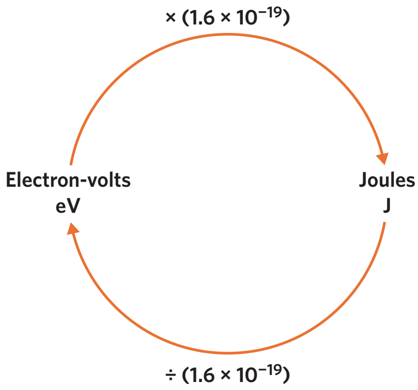

Figure 1 Converting between electron-volts and joules

PROGRESS QUESTIONS

Question 1

Electron-volts are a measure of

A. charge. **B.** energy. **C.** voltage. **D.** current.

Question 2

5.5 eV when converted to joules is closest to

A. 3.4×10^{-19} J.
B. 5.5×10^{-19} J.
C. 6.8×10^{-19} J.
D. 8.8×10^{-19} J.

Understanding the photoelectric effect experiment 4.1.8.2

The photoelectric effect demonstrates how light striking a metal surface is able to free electrons from the metal and provides one of the key pieces of evidence supporting the particle model of light. The electrons released are known as photoelectrons, and once they reach the collector electrode they create a current in the circuit known as a **photocurrent**.

How is the photoelectric effect experiment setup?

Metals are made up of positively charged particles called cations and delocalised (without a fixed location) negatively charged electrons (Figure 2).

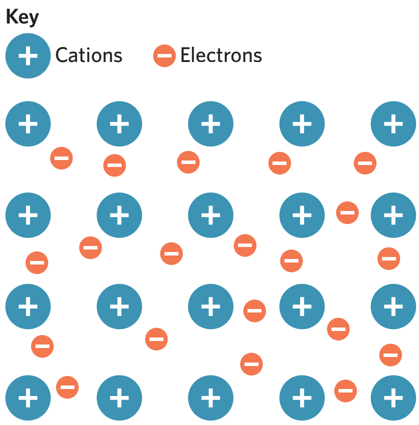

Figure 2 The basic structure of a metal

These opposite charges exert an attractive electric force on each other that holds the electrons within the metal structure. When light hits the metal surface, electrons that are held within the metal absorb the energy from the light, which may cause them to be ejected (Figure 3).[1]

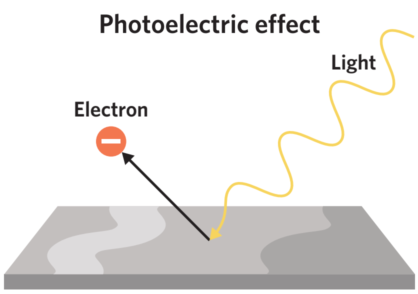

Figure 3 Incident light shone upon a metal surface can result in electrons being emitted from the surface.

KEEN TO INVESTIGATE?

[1] **How can we visualise the photoelectric effect in action?**
Search YouTube: Photoelectric effect demonstration

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The photoelectric effect experiment is set up using a photocell composed of two metal plates: one to eject electrons and one to collect them. The photocell is connected to a **variable voltage source** (Figure 4):

- The metal surface used to emit electrons has light incident on it, potentially causing the emission of photoelectrons.
- The collector, known as the collector electrode, is connected to the positive terminal of the variable voltage source.
- Any emitted photoelectrons are attracted to the positively charged collector electrode, resulting in a photocurrent flowing through the circuit.
- An ammeter can be connected to measure the photocurrent.

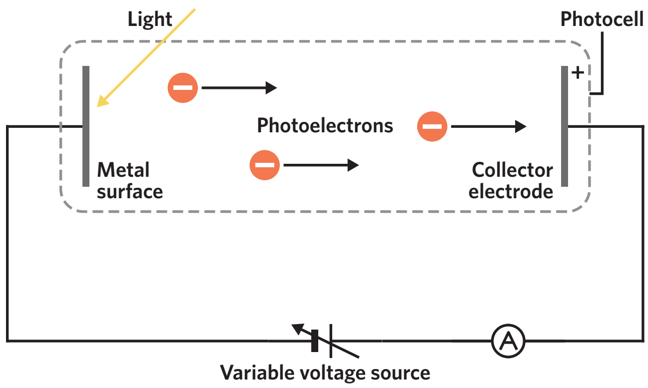

Figure 4 The photoelectric experimental setup

Table 1 outlines the components of the photoelectric experiment and their purpose.

MISCONCEPTION

'The variable voltage source provides current to the circuit.'

The purpose of the variable voltage source is to charge the collector electrode so that it can attract or repel electrons emitted by the metal surface. As the circuit is not closed, there is no current in the circuit until the photoelectrons reach the detector. This is known as photocurrent.

Table 1 The components of the photoelectric experiment and their purpose

Component	Purpose
Incident light	Provides energy to the electrons in order to liberate them from the metal surface
Metal surface	Provides the electrons to be emitted
Collector electrode	Collects the emitted electrons
Ammeter	Measures the photocurrent through the circuit after electrons have been collected by the collector electrode
Variable voltage source	Applies a voltage across the collector electrode to positively charge it. Causes it to attract and collect the maximum number of electrons emitted

PROGRESS QUESTIONS

Question 3

Circle the correct terms to complete this activity.

The variable voltage source is used to (negatively / positively) charge the collector electrode in order to (attract / repel) any emitted (cations / photoelectrons) from the metal surface.

Question 4

What is the role of the ammeter in the circuit?

A. to collect electrons

B. to repel the electrons from the metal surface

C. to measure the photocurrent running through the circuit

D. to measure the potential difference across the two metal plates

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Work function 4.1.8.3

The **work function** is a property of a metal that relates to how strongly electrons are held within its structure. The work function has an important influence over whether electrons will be liberated from the metal surface and, if they are, how much kinetic energy they have.

How can we analyse the kinetic energy of electrons?

Electrons in different metals are bound by different amounts of energy, and therefore require different amounts of energy to be removed. The work function (ϕ or W) is a measure of the amount of energy required to release the most loosely bound electron from a metal – it is the minimum amount of energy required for light to eject photoelectrons. Each metal has a unique work function.

When light interacts with an electron in a metal, some of the light's energy is used to liberate the electron from the metal and any remaining energy is transferred to the photoelectron as kinetic energy (since energy is always conserved). If the light energy absorbed by each electron is less than the work function, electrons will not be ejected.

As some electrons are more loosely bound than others, electrons will be ejected with a range of kinetic energies. KE_{max} (or $E_{k\,max}$) is used to describe the kinetic energy of the most loosely bound electron – the electron which needs the least amount of energy to overcome the work function and escape the metal.

This relationship can be expressed as an equation, using the conservation of energy:

$$\Sigma E_i = \Sigma E_f$$
$$\Rightarrow E_{light} = \phi + KE_{max}$$
$$\Rightarrow KE_{max} = E_{light} - \phi$$

The details of the amount of energy delivered to each electron will be further explained in Lessons 9C and 9D.

MISCONCEPTION

'The work function represents the energy required for all electrons to escape the metal.'

The work function represents the amount of energy required for only the most loosely bound electron to escape from the metal surface.

WORKED EXAMPLE 1

Students conduct a photoelectric experiment using sodium, that has a work function of 2.3 eV. Given that each electron absorbs 3.2 eV of energy from the light, calculate the maximum kinetic energy of the photoelectrons produced.

Step 1

Identify known and unknown variables and write down the formula that relates these variables.

$E_{light} = 3.2$ eV, $\phi = 2.3$ eV, $KE_{max} = ?$

$KE_{max} = E_{light} - \phi$

Step 2

Substitute values into the formula and solve for the work function of the metal.

Note that the units we are working with are eV.

$KE_{max} = 3.2 - 2.3 = 0.9$ eV

PROGRESS QUESTIONS

Question 5

Which of the following best describes the work function?

A. The energy of incident light in the photoelectric experiment.

B. The maximum energy required to liberate an electron from a collector electrode.

C. The minimum energy required to liberate an electron from a specific metal surface.

D. A property of metals due to the interaction of negative cations and positive electrons.

Continues →

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Question 6

What is the maximum kinetic energy of photoelectrons ejected, when they absorb 2.4 eV of light energy and escape a metal with a work function of 1.7 eV?

A. 0.70 eV **B.** 1.7 eV **C.** 2.4 eV **D.** 4.1 eV

Stopping voltage as a way to determine the maximum kinetic energy of electrons 4.1.8.5

USEFUL TIP

For simplicity, whenever this chapter refers to a potential difference or voltage applied to the collector electrode, it is referring to the potential difference applied between two points: the metal surface and the collector electrode.

Stopping voltage (V_0 or V_s), alternatively called **cut-off potential**, is used to measure the maximum kinetic energy of photoelectrons.

How can we determine the maximum kinetic energy of photoelectrons?

In order to determine the maximum kinetic energy of emitted photoelectrons, the photoelectric effect experiment can be modified:

- The direction of the variable voltage source can be reversed, making the collector electrode negatively charged.
- This slows emitted photoelectrons down and even repels some back towards the emitting metal surface (Figure 5).
- As the reverse voltage across the plates is increased, less electrons reach the collector electrode, decreasing the photocurrent.
- The voltage at which no electrons reach the collector electrode and the photocurrent reaches zero is called the stopping voltage, V_0.
- The magnitude of the stopping voltage, measured in V, has the same numerical value as the KE_{max} of the electrons when measured in eV. For example, if the stopping voltage is 1.7 V then the kinetic energy of the fastest electron is 1.7 eV.

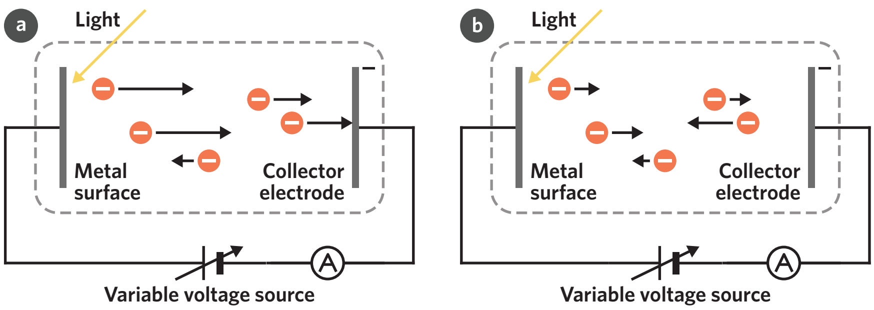

Figure 5 **(a)** Reversing the direction of the voltage source causes the collector electrode to repel electrons which reduces the photocurrent. **(b)** The voltage at which no electrons reach the collector electrode is the stopping voltage.

USEFUL TIP

The reason for the stopping voltage having the same magnitude in V as the KE_{max} in eV can be seen when using the work function formula $W = qV$.

- The work done in joules on the electron by the potential difference across the plates is equivalent to the change in kinetic energy of the electron: $\Delta KE = qV$.
- This value will be equal to the charge of the electron, 1.6×10^{-19} C, multiplied by the stopping voltage (in V): $\Delta KE = 1.6 \times 10^{-19} \times V$.
- The conversion between joules and electron-volts requires a division by 1.6×10^{-19}, meaning for a value of kinetic energy in eV, the equation is $\Delta KE = \frac{1.6 \times 10^{-19} \times V}{1.6 \times 10^{-19}} = V$.

Note that this equation is only applicable for measuring the kinetic energy of electrons in eV.

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To better understand the idea of determining the maximum kinetic energy of electrons by measuring another variable, consider the analogy of rolling a ball up a frictionless hill.

- When the ball reaches the top of the hill, it will have less kinetic energy than when it started (Figure 6a).
- We can increase the height of the hill until the ball no longer reaches the top (h_0). This is similar to increasing the potential difference across the plates until the current becomes zero (V_0) (Figure 6b).
- If we know the mass of the ball (which is like knowing the charge of the electron) we could determine the initial kinetic energy of the ball by measuring the height of the hill required to stop the ball reaching the top.
- Similarly, the size of the V_0 tells us the KE_{max} of the electrons.

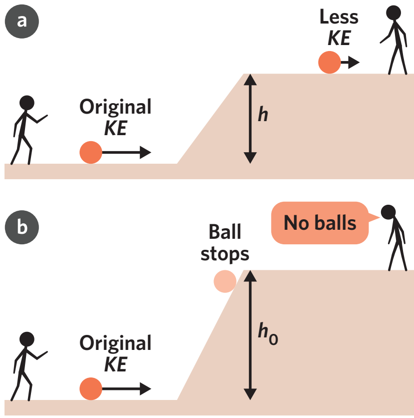

Figure 6 Negatively charging the collector electrode is like a hill which a ball must roll up.

USEFUL TIP

To understand the similarity between mass and charge in circumstances involving gravitational and electric fields, we can look at the equations for gravitational and electrical force: $F_g = mg$ and $F_E = qE$. In this case, both g and E represent the field strengths, and both F_g and F_E represent forces measured in newtons. Therefore, for analogies comparing gravitational potential energy and electrical potential energy, we can assume mass and charge are equivalent variables.

WORKED EXAMPLE 2

Bill and Bob wish to find the work function of a metal. They shine light on the metal surface that transfers 4.7 eV to each electron. When a potential difference of 1.2 V is applied across the plates, the current reaches zero. What is the work function of the metal?

Step 1

Identify known and unknown variables and write down the formula that relates these variables.

Note that the potential difference at which current drops to zero is the stopping voltage. This has the same numerical value as the maximum kinetic energy of the electrons in eV.

$KE_{max} = 1.2$ eV, $E_{light} = 4.7$ eV, $\phi = ?$

$KE_{max} = E_{light} - \phi$

Step 2

Substitute values into the formula and solve for the work function of the metal.

$1.2 = 4.7 - \phi$

$\phi = 3.5$ eV

PROGRESS QUESTIONS

Question 7

The photoelectric experiment is set up so that the collector electrode is negatively charged. A voltage is applied that is less than the stopping voltage. Which of the following statements is true?

A. The photocurrent is zero.

B. The photocurrent is a maximum amount.

C. The photocurrent is less than the maximum amount.

D. We can't make assumptions about the current without knowing more context.

Question 8

The stopping voltage, measured in V, has the same numerical value as the

A. light energy in eV.

B. work function in eV.

C. KE_{max} of the emitted photoelectrons in V.

D. KE_{max} of the emitted photoelectrons in eV.

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Dependent and independent variables of the photoelectric effect experiment 4.1.8.4

The photoelectric effect experiment has both independent and dependent variables that are fundamental to the evidence it provides about the nature of light. These ideas will be expanded upon in the following lessons.

How is the photoelectric experiment conducted?

Table 2 summarises some of the variables in the photoelectric effect experiment.

Table 2 The variables in the photoelectric experiment

Variable	Type	Description
Intensity of light (brightness)	Independent	The intensity of the light can be thought of as 'more' or 'less' light hitting the surface of the metal surface, and is independent of frequency.
Frequency of light	Independent	The higher the frequency of the light, the more energy is delivered to the electrons, and is independent of intensity. This will be explained further in Lesson 9C.
Work function	Independent	The work function is a property of a metal that relates to how strongly electrons are held within its structure. This can be changed by changing the metal surface.
Electrode potential/voltage	Independent	The potential difference between the metal surface and the collector electrode may cause the electrode to either attract or repel photoelectrons, so it affects the maximum photocurrent measured.
Photocurrent	Dependent	Photocurrent describes the rate of flow of charge due to the electrons being ejected from the metal surface and reaching the collector. It is measured by an ammeter in the external circuit.
Maximum kinetic energy of photoelectrons	Dependent	The maximum kinetic energy of photoelectrons can be calculated using the formula $KE_{max} = E_{light} - \phi$ or by measuring the stopping voltage.
Stopping voltage	Dependent	The stopping voltage can be measured using the maximum kinetic energy of photoelectrons.

For an experiment to be valid, the experiment should only have one independent variable: when the intensity of light is changed, the frequency should be kept constant and vice versa. The metal surface, and hence work function, is typically kept constant for a given experiment too.

PROGRESS QUESTIONS

Question 9

Identify the independent variables in the photoelectric experiment. **(Select all that apply)**

A. the intensity of the light

B. the work function of the metal

C. the frequency of the incident light

D. the photocurrent through the ammeter

Question 10

During the photoelectric effect experiment, the frequency and intensity of the light was changed at the same time to measure the effect this had on the photocurrent. Which of the following best describes the state of this experiment?

A. This experiment is valid because it is still measuring the same dependent variable.

B. This experiment is valid because both variables changed were properties of the light.

C. This experiment is invalid because more than one independent variable was changed at a time.

D. This experiment is invalid because the photocurrent doesn't stay the same throughout the whole experiment.

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Theory summary

- An electron-volt is a measure of energy that is equivalent to 1.6×10^{-19} J.
- The photoelectric effect describes how light is able to liberate electrons, called photoelectrons, from a metal surface to produce a photocurrent.
- The work function is specific to each metal and is the amount of energy required to free the most loosely bound electron.
- The maximum kinetic energy of electrons is given by: $KE_{max} = E_{light} - \phi$
- The independent variables of the photoelectric effect experiment are:
  - the intensity of light.
  - the frequency of light.
  - the work function of the metal surface.
  - the electrode voltage.
- The dependent variables of the photoelectric effect experiment are:
  - the photocurrent.
  - the maximum kinetic energy of electrons (KE_{max}) measured in electron-volts or joules, which can be determined by measuring the stopping voltage in volts.
  - the stopping voltage.

KEEN TO INVESTIGATE?

How can the photoelectric effect be used to see at night?
Search: How night vision goggles work – Physlink

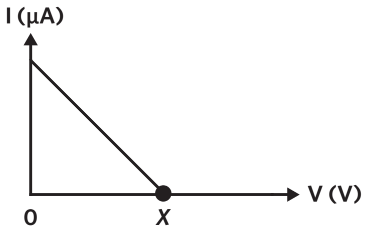
9A Questions

Mild Medium Spicy

Deconstructed exam-style

Use the following information to answer questions 11–13.

The photoelectric experiment is set up so that the collector electrode is negatively charged. The graph shows how the photocurrent, measured in μA, varies with voltage, measured in V.



Question 11 (1 MARK)

The stopping voltage represents

A. the voltage where the photocurrent reaches zero.

B. the voltage where the photocurrent reaches its maximum value.

C. the voltage where the incident light stops hitting the metal surface.

D. the voltage where the photocurrent travels in the negative direction.

Question 12 (1 MARK)

The maximum kinetic energy of the photoelectrons can be determined using the

A. work function.

B. stopping voltage.

C. maximum photocurrent.

D. frequency of the incident light.

Question 13 (3 MARKS)

Describe the shape of the graph and explain why the photocurrent drops to zero at point X and how maximum kinetic energy of the electrons can be determined.

Adapted from 2011 VCAA Exam 2 Section A AoS 2 Q5

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Exam-style

Question 14 (2 MARKS)

The surface of a metal has a work function of 3.2 eV.

What is the minimum energy that light must transfer to an electron to release a photoelectron in joules?

Adapted from 2018 VCAA NHT Exam Section A Q17

Question 15 (1 MARK)

A specific metal used in a photoelectric experiment has a work function of 2.3 eV and ejects electrons at a maximum energy of 0.2 eV. What is the cut-off potential required so that no photoelectrons reach the collector electrode?

A. 0.2 V

B. 2.1 V

C. 2.3 V

D. 2.5 V

Question 16 (2 MARKS)

Key science skill

Investigations into the photoelectric effect have multiple independent and dependent variables. Outline a key controlled variable of the photoelectric experiment and explain why it is necessary to keep it controlled.

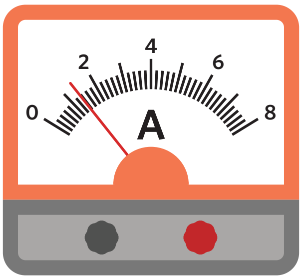
Adapted from 2017 VCAA Sample Exam Section B Q17e

FROM LESSON 12A

Question 17 (1 MARK)

Key science skill

This ammeter is used to measure the photocurrent during a photoelectric effect experiment.



What type of error is likely to be introduced when reading this device?

Adapted from 2018 VCAA Exam Section A Q19

FROM LESSON 12C

Question 18 (2 MARKS)

An electron has a mass of 9.1×10^{-31} kg and is shot out of an electron gun at a speed of 2.2×10^{6} m s^{-1}.

Measured in electron-volts, what is the kinetic energy of the electron?

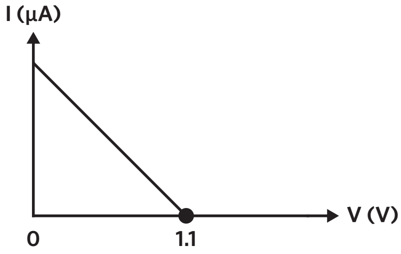
Question 19 (2 MARKS)

During an investigation into the photoelectric effect, a scientist uses light which can transfer energy of 3.70 eV to an electron in the attempt to release electrons from a metal of work function $\phi = 2.90$ eV.

Calculate the maximum kinetic energy of the photoelectrons in J.

Question 20 (2 MARKS)

A group of keen students are investigating the relationship between the photocurrent and stopping voltage. The results of their experiment is shown in a graph.



Determine the maximum kinetic energy of the photoelectrons in both electron-volts and joules.

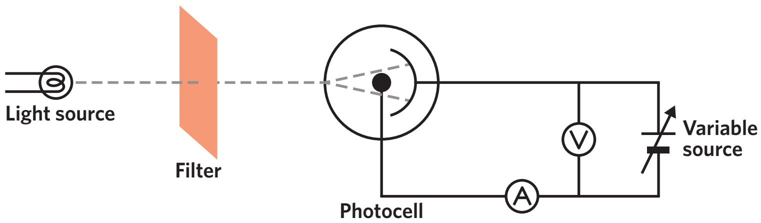
Adapted from 2011 VCAA Exam 2 Section A AoS 2 Q5

Question 21 (3 MARKS)

A specific metal has a work function of 2.8 eV. Describe the kinetic energies of the ejected photoelectrons when each electron absorbs 2.9 eV from light incident on the metal surface. Explain your answer.

Question 22 (1 MARK)

The diagram shows a circuit that is used to study the photoelectric effect.



Which of the following is essential to the measurement of the maximum kinetic energy of the emitted photoelectrons?

A. the level of brightness of the light source

B. the wavelengths that pass through the filter

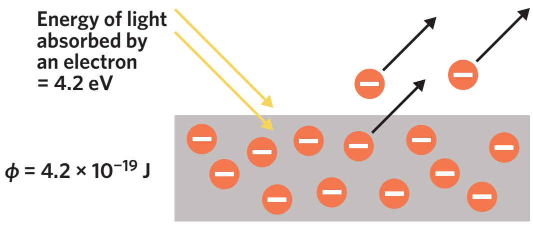
C. the reading on the ammeter when the voltage is at a maximum value

D. the reading on the voltmeter when the current is at a minimum value

Adapted from 2021 VCAA Exam Section A Q16

Question 23 (2 MARKS)

Use the diagram to find the maximum kinetic energy of the ejected photoelectrons in eV.



Question 24 (4 MARKS)

Riswan sets up an apparatus to study the photoelectric effect in which the light used can transfer an energy of 4.48×10^{-19} J to individual electrons in the metal surface. Riswan uses a variable power supply to negatively charge the collector electrode. He finds that the lowest voltage for which no current is measured is 0.60 V.

Determine the work function of the metal. Show your working.

Adapted from 2017 VCAA NHT Exam Section B Q18

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Question 25 (3 MARKS)

Tony Stank decides to take time out of his busy day to investigate the photoelectric effect with zinc. Using his hand lasers, he fires monochromatic light onto a zinc metal surface. He applies a voltage that stops all photoelectrons from reaching the collector electrode at 6.67 V. If If the work function of zinc is 6.93×10^{-19} J, calculate the energy of the light in joules.

Question 26 (4 MARKS)

Key science skill

Two students, Yousef and Ehsan, are conducting the photoelectric effect experiment to measure the maximum kinetic energy of ejected photoelectrons.

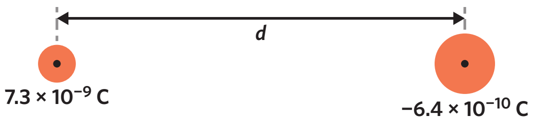
- Yousef decides to measure the KE_{max} by measuring the average velocity of the electrons and then use $KE = \frac{1}{2}mv^2$ along with the known mass of a photoelectron.
- Ehsan decides to measure the stopping voltage in order to determine KE_{max}.
- After undertaking the experiment, they calculated different results.

Evaluate the accuracy of the students' methods of finding the KE_{max} of the photoelectrons.

Previous lessons

Question 27 (2 MARKS)

A metal sphere has a charge of $+7.3 \times 10^{-9}$ C. A larger sphere with a charge of -6.4×10^{-10} C is placed to the right of the first sphere.

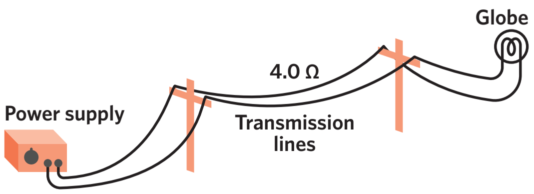


If the force on the larger sphere is 6.6×10^{-4} N, determine the magnitude of the force on the larger sphere if it were moved three times further away.

FROM LESSON 4A

Question 28 (2 MARKS)

Two students are experimenting with a model of a transmission line.



The 'transmission lines' consist of two wires with a total resistance of 4.0 Ω. As a load they use a globe which operates at 9.0 W when there is 1.5 V across it.

The connecting wires from the power supply to the transmission lines and from the transmission lines to the globe have negligible resistance.

The students notice that the power delivered to the light bulb is less than the power supply.
Explain why this is the case and what the students could add to the system to decrease this power loss.

FROM LESSON 6C

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9B Changing intensity in the photoelectric effect

Image: Gkgk999/Shutterstock.com

How can a sensor detect motion?

In motion-activated outdoor lighting systems, the photoelectric effect may be employed to detect low light levels. When motion is sensed, the resulting increase in light intensity leads to a higher photocurrent and brighter illumination. In this lesson, we will look at how changing the intensity of the incident light used in the photoelectric effect experiment affects the maximum photocurrent and maximum kinetic energy of photoelectrons.

STUDY DESIGN DOT POINT

- analyse the photoelectric effect with reference to:
  - evidence for the particle-like nature of light
  - experimental data in the form of graphs of photocurrent versus electrode potential and of kinetic energy of electrons versus frequency
  - kinetic energy of emitted photoelectrons: $E_{k\,max} = hf - \phi$, using energy units of joule and electron-volt
  - effects of intensity of incident irradiation on the emission of photoelectrons

9A 9B 9C 9D

4.1.8.6 Photocurrent-electrode potential graphs

4.1.8.7 Effect of changing the intensity of light

ESSENTIAL PRIOR KNOWLEDGE

9A Converting between J and eV
9A The photoelectric effect experimental setup
9A Stopping voltage
12D Graphing conventions
See questions 78–81.

KEY TERMS AND DEFINITIONS

intensity the number of light particles incident per area per unit of time (according to the particle model of light)

Photocurrent-electrode potential graphs 4.1.8.6

There are two kinds of graphs commonly used to analyse the photoelectric effect: photocurrent-electrode potential graphs and kinetic energy-frequency graphs (explored in Lesson 9C). Photocurrent-electrode potential graphs have photocurrent on the vertical axis and electrode potential on the horizontal axis. Key points on photocurrent-electrode potential graphs are the stopping voltage and the maximum photocurrent.

How can we visualise the relationship between photocurrent and electrode potential difference?

Photocurrent-electrode potential graphs show the photocurrent for a range of values of potential difference, caused by incident light of a fixed frequency and **intensity**.

- If either the frequency or intensity of the incident light change, the photocurrent-electrode potential graph will change.
- The positive side of the horizontal axis represents a positive voltage applied to the collector electrode in order to attract the photoelectrons.
- The negative side of the horizontal axis represents a negative voltage applied to the collector electrode in order to repel photoelectrons (Figure 1a).

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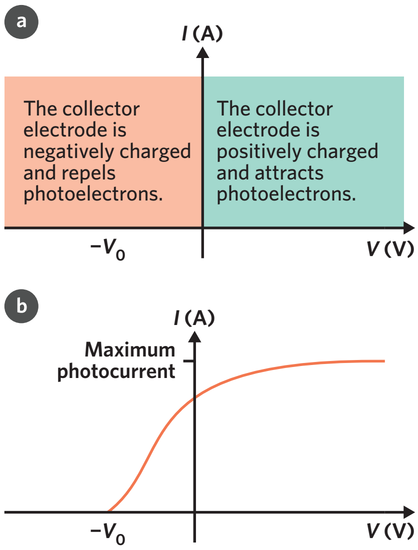


Figure 1 **(a)** A positive voltage applied to the collector electrode attracts electrons while a negative voltage repels them. **(b)** A typical photocurrent-electrode potential graph of the photoelectric effect.

USEFUL TIP

The attraction and repulsion of photoelectrons from the collector electrode can be explained using an electric field model. When the collector electrode is positive, the electric field causes photoelectrons to be attracted to the collector electrode. When the collector electrode is negative, the electric field causes photoelectrons to be repelled from the collector electrode.

Table 1 shows some key features of the photocurrent-electrode potential graph, shown in Figure 1b, and their interpretations.

Table 1 Key features of photocurrent-electrode potential graphs

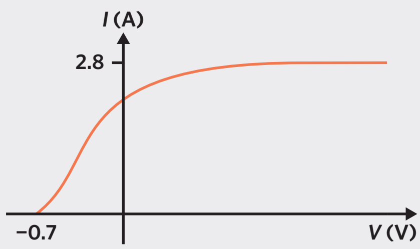
Feature of the photocurrent-electrode potential graph	Interpretation
Horizontal axis intercept	The negative value of the stopping voltage $(-V_0)$
Vertical axis intercept	The value of the photocurrent when no voltage is applied to the collector electrode
Maximum vertical axis value	The maximum photocurrent

From the graph, we can make the following observations:

- The photocurrent is a measure of how many photoelectrons are collected by the collector electrode every second.
- When the collector electrode is positively charged, the applied voltage is positive, and electrons emitted from the metal surface are attracted to the collector electrode:
  - Only a small positive voltage is needed to reach the maximum photocurrent.
  - A greater positive voltage does not liberate more photoelectrons.
  - This is represented by the photocurrent quickly flattening out to a maximum after a small positive voltage.
- When the collector electrode is negatively charged, the applied voltage is negative, and emitted electrons are repelled from the collector electrode:
  - The photocurrent decreases as fewer photoelectrons reach the collector electrode.
  - The photocurrent reaches zero when the voltage reaches the stopping voltage, V_0. This occurs at the horizontal axis intercept on the photocurrent-electrode potential graph.

WORKED EXAMPLE 1

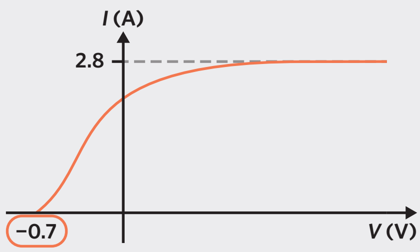
A photocurrent-electrode potential graph is generated from a photoelectric experiment.



a. Identify the value of the stopping voltage.

Breakdown

The horizontal axis intercept represents the negative value of the stopping voltage.



Answer

$V_0 = -(-0.7) = 0.7 \text{ V}$

Continues →

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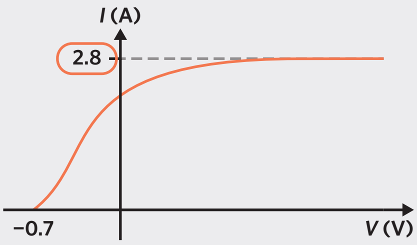
b. Identify the value of the maximum photocurrent produced.

Breakdown

The maximum vertical axis value represents the value of the maximum photocurrent produced.



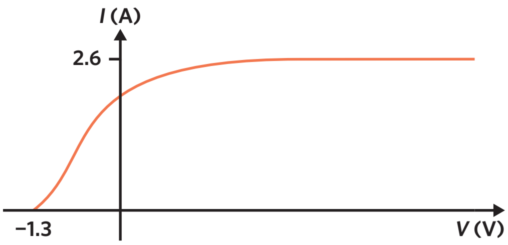
Answer

$I_{max} = 2.8$ A

PROGRESS QUESTIONS

Use the following information to answer questions 1–3.

Consider the following *I*-*V* graph.



Question 1

The horizontal axis intercept of the photocurrent-electrode potential graph represents the

A. the stopping voltage.

B. direction of the stopping voltage.

C. negative value of the stopping voltage.

D. value of the maximum potential difference.

Question 2

Which of the following is true about the voltage applied to the collector electrode?

A. No photocurrent will be measured if no voltage is applied.

B. A negative voltage will attract photoelectrons to the collector electrode.

C. To measure the maximum photocurrent, only a small positive voltage is needed.

D. As a positive voltage increases, the photocurrent detected increases proportionally.

Question 3

From the graph shown, the value of the stopping voltage is

A. −2.6 V **B.** 1.3 V **C.** 2.6 V **D.** 3.38 V

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Effect of changing the intensity of light 4.1.8.7

Changing the intensity of the incident light in the photoelectric effect experiment affects the maximum photocurrent produced but does not affect the maximum kinetic energy of the emitted photoelectrons.[1]

KEEN TO INVESTIGATE?

[1] How can we simulate the photoelectric effect experiment?
Search: Photoelectric effect - light simulation

What is the effect of changing the intensity of light in the photoelectric experiment?

The intensity of light can be modelled (using the particle model of light) as the number of light particles hitting the metal surface. By increasing the intensity, we increase the number of light particles without increasing the amount of energy each light particle possesses.

Assuming photoelectrons are already being emitted:

- Increasing the intensity of light increases the number of photoelectrons emitted and therefore the maximum photocurrent.
- Decreasing the intensity of light decreases the number of photoelectrons emitted and therefore decreases the maximum photocurrent (Figure 2).

Changing the intensity of light does not change the kinetic energy of photoelectrons and therefore it does not change the stopping voltage (assuming frequency is constant).

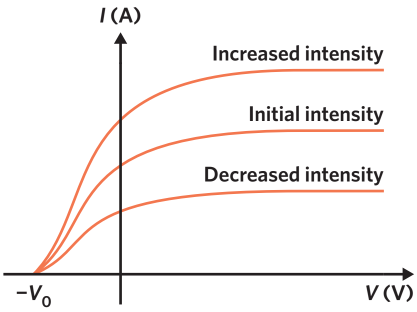


Figure 2 The maximum photocurrent is different for different intensities of light.

PROGRESS QUESTIONS

Question 4

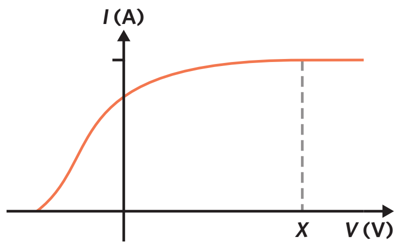
Increasing the voltage beyond point *X* will result in the photocurrent

A. increasing.

B. decreasing.

C. reducing to zero.

D. remaining unchanged.



Question 5

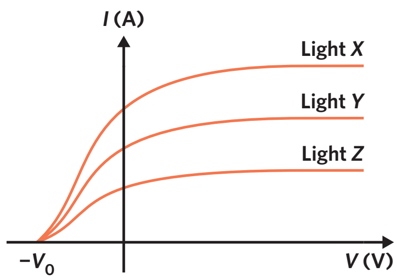
Using the graph, which of the following statements is true? **(Select all that apply)**

A. Light *X* has a higher intensity than Light *Y*.

B. Light *Y* has a higher intensity than Light *Z*.

C. Light *Z* has a higher intensity than Light *Y*.

D. Light *Z* has a higher intensity than Light *X*.



Theory summary

- Photocurrent–electrode potential graphs display two important features of the photoelectric experiment:
  - the maximum photocurrent
  - the stopping voltage, which is shown as the negative of the horizontal axis intercept
- For a situation where a photocurrent is already being measured, increasing the incident light intensity results in an increase in maximum photocurrent.
- Changing the intensity of light does not change the stopping voltage (the kinetic energy of the photoelectrons is unchanged).

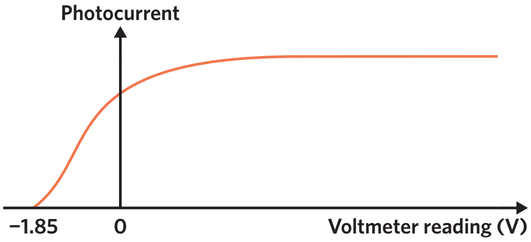
9B Questions

Mild 🌶 Medium 🌶🌶 Spicy 🌶🌶🌶

Deconstructed exam-style

Use the following information to answer questions 6–8.

A photoelectric experiment was undertaken and as a result, a graph was drawn.



Question 6 🌶 (1 MARK)

The horizontal axis intercept on the graph represents

A. the maximum voltage.

B. the maximum photocurrent.

C. the voltage across the collector electrode for which the photocurrent is zero.

D. the voltage across the collector electrode which produces the maximum photocurrent.

Question 7 🌶 (1 MARK)

Describe the relationship between the maximum kinetic energy of photoelectrons emitted by the incident light and the stopping voltage measured in the photoelectric effect experiment.

Question 8 🌶🌶 (3 MARKS)

Using the graph, calculate the maximum kinetic energy in joules of the photoelectrons emitted in this experiment.

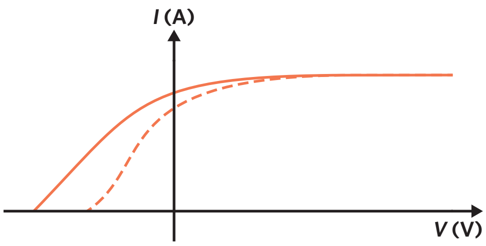
Adapted from VCAA 2013 exam Short answer Q21a

Exam-style

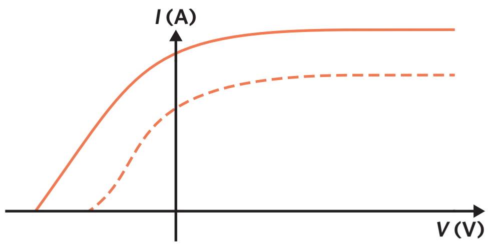
Question 9 🌶 (1 MARK)

Katie is measuring the photocurrent produced when she varies the applied voltage in the photoelectric effect experiment, plotting the results as a dashed line. She then doubles the intensity of the light (keeping the frequency of light constant) and plots the results as a continuous line. Identify which graph below best illustrates the results of the second experiment.

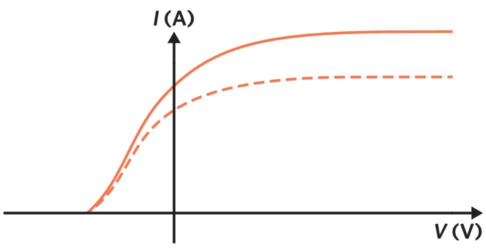
A.



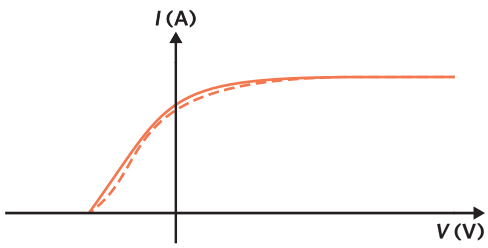
B.



C.



D.



Adapted from 2017 VCAA NHT Exam Section A Question 18e

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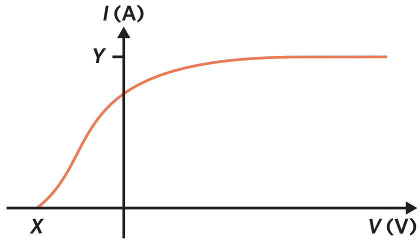
Question 10 🌶 (1 MARK)

Consider the photocurrent-potential graph shown. *X* represents the value at the horizontal axis intercept and *Y* represents the maximum value on the vertical axis.

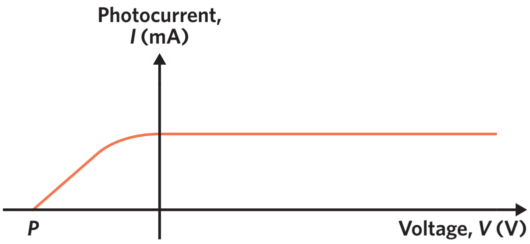
Which of the following describes how the values of *X* and *Y* would be affected if the intensity of incident light was reduced, while the frequency was held constant.



	Change to *X*	Change to *Y*
A.	No change	Decrease
B.	Decrease	Decrease
C.	Decrease	No change
D.	No change	No change

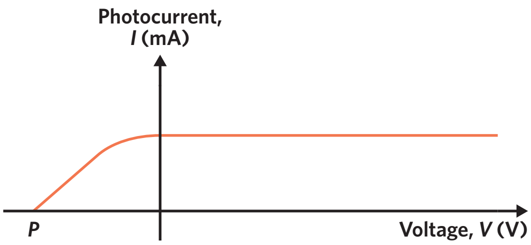
Question 11 (3 MARKS)

Sam undertakes a photoelectric effect experiment and produces a graph of photocurrent, *I*, in milliamperes, versus voltage, *V*, in volts, as shown.



a. Identify what point *P* represents on the graph. 🌶 1 MARK

b. Sam then increases the intensity of the light. Sketch the resulting graph. The existing, solid line represents the original data. 🌶 2 MARKS



Adapted from VCAA 2022 exam Short answer Q14

Question 12 (5 MARKS)

Keiran is conducting a photoelectric experiment where they negatively charge the collector electrode and shine blue light of constant intensity onto a piece of metal. They measure the maximum kinetic energy of the photoelectrons emitted by increasing the voltage until the photocurrent is zero. They graph their results on a photocurrent–electrode potential graph.

a. ***Key science skill***
Explain why voltage is the independent variable and the photocurrent is the dependent variable in this experiment. 🌶🌶 2 MARKS

FROM LESSON 12A

b. ***Key science skill***
What kind of variable is the intensity of the incident light? 🌶 1 MARK

FROM LESSON 12A

c. ***Key science skill***
Keiran now positively charges the collector electrode and increases the intensity of the light while measuring the photocurrent. Predict the results of this experiment. Justify your answer. 🌶🌶 2 MARKS

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Question 13 (5 MARKS)

Crissy and Moses are undertaking a photoelectric effect experiment. They measure a voltage of −4.6 V when the photocurrent is zero. They reverse the direction of the power source and notice that when the voltage is increased above 5.0 V, the photocurrent remains constant at 3.0 A.

Using this information, sketch a photocurrent-electrode potential graph of their results. Be sure to include titles and units on the axes and label any important values.

Question 14 (4 MARKS)

Key science skill

Liam and Nadia are conducting a photoelectric experiment where they keep the colour of light constant but change the voltage across the plates and also the intensity of light. They only change one of these variables at a time and measure the photocurrent produced. They find that increasing the voltage rapidly increases the photocurrent but then it reaches an upper limit where increasing the voltage fails to affect the photocurrent. They find the only way to increase this upper limit is to increase the intensity of light.

Use the particle model of light to explain these results.

Previous lessons

Question 15 (3 MARKS)

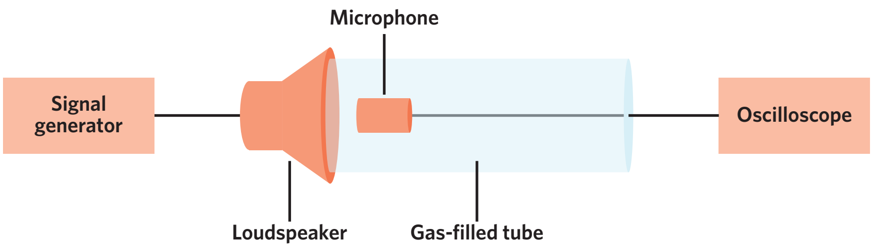
Determine the magnitude and direction of the electric force experienced by a proton when it is 2.00 mm to the right of a $+3.50 \times 10^{-10}$ C point charge. Take the charge on a proton to be $+1.6 \times 10^{-19}$ C, the mass of a proton to be 1.67×10^{-27} kg, and Coulomb's constant to be 8.99×10^{9} N m^2 C^{-2}.

FROM LESSON 4A

Question 16 (2 MARKS)

Students utilise a tube filled with hydrogen to investigate the speed of sound through a gas. They measure the distance between the microphone and the loudspeaker to be 0.25 m and the time taken for sound to travel between them to be 0.20 ms.

Knowing that the wavelength of the sound used is 9.0 m, calculate the frequency of sound used.



FROM LESSON 7A

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9C Changing frequency in the photoelectric effect

Image: Triff/Shutterstock.com

STUDY DESIGN DOT POINT

- analyse the photoelectric effect with reference to:
  - evidence for the particle-like nature of light
  - experimental data in the form of graphs of photocurrent versus electrode potential and of kinetic energy of electrons versus frequency
  - kinetic energy of emitted photoelectrons: $E_{k\ max} = hf - \phi$, using energy units of joule and electron-volt
  - effects of intensity of incident irradiation on the emission of photoelectrons

9A 9B 9C 9D

4.1.8.9 Kinetic energy-frequency graphs

4.1.8.8 Effect of changing the frequency of light

ESSENTIAL PRIOR KNOWLEDGE

9A Converting between J and eV
9A The photoelectric effect experimental setup
9A Work function
9B Photocurrent-electrode potential graphs
12D Graphing conventions

See questions 82-86.

How can a digital camera detect different colours of light?

In digital cameras, each pixel on the image sensor is designed with a specific threshold frequency corresponding to the desired colours, enabling it to be sensitive to certain colours of light. The electrical signals generated by the pixels, based on their threshold frequencies, are then processed to create colourful digital images with a wide range of accurate colours. This lesson explores how changing the frequency of the incident light in the photoelectric effect experiment affects the photocurrent produced. It will also introduce a key piece of evidence for the particle model of light.

KEY TERMS AND DEFINITIONS

threshold frequency the minimum frequency of light required to liberate electrons from a metal surface

FORMULAS

- **maximum kinetic energy of photoelectrons**
  $KE_{max} = hf - \phi$
- **energy of light**
  $E_{light} = hf$
- **threshold frequency**
  $\phi = hf_0$

Kinetic energy-frequency graphs 4.1.8.9

Lesson 9B explored photocurrent-electrode potential graphs and how changing the intensity of incident light affects the maximum photocurrent produced. Kinetic energy-frequency graphs are another type of graph that can be used to analyse the results of the photoelectric experiment.

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How can we represent the relationship between the maximum kinetic energy of photoelectrons and the frequency of incident light?

A kinetic energy-frequency graph shows the maximum kinetic energy of photoelectrons (or stopping voltage) for a range of frequencies of light incident on a specific metal surface (Figure 1).

Table 1 outlines three key features that we need to interpret from these graphs (Figure 2).

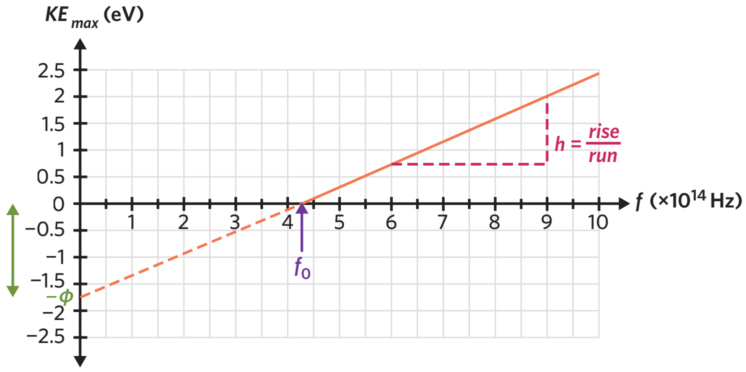

Figure 2 A kinetic energy-frequency graph and its key features

When analysing a kinetic energy-frequency graph, it's important to note that:

- The graph is always a straight line with a gradient equal to planck's constant, h.
- The **threshold frequency**, f_0, is the minimum frequency of light required to liberate electrons from the metal surface. This will be discussed in more detail later in this lesson.
- Each metal has its own work function and threshold frequency and so produces its own parallel straight line (Figure 3).
- The negative portion of the kinetic energy-frequency graph is usually dashed as it is not possible to have negative kinetic energy. However, it is often drawn to show the work function.

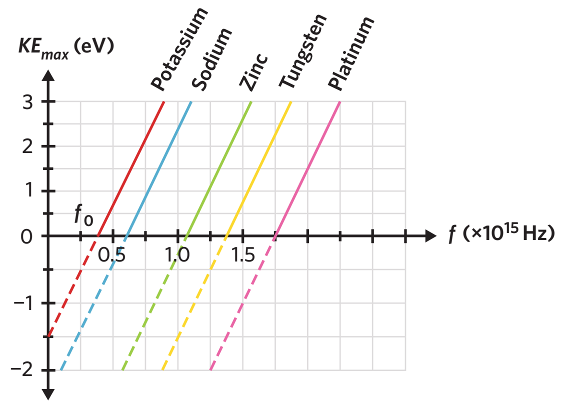

Figure 3 Each metal has a different work function, and hence a different kinetic energy-frequency graph.

Table 2 shows how the features of kinetic energy-frequency graphs shown in Table 1 correspond to the variables in the general equation for a straight line, $y = mx + c$.

Table 2 Comparing the general linear equation to a kinetic energy-frequency graph

	Vertical axis variable	Gradient	Horizontal axis variable	Vertical axis intercept
$y = mx + c$	y	m	x	c
Kinetic energy-frequency graph (Figure 2)	KE_{max}	h	f	$-\phi$

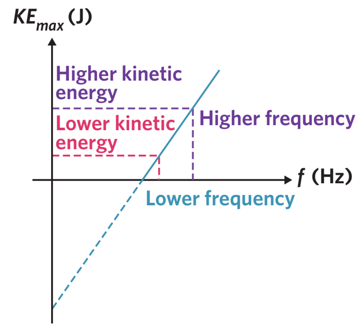

Figure 1 A kinetic energy-frequency graph showing how the maximum kinetic energy of photoelectrons increases as frequency increases

Table 1 Key features of kinetic-energy frequency graphs

Kinetic energy-frequency graph feature	What the feature represents
Horizontal axis intercept	Threshold frequency (f_0)
Vertical axis intercept	Negative value of work function $(-\phi)$
Gradient	Planck's constant (h)

USEFUL TIP

Kinetic energy-frequency graphs can also be referred to as stopping voltage-frequency graphs, with the stopping voltage on the vertical axis instead of the maximum kinetic energy. This is because the maximum kinetic energy of electrons in eV is equal to the stopping voltage in V.

MISCONCEPTION

'The work function is negative energy.'

The work function is always a positive value because it represents the amount of energy required to free the most loosely bound electron from the metal surface. The negative in front of ϕ represents the 'difference' between the KE_{max} and E_{light}, shown in the formula $KE_{max} = E_{light} - \phi$.

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Using this information, we can conclude that:

FORMULA

$KE_{max} = hf - \phi$

KE_{max} = maximum kinetic energy of electrons (eV or J)
h = Planck's constant (6.63×10^{-34} J s or 4.14×10^{-15} eV s)
f = frequency (Hz)
ϕ = work function (eV or J)

STRATEGY

Planck's constant has two different values and units that cannot be used interchangeably.

- 6.63×10^{-34} J s
  - Use this value when all values in an equation are measured in SI units (including J).
  - This will be the value of the gradient of a kinetic energy-frequency graph when the maximum kinetic energy values are measured in J.
- 4.14×10^{-15} eV s
  - Use this value when working in eV and when the desired answer is in eV.
  - This will be the value of the gradient of a stopping voltage-frequency graph or a kinetic energy-frequency graph when the maximum kinetic energy values are measured in eV.
- These two values are related by the conversion between eV and J from Lesson 9A.

USEFUL TIP

It is common for VCAA to ask students to find Planck's constant from a graph or set of data. In this case, find the gradient of the line of best fit using $m = \frac{rise}{run}$. Do not quote values of Planck's constant from the formula sheet.

Comparing the equation $KE_{max} = hf - \phi$, and the equation $KE_{max} = E_{light} - \phi$ from Lesson 9A, we can see that:

FORMULA

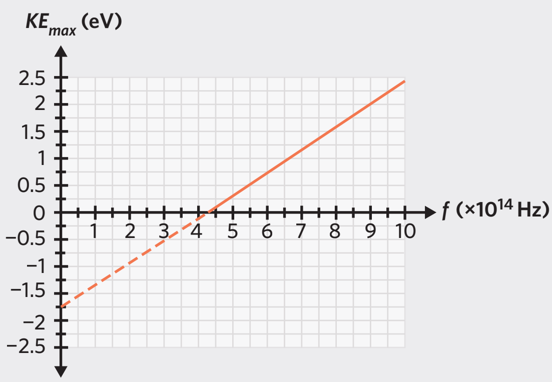
$E_{light} = hf$

E_{light} = light energy (modelling light as a particle) (eV or J)
h = Planck's constant (6.63×10^{-34} J s or 4.14×10^{-15} eV s)
f = frequency (Hz)

When applied to the particle model of light, this relationship shows that each particle of light has a discrete or distinct amount of energy that depends only on the frequency. This relationship will be explored further in Lesson 9D.

WORKED EXAMPLE 1

A kinetic energy-frequency graph is generated from an experiment.



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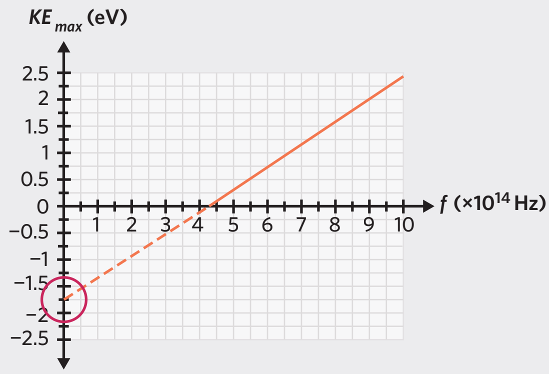
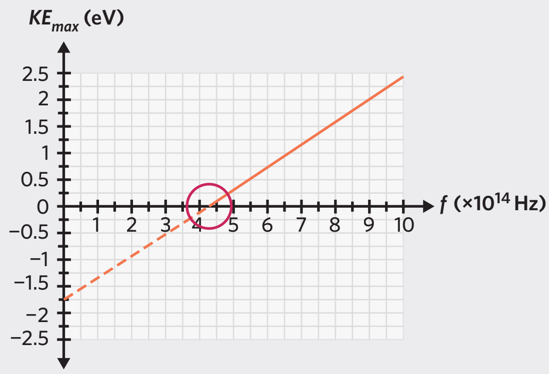
a. Use the graph to determine the work function.

Step	Answer
Work function is the negative of the vertical axis intercept.	$\phi = 1.75$ eV



b. Use the graph to determine the threshold frequency.

Step	Answer
Threshold frequency is the horizontal axis intercept.	$f_0 = 4.25 \times 10^{14}$ Hz



c. Use the graph to calculate Planck's constant.

Step 1

Identify known and unknown variables and write down the formula that relates these variables.

Note that Planck's constant is the gradient of the line.

Two points: $(6.0 \times 10^{14}, 0.75)$ and $(9.0 \times 10^{14}, 2.0)$, $h = ?$

$h = \frac{rise}{run}$

Step 2

Substitute values into the formula and solve for h.

Note that the unit for Planck's constant is eV s because the vertical axis is in eV and the horizontal axis is in Hz or s^{-1}.

$h = \frac{2.0 - 0.75}{9.0 \times 10^{14} - 6.0 \times 10^{14}}$

$h = 4.17 \times 10^{-15} = 4.2 \times 10^{-15}$ eV s

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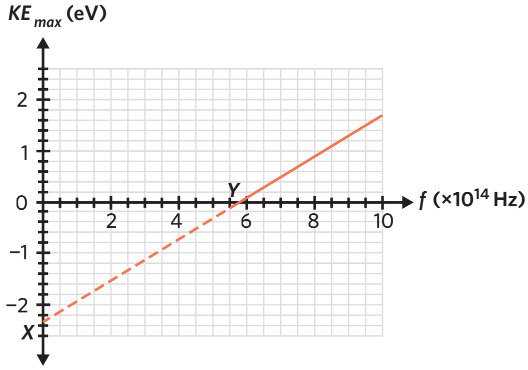
PROGRESS QUESTIONS

Use the following information to answer questions 1 and 2.

The graph shows a kinetic energy-frequency graph for a photoelectric experiment.



Question 1

Which option correctly describes X and Y on the graph?

A. X = threshold frequency, Y = work function

B. X = work function, Y = threshold frequency

C. X = Planck's constant, Y = threshold frequency

D. X = negative work function, Y = threshold frequency

Question 2

Which of the following changes would cause the graph to change?

A. changing the specific metal used

B. increasing the intensity of incident light

C. decreasing the frequency of incident light

D. increasing the electrode potential difference

How can we describe the threshold frequency?

The threshold frequency is the minimum frequency of light required for electrons to overcome the work function. It is represented by the horizontal axis intercept of a kinetic energy-frequency graph (Figure 4). It's important to note that:

- If the frequency of the incident light is below the threshold frequency, the photocurrent will be zero regardless of intensity.
- This is because no matter how much light is incident on the metal surface, if the individual particles of light don't have enough energy for the electrons to overcome the work function, there will be no photoelectrons emitted and therefore no photocurrent.

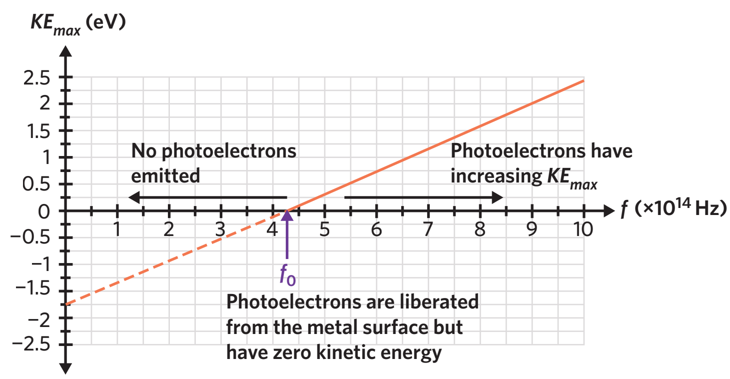


Figure 4 The threshold frequency represents the minimum frequency of light needed to liberate an electron from a metal surface.

Recall from Lesson 9A that the work function of a metal, ϕ, differs between metals, and describes the minimum amount of energy required to release the most loosely bound electron from the metal's surface.

- The threshold frequency represents the minimum frequency of incident light required to overcome the work function.
- If light of a frequency equal to the threshold frequency is incident on a particular metal, then we can say that $f = f_0$ and $E_{light} = \phi$. Substituting this into the equation $E_{light} = hf$ gives:

FORMULA

$$\phi = hf_0$$

ϕ = work function (eV or J)
h = Planck's constant (6.63×10^{-34} J s or 4.14×10^{-15} eV s)
f_0 = threshold frequency (Hz)

Knowing this, we can modify our equation for KE_{max}.

$$KE_{max} = hf - hf_0 = h(f - f_0)$$

WORKED EXAMPLE 2

The threshold frequency of sodium is 4.40×10^{14} Hz. Determine the work function of sodium in electron-volts.

Step 1

Identify known and unknown variables and write down the formula that relates these variables.

Note that we have chosen to use $h = 4.14 \times 10^{-15}$ eV s to obtain a result in electron-volts.

$h = 4.14 \times 10^{-15}$ eV s, $f_0 = 4.40 \times 10^{14}$ Hz, $\phi = ?$

$\phi = hf_0$

Step 2

Substitute values into the formula and solve for the work function of sodium.

$\phi = 4.14 \times 10^{-15} \times 4.40 \times 10^{14}$

$\phi = 1.822 = 1.82$ eV

PROGRESS QUESTIONS

Question 3

The threshold frequency is best described as

A. the energy of incident light required to overcome a reverse potential.

B. the frequency corresponding to the maximum kinetic energy of electrons.

C. a frequency that is the same for all metals causing photoelectrons to be released.

D. the minimum frequency of incident light required to release electrons from a metal surface.

Question 4

What is the threshold frequency of a metal if the minimum energy needed to liberate electrons from it is 2.9 eV?

A. 1.9×10^{-33} Hz

B. 1.2×10^{14} Hz

C. 7.0×10^{14} Hz

D. 1.2×10^{33} Hz

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Effect of changing the frequency of light 4.1.8.8

Changing the frequency of the incident light in the photoelectric effect experiment affects the maximum kinetic energy of emitted electrons but does not affect the maximum photocurrent.

How does changing the frequency of light affect the results of the photoelectric effect experiment?

Assuming the frequency of light is above the threshold frequency, when the frequency of light incident on a piece of metal is increased:

- The maximum kinetic energy of liberated photoelectrons increases, as each electron absorbs more energy according to $E_{light} = hf$.
- As the maximum kinetic energy of the photoelectrons increases, the stopping voltage, V_0, also increases. This is represented by a greater magnitude of V_0 on a photocurrent-electrode graph (Figure 5).
- However, the number of electrons liberated does not change, meaning the maximum photocurrent doesn't change.

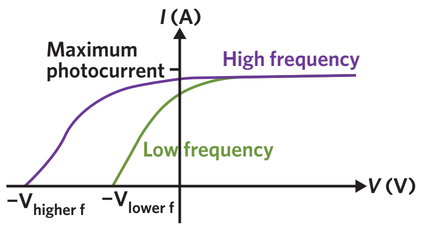

Figure 5 The stopping voltage is affected by the frequency of incident light, but the maximum photocurrent is not.

How does changing the work function affect a kinetic energy-frequency graph?

Different metals have different work functions and will translate the kinetic energy-frequency graph in the vertical direction (Figure 6). This is equivalent to changing the value of c in the general linear equation $y = mx + c$. Since the threshold frequency is related to the work function through $\phi = hf_0$, this means:

- Metals with a higher work function have a higher threshold frequency and will appear further along the right of the horizontal axis.
- Metals with a lower work function have a lower threshold frequency and will appear further along the left of the horizontal axis.

Different metals have different threshold frequencies, but their kinetic energy-frequency graphs will remain parallel with a gradient equal to Planck's constant.

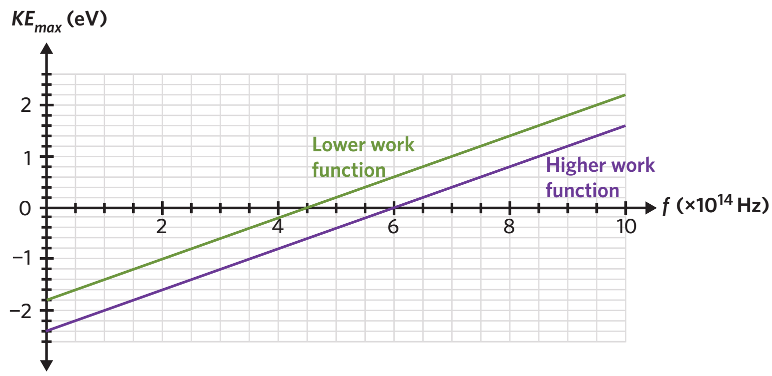

Figure 6 Kinetic energy-frequency graphs for two different metals

Changing the work function affects the horizontal axis intercept of a photocurrent-electrode potential graph. When shining light of a constant frequency above the threshold frequency:

- Changing to a metal with a higher work function results in the maximum kinetic energy of the emitted photoelectrons decreasing. This can be shown using $KE_{max} = hf - \phi$.
- As the stopping voltage is directly related to the maximum kinetic energy of photoelectrons, this means that the stopping voltage also decreases. This is represented by a smaller magnitude of V_0 on a photocurrent-electrode graph (Figure 7).

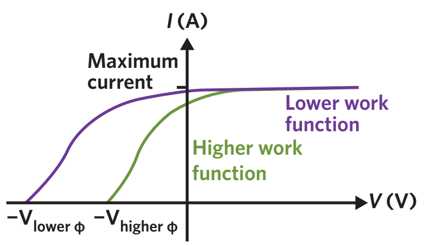

Figure 7 Increasing the work function of the metal plate decreases the stopping voltage.

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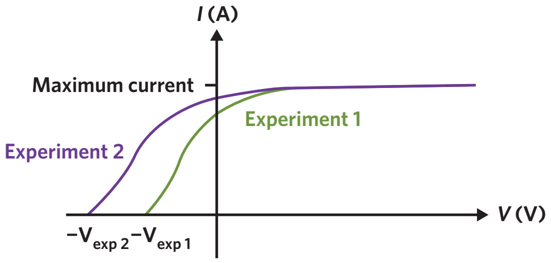
PROGRESS QUESTIONS

Use the following information to answer questions 5 and 6.

Two photoelectric effect experiments were undertaken and the following graph was produced.



Question 5

Which variables could have been changed between these two experiments? **(Select all that apply)**

A. the type of metal used

B. the frequency of light used

C. the intensity of the incident light

D. the voltage applied to the collector electrode

Question 6

If only the frequency of light was changed, how does the frequency compare between experiment 1 and experiment 2?

A. The frequency is lower in experiment 1 compared to experiment 2.

B. The frequency is higher in experiment 1 compared to experiment 2.

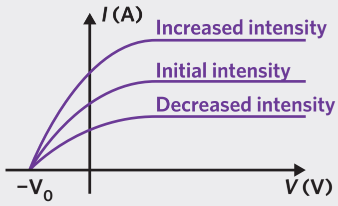
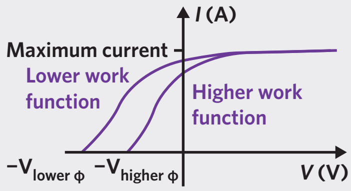
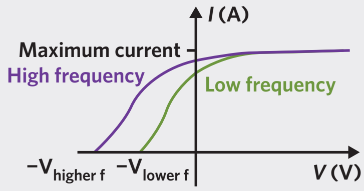
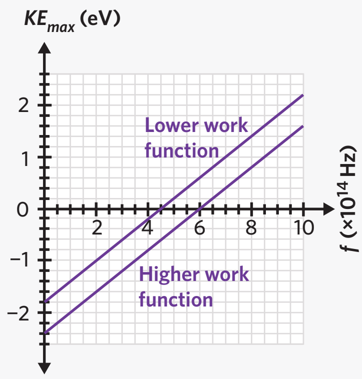
C. The frequency is the same in experiment 1 compared to experiment 2.

D. We cannot tell the difference between the two frequencies as this is not a kinetic energy-frequency graph.

Theory summary

- Changing the frequency of light incident on a metal surface will directly affect the maximum kinetic energy of photoelectrons and hence their stopping voltage.
- This has no impact on the number of electrons released and therefore the photocurrent produced.
- Kinetic energy-frequency graphs show the KE_{max} of photoelectrons for all frequencies of light incident on a specific metal surface.
  - The horizontal axis intercept represents the threshold frequency, f_0.
  - The vertical axis intercept represents the negative work function, $-\phi$.
  - The gradient represents Planck's constant, h.
- The graph can be described by the equation $KE_{max} = hf - \phi$, where h is Planck's constant equal to 6.63×10^{-34} J s or 4.14×10^{-15} eV s.
- The threshold frequency, f_0, is the minimum frequency of light required to release photoelectrons from a metal surface. If $f < f_0$, there will be no photocurrent.
- A metal with a higher work function will have a higher threshold frequency.
- The work function is linked to the threshold frequency by the equation $\phi = hf_0$, forming the equation $KE_{max} = hf - hf_0 = h(f - f_0)$.
- A summary of how different variables affect both photocurrent-electrode potential graphs and kinetic energy-frequency graphs can be found in Table 3.

Table 3 A summary of how variables affect both photocurrent-electrode potential and kinetic energy-frequency graphs

	Changing the intensity	Changing the work function	Changing the frequency
How does this affect a photocurrent-electrode potential graph?			
How does this affect a kinetic energy-frequency graph?	No effect		Not applicable

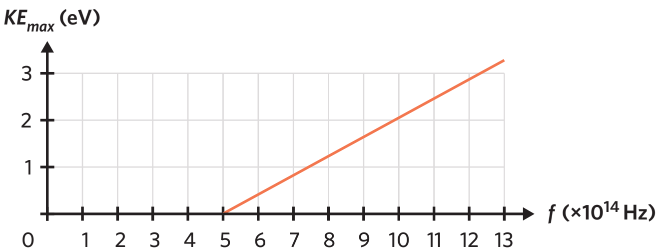
9C Questions

Mild 🌶 Medium 🌶🌶 Spicy 🌶🌶🌶

Deconstructed exam-style

Use the following information to answer questions 7–9.

Students conducted an experiment to investigate the photoelectric effect. For the experiment, they used light of various frequencies to shine on the metal surface. They produced the following kinetic energy-frequency graph.



Question 7 🌶 (1 MARK)

What represents Planck's constant on a kinetic energy-frequency graph?

A. the gradient

B. the vertical axis intercept

C. the horizontal axis intercept

D. the maximum vertical axis value

Question 8 🌶 (1 MARK)

Identify two coordinate points that sit on the kinetic energy-frequency graph.

Question 9 🌶🌶 (2 MARKS)

Use the graph to calculate the value of Planck's constant for the experiment.

Adapted from VCAA 2015 exam Short answer Q18b

Exam-style

Question 10 (1 MARK)

If a metal has a threshold frequency of 3.6×10^{14} Hz, what is the value of the metal's work function in electron volts?

A. 2.4×10^{-19} eV

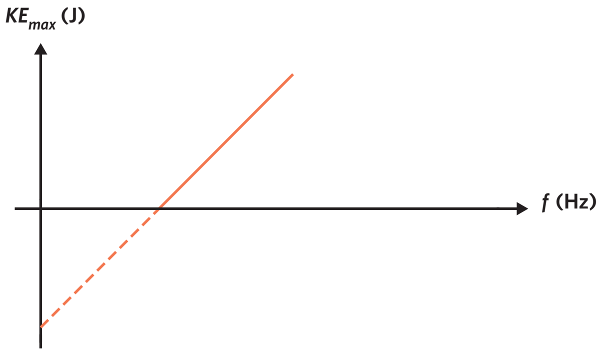
B. 0.1 eV

C. 1.4 eV

D. 1.5 eV

Question 11 (3 MARKS)

Colin is performing a photoelectric effect experiment, analysing how changing the frequency of light impacts the maximum kinetic energy of the emitted photoelectrons. He produces the graph shown. He then doubles the intensity of the light and conducts the experiment a second time.



a. On the same axis, draw a graph of the results of the second experiment. 1 MARK

b. Explain the similarities or differences between the graphs. 2 MARKS

Adapted from VCAA 2015 exam Short answer Q18c

Question 12 (3 MARKS)

A metal is illuminated with light that has a frequency of 9.5×10^{14} Hz and is found to eject electrons with an energy of 0.80 eV.

a. Show that the work function of the metal is 3.1 eV. 1 MARK

b. Calculate the value of the metal's threshold frequency 2 MARKS

Question 13 (2 MARKS)

Green Lantern's green lantern has a frequency of 5.5×10^{14} Hz, which corresponds to the threshold frequency of a particular metal. What frequency of light must be used on this metal for photoelectrons to have a maximum kinetic energy of 2.6×10^{-19} J?

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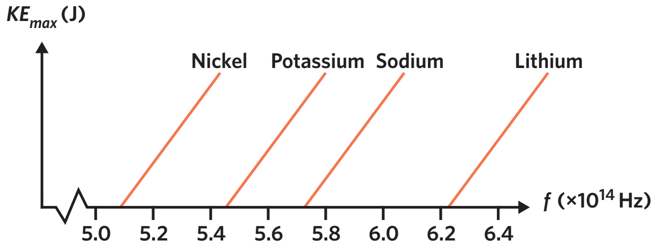
Question 14 (1 MARK)

The diagram shows a plot of maximum kinetic energy vs. frequency for various metals capable of emitting photoelectrons.



Which one of the following correctly ranks these metals in terms of their work function, from highest to lowest in numerical value?

A. sodium, potassium, lithium, nickel

B. nickel, potassium, sodium, lithium

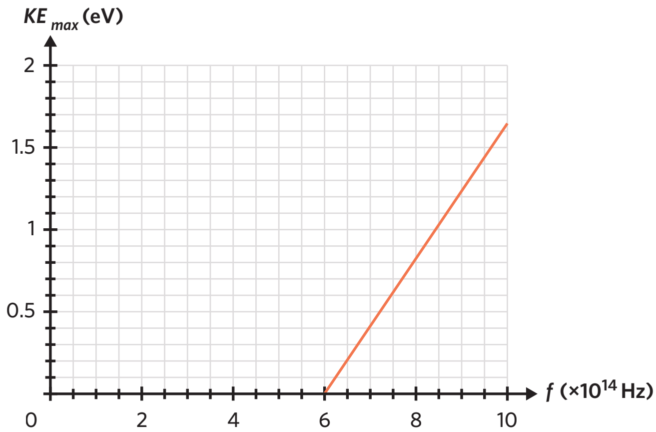
C. potassium, nickel, lithium, sodium

D. lithium, sodium, potassium, nickel

Adapted from VCAA 2020 exam Short answer Q16

Question 15 (2 MARKS)

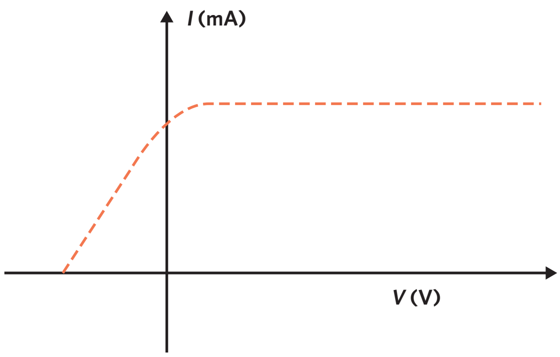
The graph shows the maximum kinetic energy vs. frequency for a photoelectric experiment.
In a subsequent experiment, the scientists decide that they will use a metal with a work function one-third larger than the original metal. On the same axis, use a dotted line to show what the graph will look like with the new metal.



Adapted from 2015 VCAA Exam Section A Q18d

Question 16 (3 MARKS)

Tobias is experimenting with changing the frequency of light in the photoelectric effect experiment. He starts with a green filter and graphs the result. He then replaces the green filter with a violet filter, keeping the intensity of the light constant.



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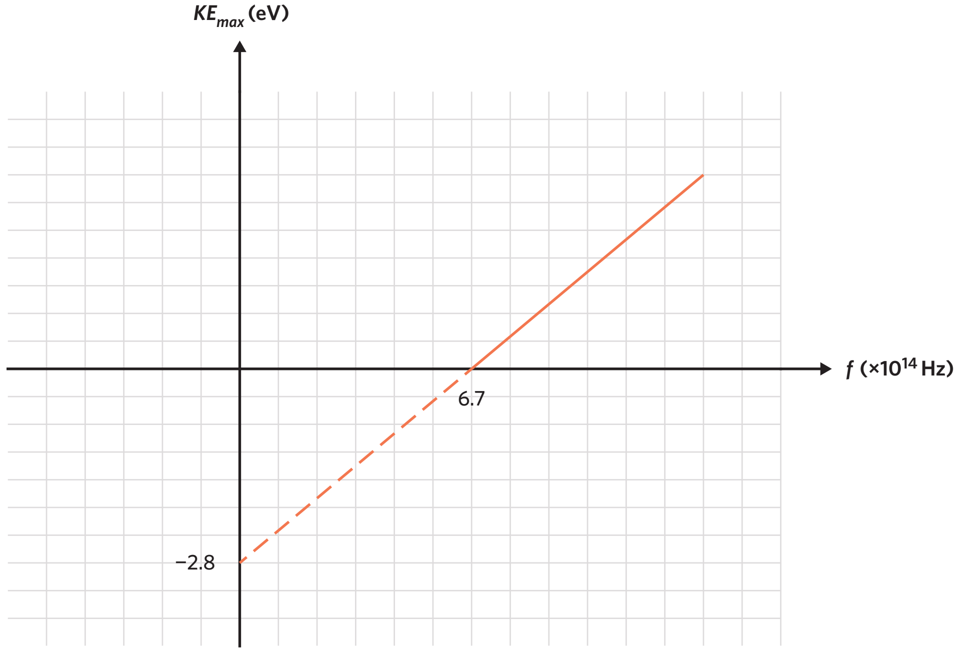
a. The dashed line represents the results of the green light. On the same axis, sketch the resulting graph for the violet light. 2 MARKS

b. Further experiments produce the kinetic energy-frequency graph shown.



Using the graph, determine the work function in eV of the metal surface used in the experiment. 1 MARK

Adapted from VCAA 2022 exam Short answer Q14

Question 17 (2 MARKS)

A photoelectric effect experiment is carried out by students. They measure the threshold frequency of light required for photoemission to be 6.5×10^{14} Hz and the work function of the metal to be 3.2×10^{-19} J. Using the students' measurements, what value would they calculate for Planck's constant? Show your working and give your answer in joule-seconds.

Taken from VCAA 2021 exam Short answer Q15

Question 18 (2 MARKS)

Two students, Sam and Isabella, are conducting a photoelectric experiment and have conflicting views as to why they observe no photocurrent despite light being incident on the metal surface. Sam says that if they simply increase the brightness of the light, they will measure a current. Isabella suggests that only by increasing the frequency will they produce a current.

Who is correct? Explain your answer.

Adapted from 2018 VCAA Exam Section B Q17aii

Question 19 (12 MARKS)

Students in a physics class are conducting an experiment to investigate the photoelectric effect on an unknown metal. Their results are shown in the table.

Stopping voltage (V)	0.25	0.60	0.90	1.50	1.90
Frequency (Hz)	6.0×10^{14}	7.0×10^{14}	8.0×10^{14}	9.0×10^{14}	10.0×10^{14}

a. *Key science skill*
Identify the independent and dependent variables in the experiment. 2 MARKS
FROM LESSON 12A

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b. ***Key science skill***
Use the data to plot a graph of the stopping voltage on the vertical axis against the frequency on the horizontal axis. Be sure to include: 5 MARKS

- axis labels and units
- an appropriate scale
- a straight line of best fit, extrapolated to show the y-intercept of the line

FROM LESSON 12D

c. ***Key science skill***
Use the graph to estimate the threshold frequency. 1 MARK

d. ***Key science skill***
Use the graph to estimate the value of Planck's constant obtained by the students. 2 MARKS

FROM LESSON 12D

e. Using the included table, determine which metal is being used as a metal surface in this investigation. 2 MARKS

Element	Work Function (eV)
Cesium	1.9
Europium	2.5
Magnesium	3.7
Manganese	4.1

Adapted from 2017 VCAA Sample Exam Section B Q17

Question 20 (6 MARKS)

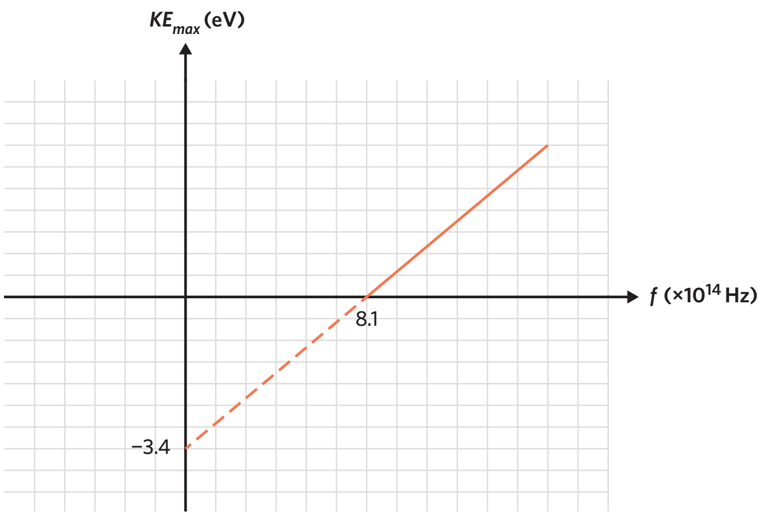
A scientist is conducting a photoelectric experiment to determine the work function of a newly discovered metal that landed on Earth. To accomplish this, she sets her laser to 375 nm and shines it onto the metal, recording the maximum kinetic energy of released photoelectrons to be 1.25 eV.

a. Calculate the work function of the metal in joules. 4 MARKS

b. Calculate the threshold frequency. 2 MARKS

Question 21 (3 MARKS)

A photoelectric effect experiment results in a kinetic energy-frequency graph. From the graph, calculate, in joule-seconds, the value of Planck's constant. Show your working.



Adapted from VCAA 2022 exam Short answer Q14e

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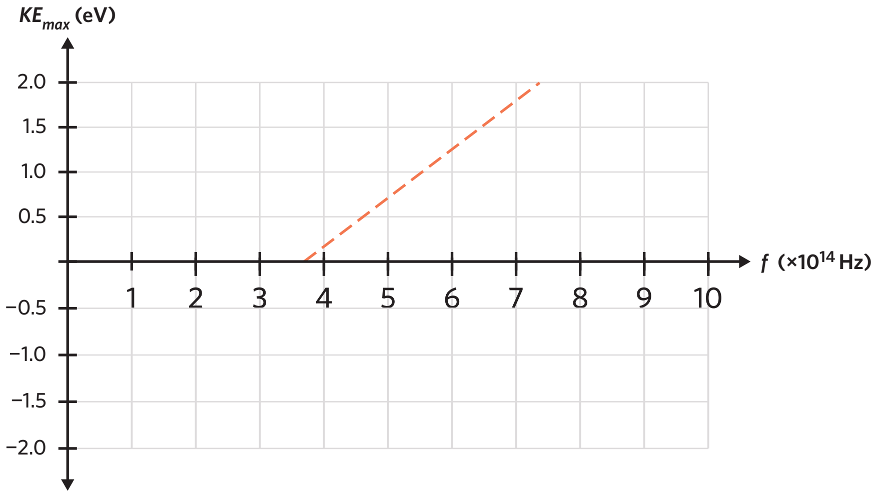
Question 22 (2 MARKS)

In a photoelectric effect experiment, the work function for a metal used is ϕ. It was replaced with a new metal with a work function of $\frac{1}{2}\phi$. On the graph, draw the line that would be obtained using the new metal. The original graph is shown as a dashed line.



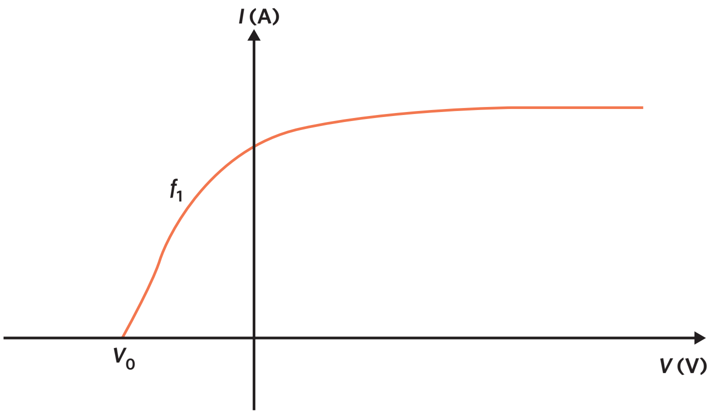
Adapted from VCAA 2019 exam Short answer Q16b

Question 23 (4 MARKS)

Pauline conducts a photoelectric experiment in which the incident light with a frequency of 7.3×10^{14} Hz is shone on a metal with a threshold frequency of 5.8×10^{14} Hz.

a. Calculate the stopping voltage in volts. 2 MARKS

b. Pauline repeats the experiment with a new increased frequency, f_2, whilst also significantly increasing the intensity. The graph shows the photocurrent-electrode potential curve for the original frequency, f_1. On the same axis, sketch the new curve that Pauline would obtain using a dotted line. 2 MARKS



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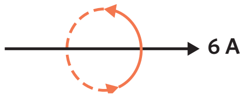
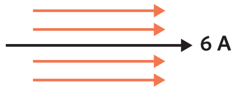
9C QUESTIONS

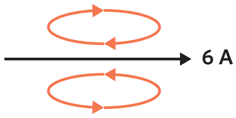
Previous lessons

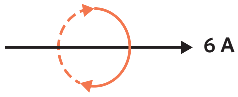
Question 24 (1 MARK)

A wire carries a 6 A current to the right. Which of the following diagrams shows the magnetic field produced by the current?

A.


B.


C.


D.


Adapted from VCAA 2018 exam Multiple choice Q3

FROM LESSON 4B

Question 25 (2 MARKS)

A person is at a concert and is sitting within an interference pattern of two coherent speakers. The person's location has a path difference of 12 m and is on the third antinode. What is the wavelength of the soundwave?

FROM LESSON 7B

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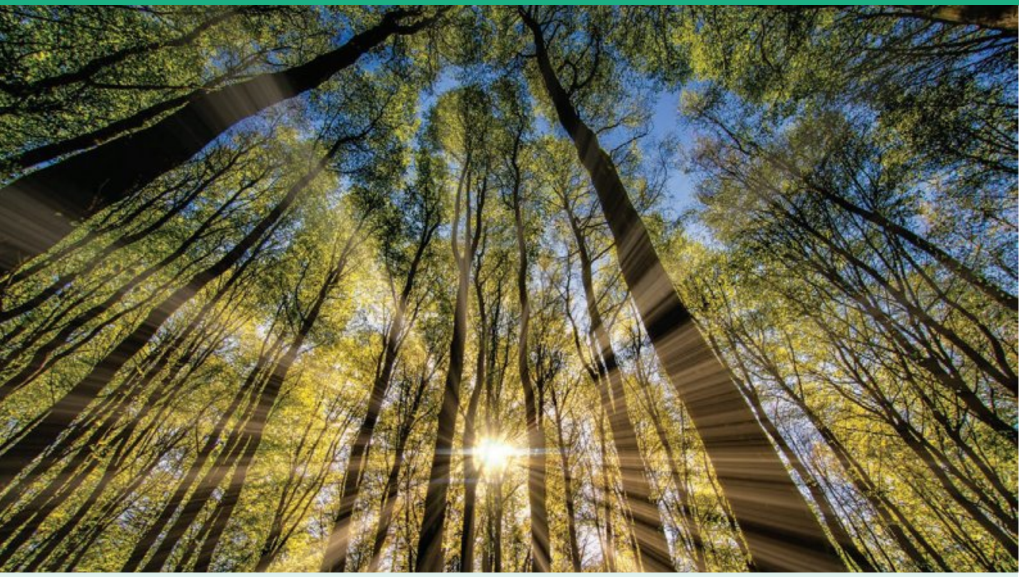
9D Explaining the photoelectric effect



Is light a wave or is it a particle?

So far, we have explored modelling light as a wave and as a particle. While both of these models explain some of light's properties, they fail to accurately explain others. This lesson will shine light on our knowledge of the photoelectric effect by interpreting the results of the photoelectric experiment as evidence for the particle model of light.

STUDY DESIGN DOT POINTS

- apply the quantised energy of photons: $E = hf = \frac{hc}{\lambda}$
- analyse the photoelectric effect with reference to:
  - evidence for the particle-like nature of light
  - experimental data in the form of graphs of photocurrent versus electrode potential, and of kinetic energy of electrons versus frequency
  - kinetic energy of emitted photoelectrons: $E_{k\,max} = hf - \phi$, using energy units of joule and electron-volt
  - effects of intensity of incident irradiation on the emission of photoelectrons
- describe the limitation of the wave model of light in explaining experimental results related to the photoelectric effect

9A 9B 9C 9D

- 4.1.9.1 Why the wave model fails
- 4.1.8.10 Evidence for the particle-like nature of lights
- 4.1.8.11 & 4.1.7.1 The energy of a photon

ESSENTIAL PRIOR KNOWLEDGE

- 9A The photoelectric effect experiment
- 9B Photocurrent and intensity in the photoelectric effect experiment
- 9C Kinetic energy and frequency in the photoelectric effect experiment

See questions 87–89.

KEY TERMS AND DEFINITIONS

discrete limited to certain values (not continuous)

photon a massless particle of electromagnetic radiation with a discrete amount of energy

quantised see discrete

FORMULA

- **photon energy**
  $E_{ph} = hf = \frac{hc}{\lambda}$

Why the wave model fails 4.1.9.1

While the wave model of light explained the results of the double-slit experiment, it failed to predict the results of the photoelectric experiment.

What does the wave model predict about the photoelectric effect experiment?

The wave model makes three incorrect predictions about the photoelectric effect (Table 1).

The failure of the wave model to predict the observed results of the photoelectric effect was a major blow to the wave theory of light. This resulted in a new quantum theory for light being developed, in which light possesses both wave and particle characteristics.

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Table 1 The incorrect predictions of the wave model of light compared with the actual observations

What the wave model predicts		Observed result of the photoelectric effect
Time delay	A wave is a continuous distribution of energy. When a wave hits an electron, the wave's energy would be absorbed by the electron until the electron has enough energy to escape the metal plate. A time delay would be observed as it takes time for the electron to absorb enough energy to be emitted.	Negligible time delay. Photoelectrons are emitted almost instantaneously.
Any frequency of light should produce a photocurrent	As a light wave is continuous, it can deliver energy continuously to an electron absorbing it. This means that even though a lower frequency wave carries less energy, all frequencies of light should produce a photocurrent if given sufficient time.	A threshold frequency exists. Light of a frequency less than the threshold frequency will not emit photoelectrons, no matter how long the light is incident on the metal.
The maximum kinetic energy of the emitted photoelectrons depends on intensity of light	A wave's energy is determined by both its frequency and its intensity (amplitude). A greater intensity should transfer more energy to the electrons. Therefore, light of a higher intensity should increase the maximum kinetic energy of the emitted photoelectrons.	The maximum kinetic energy of emitted photoelectrons is independent of the intensity of light.

WORKED EXAMPLE 1

Identify one result of the photoelectric effect that the wave model fails to predict and explain how it's different to the wave model prediction.

Breakdown	Answer
Identify one observed result of the photoelectric effect that the wave model failed to predict. Note that there are multiple pieces of evidence to choose from.	A result from the photoelectric experiment is the existence of the threshold frequency. Light of a frequency less than the threshold frequency will not produce a photocurrent.
Explain how it is different from the wave model prediction.	The wave model of light predicted that light delivers energy continuously to an electron. Therefore, any frequency of light should produce a photocurrent if given sufficient time.

USEFUL TIP

The time delay being measured is between the light source being turned on, and the detection of a photocurrent in the circuit.

PROGRESS QUESTIONS

Question 1

The wave model of light incorrectly predicts which of the following? **(Select all that apply)**

A. Given enough time, any frequency of light can produce a photocurrent.

B. The kinetic energy of electrons is dependent on the intensity of the light.

C. There is a minimum frequency of light required to produce a photocurrent.

D. A negligible time delay is expected for photocurrent to be measured from when the light is turned on.

Question 2

Which result of the photoelectric experiment does the wave model not predict?

A. The current depends on the intensity of light.

B. The total amount of energy in light depends on frequency.

C. Kinetic energy of electrons depends on the work function.

D. Only light above a certain frequency can produce a current.

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Evidence for the particle-like nature of light 4.1.8.10

Newton's particle (corpuscle) model for light modelled light of different colours as particles of varying sizes. However, even he admitted there was insufficient evidence to support this theory. With the results from Young's double slit experiment and then the photoelectric effect, it fell to a patent clerk in Switzerland, named Albert Einstein, to develop a theory for light that accurately explained both the wave and particle properties shown in these experiments.

Einstein took Max Planck's idea that atoms can only absorb **discrete** 'quanta' of energy, and proposed that light is made up of particles called **photons**. A photon is a massless particle that carries energy proportional to its wavelength or frequency. If the photon's frequency is sufficient to liberate an electron from an atom in the metal's surface, then the collision produces the photoelectric effect.

How can we model light as a particle?

We can think of photons as 'wave packets', with the frequency of the photon being a property of the photon itself (Figure 1).

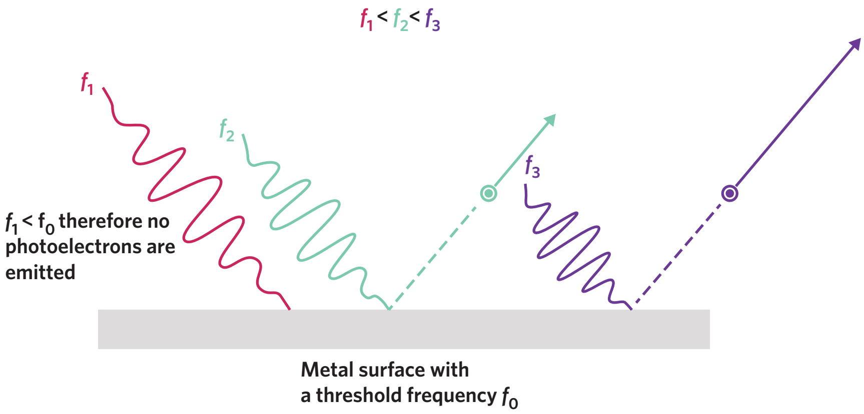

Figure 1 Photons can be thought of as 'wave packets' or massless particles with a particular wavelength. Only photon's with a frequency higher than the threshold frequency will emit photoelectrons.

Table 2 shows how the frequency and intensity of light is explained using the wave and particle model. Figure 2 shows how this can be represented visually using the wave and particle models.

Table 2 Wave and particle interpretations of frequency and intensity

	Wave interpretation	Particle interpretation
Frequency (colour)	The number of wave cycles completed per unit of time	A property of individual photons related to the photon's energy
Intensity (brightness)	The amplitude of the wave	A measure of the number of incident photons per unit area per unit of time (assuming the frequency is held constant)

USEFUL TIP

'Intensity' is often a better word to use than 'amplitude' to describe brightness as it can be used when referring to both waves or particles.

MISCONCEPTION

'Photons are short pulses of electromagnetic waves.'

While photons demonstrate wave properties like interference, they also demonstrate particle properties, such as momentum. This will be discussed further in Lesson 10A.

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9D THEORY

USEFUL TIP

Wave-particle duality claims light demonstrates both wave and particle behaviours depending on the situation. Therefore it is important never to state that light 'is' a wave or 'is' a particle. Instead, state that light 'can behave/be modelled' as a wave or particle.

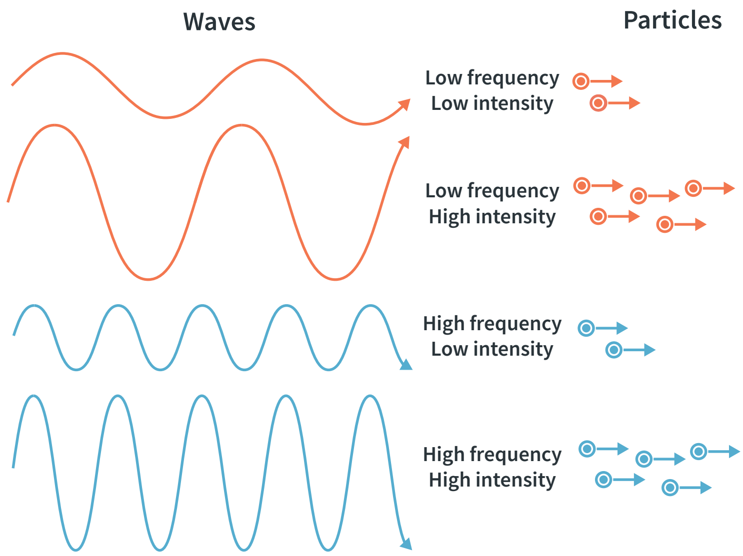

Figure 2 A visual comparison between the photon and wave models of light

PROGRESS QUESTIONS

Question 3

A photon is most accurately modelled as

A. a particle.

B. a continuous, self-propagating wave.

C. a discrete 'packet' of energy with wave-like properties.

D. a discrete 'packet' of energy with wave-like and particle-like properties.

Question 4

How is increasing the intensity of light modelled using photons?

A. The energy of each photon increases.

B. The frequency of each photon increases.

C. The number of incident photons increases.

D. The number of incident photons decreases.

How can photons explain the photoelectric effect?

We can now use our understanding of photons to explain the observations of the photoelectric effect experiment (Table 3).[1]

KEEN TO INVESTIGATE?

1 **What did Einstein win his Nobel prize for?**
Search YouTube: Albert Einstein and the photoelectric effect

Table 3 Explaining the observations of the photoelectric effect experiment

What is observed	How can we explain the observation?
Negligible time delay	When a photon is absorbed by an electron, all of the photon's energy is absorbed instantly, rather than being absorbed over time like a wave. If the photon has sufficient energy, then the electron will be emitted. If the photon does not have enough energy, then the electron will not be emitted.
Existence of the threshold frequency	A photon's energy is discrete and proportional to its frequency. A single electron will absorb a single photon, and if that photon's energy is less than the work function of the metal, then the electron will not be emitted. Hence, photons with a frequency less than a metal's threshold frequency will not produce a photocurrent.

Continues →

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Table 3 Continued

What is observed	How can we explain the observation?
Maximum kinetic energy of emitted electrons is independent of intensity	An electron will absorb and gain the energy of a single photon. Intensity is modelled as the number of photons rather than any change in the energy of an individual photon. This means the intensity of the incident light does not affect the kinetic energy of individual electrons.

WORKED EXAMPLE 2

Identify one result from the photoelectric experiment that supports the particle model of light and justify how it provides evidence for this model.

Breakdown	Answer
Identify one result from the experiment which supports the particle model. Note that there are multiple pieces of evidence to choose from.	A result from the photoelectric experiment is the existence of the threshold frequency.
Justify how this result supports the particle model.	This supports the particle model of light because each photon has a discrete amount of energy. If the photon doesn't have enough energy to liberate an electron, no photocurrent will be produced.

PROGRESS QUESTIONS

Question 5

Which of the following best describes why there is a negligible time delay between incident light and photocurrent measured?

A. Because the photocurrent is measured using a really accurate ammeter.

B. Because there is photocurrent in the circuit even before the light is turned on.

C. Because the photons have a discrete amount of energy and are absorbed instantly.

D. Because the light waves travel at the speed of light which is so fast it's almost instantaneous.

Question 6

Which of the following statements is correct?

A. Light is a wave.

B. Light is a particle.

C. Light has wave and particle properties.

D. Light is made from short pulses of electromagnetic waves.

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The energy of a photon 4.1.8.11 & 4.1.7.1

A photon's energy can be calculated if the frequency or wavelength of the photon is known.

MISCONCEPTION

'Only visible light produces a photocurrent in the photoelectric effect experiment.'

Light from all across the electromagnetic spectrum can produce a photocurrent, provided its frequency is above the threshold frequency for the metal surface being used.

How can we calculate the energy of a photon?

Each photon has a **quantised** amount of energy. The energy of a photon can be calculated using:

FORMULA

$$E_{ph} = hf$$

E_{ph} = photon energy (J or eV)
h = Planck's constant (6.63×10^{-34} J s or 4.14×10^{-15} eV s)
f = light frequency (Hz)

Given that $c = f\lambda$, for light in a vacuum, the photon energy formula also takes the following form:

FORMULA

$$E_{ph} = \frac{hc}{\lambda}$$

E_{ph} = photon energy (J or eV)
h = Planck's constant (6.63×10^{-34} J s or 4.14×10^{-15} eV s)
c = speed of light (3.0×10^{8} m s^{-1})
λ = wavelength (m)

The photon energy equation may be recognisable as the first part of the equation $KE_{max} = hf - \phi$. We can rewrite this equation as:

$$KE_{max} = \frac{hc}{\lambda} - \phi \text{ or } KE_{max} = E_{ph} - \phi.$$

WORKED EXAMPLE 3

A laser shines monochromatic light with a wavelength of 30 nm.

a. What is the energy of each photon in J?

Step 1

Identify known and unknown variables and write down the formula that relates these variables.

Note that to calculate the answer in J we should use $h = 6.63 \times 10^{-34}$ J s.

$h = 6.63 \times 10^{-34}$ J s, $c = 3.0 \times 10^{8}$ m s^{-1},
$\lambda = 30$ nm $= 30 \times 10^{-9}$ m, $E_{ph} = ?$

$$E_{ph} = \frac{hc}{\lambda}$$

Step 2

Substitute values into the formula and solve for the energy of each photon.

$$E_{ph} = \frac{6.63 \times 10^{-34} \times 3.0 \times 10^{8}}{30 \times 10^{-9}} = 6.63 \times 10^{-18}$$

$$E_{ph} = 6.6 \times 10^{-18} \text{ J}$$

Continues →

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b. If the laser power output is 4.0×10^{-2} J s^{-1}, calculate the number of photons being produced each second.

Step 1

Identify known and unknown variables and write down the formula that relates these variables.

$E_{total} = 4.0 \times 10^{-2}$ J, $E_{ph} = 6.63 \times 10^{-18}$ J, $n = ?$

$E_{total} = n \times E_{ph}$

Note that we have defined n as the number of photons per second. The formula $E_{total} = n \times E_{ph}$ comes from thinking about the total energy of the laser being the sum of all the photon's individual energies.

Step 2

Substitute values into the formula and solve for the number of photons being produced each second.

$4.0 \times 10^{-2} = n \times 6.63 \times 10^{-18}$

$n = 6.03 \times 10^{15} = 6.0 \times 10^{15}$ photons per second.

PROGRESS QUESTIONS

Question 7

A photon has a frequency of 3.6×10^{14} Hz. What is its energy in eV?

A. 0.87 eV **B.** 1.5 eV **C.** 2.4 eV **D.** 2.5 eV

Question 8

If a photon's energy is 5.8×10^{-18} J, what is its wavelength?

A. 3.4×10^{-8} m **B.** 4.3×10^{-8} m

C. 1.4×10^{3} m **D.** 2.1×10^{11} m

Theory summary

- For the photoelectric effect, the wave model incorrectly predicts that:
  - There will be a time delay between shining light on the metal surface and a photocurrent being produced.
  - Any frequency of light can eject electrons if given sufficient time.
  - The kinetic energy of emitted photoelectrons is related to the light intensity, as waves with a larger amplitude transfer more energy.
- The particle model correctly predicts the results of the photoelectric experiment:
  - No time delay is observed as the photon's energy is absorbed by the electron instantly.
  - As one electron can only absorb one photon, there exists a threshold frequency. Photons with a frequency less than the threshold frequency do not possess enough energy to produce a photocurrent.
  - The kinetic energy of emitted photoelectrons is independent of light intensity, as light of a greater intensity has more photons, but each photon still possesses the same amount of energy.
- The particle model of light states that:
  - Frequency is a property of individual photons which determines the photon's energy using $E_{ph} = hf$ or $E_{ph} = \frac{hc}{\lambda}$.
  - Intensity is a measure of the number of incident photons per unit of time.

KEEN TO INVESTIGATE?

How does the particle model of light explain the photoelectric effect?

Search YouTube: The photoelectric effect explained: sound on film, optical sound, photoelectric switches

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9D Questions

Mild 🌶 Medium 🌶🌶 Spicy 🌶🌶🌶

Deconstructed exam-style

Use the following information to answer questions 9–11.

Light can be described using a wave model or a particle (or photon) model. The emission of photoelectrons at very low light intensities supports one of these models but not the other. Assume the incident light is above the threshold frequency of the metal.

Question 9 🌶 (1 MARK)

Identify the model of light supported by the emission of light at very low intensities.

Question 10 🌶 (1 MARK)

Explain how the intensity of light is modelled using the particle (or photon) model.

Question 11 🌶🌶🌶 (3 MARKS)

Identify the model that is supported by the emission of light at very low intensity of light. Explain your answer.

Adapted from VCAA 2021 exam Short answer Q16

Exam-style

Question 12 🌶 (1 MARK)

Gamma radiation is often used to treat cancerous tumours. The energy of a gamma photon emitted by radioactive cobalt-60 is 1.33 MeV.

Which one of the following is closest to the frequency of the gamma radiation?

A. 1.33×10^{6} Hz

B. 3.21×10^{20} Hz

C. 3.21×10^{21} Hz

D. 2.01×10^{39} Hz

Adapted from VCAA 2022 exam Multiple choice Q17

Question 13 🌶 (1 MARK)

Which of the following is true about photons? **(Select all that apply)**

A. Photons are particles with mass.

B. Photons take time to be absorbed by electrons.

C. Photons exhibit particle and wave-like behaviour.

D. Photons with a larger amplitude produce higher intensity light.

Question 14 🌶 (2 MARKS)

An electron emits a photon with a frequency of 3.80×10^{15} Hz. What is the wavelength of the photon? Give your answer to the nearest nanometre.

Adapted from VCAA 2013 exam Short answer Q19

Question 15 🌶 (1 MARK)

State one limitation of the wave model in explaining the results of the photoelectric effect experiment.

Adapted from VCAA 2022 exam Short answer Q14f

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Question 16 (3 MARKS)

James Clerk Maxwell argues that light of a higher intensity should produce photoelectrons with a greater kinetic energy. Max Planck disagrees and argues that the intensity of light should not change the kinetic energy of the particles. Who is correct? Justify your answer by referring to the model of light each person could be basing their argument on.

Question 17 (2 MARKS)

An electron loses 15 eV of kinetic energy by emitting a photon with an equivalent energy. Calculate the frequency of the emitted photon.

Question 18 (2 MARKS)

Sam wants to increase the photocurrent produced in a photoelectric effect experiment. He uses an ultraviolet light with a frequency of 1.04×10^{15} Hz, and discovers that this is the minimum frequency of light required to emit photoelectrons.

He considers using a much brighter red light instead of the ultraviolet light source. Is Sam's idea likely to produce a greater photocurrent? Explain your answer.

Adapted from VCAA NHT 2023 exam Short answer 19b

Question 19 (3 MARKS)

Which of the following does the wave model fail to predict? Justify your answer.

Observation 1: Incident light can liberate electrons when shone on a metal plate.

Observation 2: The photocurrent depends on the intensity of incident light.

Observation 3: There is negligible time delay between when the light shines on the plate and when a photocurrent is observed.

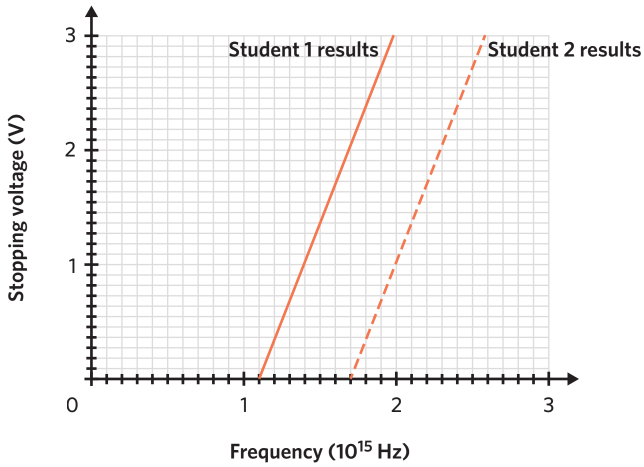
Adapted from 2010 VCAA Exam 2 Section A AoS 2 Q2

Question 20 (4 MARKS)

Albert Einstein won the Nobel prize in 1921 for his explanation of the photoelectric experiment. Identify two results from this experiment and explain how they support the particle model of light.

Question 21 (5 MARKS)

Two students performed the same photoelectric experiment by increasing the frequency of incident light on a zinc plate and measuring the stopping voltage of the photoelectrons. They compared their results and found they produced different stopping voltage vs. frequency graphs.



a. *Key science skill*
Identify the type of error that's most likely occurred and give reasons for your answer. 2 MARKS

FROM LESSON 12C

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b. ***Key science skill***

Given that the work function of this zinc plate was 3.6 eV, determine whose results were more accurate. Assume the value of Planck's constant found experimentally by the students is 4.14×10^{-15} eV s. 3 MARKS

FROM LESSON 12C

Question 22 (2 MARKS)

A group of students are experimenting with the photoelectric effect. First, they use a frequency of light that produces a photocurrent. They then change the light source to one with a different frequency. They observe that the photocurrent is zero and remains zero regardless of the size or sign of the potential difference applied across the plates. Explain this observation.

Adapted from VCAA 2013 exam Short answer 21d

Question 23 (1 MARK)

A monochromatic light source is emitting green light with a wavelength of 550 nm. The light source emits 2.8×10^{16} photons every second.

Which one of the following is closest to the power of the light source?

A. 3.3×10^{-11} W

B. 1.0×10^{-2} W

C. 2.1×10^{9} W

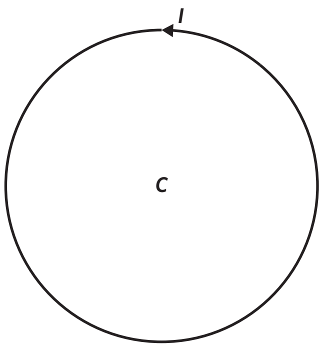
D. 6.3×10^{16} W

Adapted from VCAA 2021 exam Multiple choice Q18

Previous lessons

Question 24 (1 MARK)

A single loop of wire carries a current, I, as shown.



Which of the following best describes the direction of the magnetic field at the centre of the circle, C?

A. to the left

B. to the right

C. into the page

D. out of the page

Adapted from VCAA 2022 exam Multiple choice Q1

FROM LESSON 4B

Question 25 (2 MARKS)

A standing wave is set up on a string. It takes 5.1 seconds for a wave to travel along a string from point Y to point Z.

What is the frequency of the wave?

FROM LESSON 7C

Chapter 9 review

Mild 🌶 Medium 🌶🌶 Spicy 🌶🌶🌶

These questions are typical of one hour's worth of questions on the VCE Physics Exam.

Total marks: 50

Section A

All questions in this section are worth one mark.

Unless otherwise indicated, the diagrams in this book are not drawn to scale.

Question 1 🌶

An experiment was set up to test the effect of changing photon energy on the photocurrent produced when shining light on a zinc plate.

Which of the following is the independent variable in this photoelectric experiment?

A. voltage

B. photocurrent

C. frequency of light

D. maximum kinetic energy

Question 2 🌶

Which of the following is not an observation made in the photoelectric effect experiment?

A. the existence of a threshold frequency

B. any frequency of light can produce a photocurrent

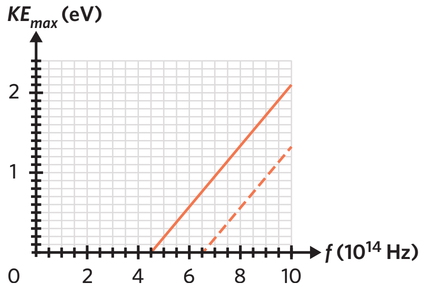
C. the maximum kinetic energy of the photoelectrons does not depend on the intensity of the incident light

D. a negligible time delay between turning on the incident light source and a photocurrent being registered

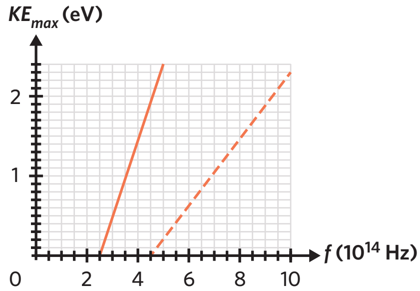
Question 3 🌶🌶

A kinetic energy-frequency graph for a particular photoelectric experiment is drawn with a solid line. The experiment is then repeated with higher intensity light and the metal surface is replaced with one that has a lower work function. The new results are recorded with a dotted line on the same set of axes. Which option best represents the student's results?

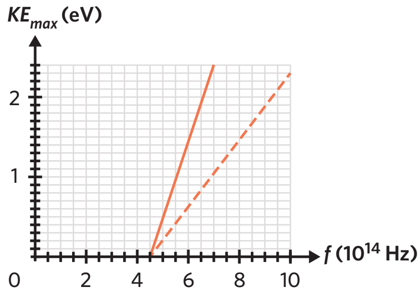
A.



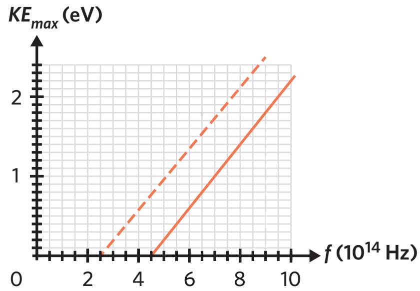
B.



C.



D.



Adapted from 2018 VCAA Exam Section A Q17

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Question 4

Photoelectrons are released with a maximum kinetic energy of 4.0 eV. What is the stopping voltage?

A. -6.4×10^{-19} J

B. 6.4×10^{-19} J

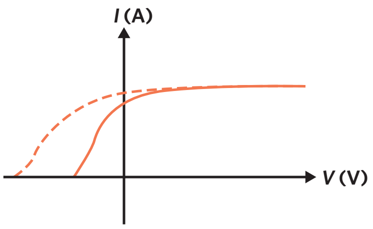
C. 4.0×10^{0} V

D. 2.5×10^{19} V

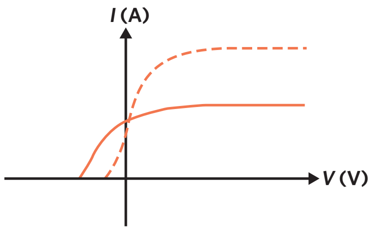
Question 5

Students conduct a photoelectric experiment. They map their first results on a photocurrent-voltage graph with a solid line. The students repeat the experiment with light that has a higher intensity and lower frequency (but it is still above the threshold frequency). They plot the new results on the same axes with a dotted line. Which of the following is closest to their results?

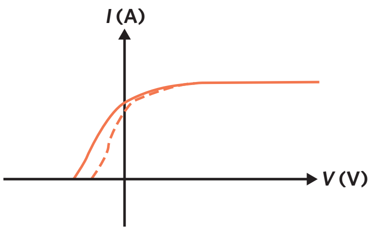
A.



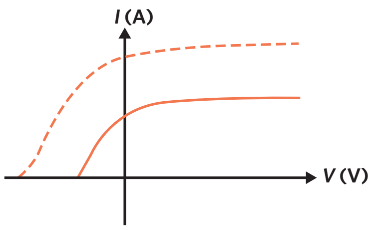
B.



C.



D.



Section B

In questions where more than one mark is available, appropriate working must be shown.

Unless otherwise indicated, the diagrams in this book are not drawn to scale.

Question 6 (2 MARKS)

Evaluate the following statement. 'When photoelectrons are emitted from a metal surface due to light of a single frequency, all photoelectrons have the same kinetic energy.'

Question 7 (9 MARKS)

Aliya performs a photoelectric experiment using a metal with a work function of 3.0 eV and a variable electrode potential.

a. In her first experiment, the light incident upon the plate has high enough energy that a steady stream of photoelectrons leaves the plate. Aliya negatively charges the collector electrode and starting from 0 V, increases the voltage until the photocurrent reaches zero. Describe the change in the photocurrent as the voltage was increased. Explain your answer. 3 MARKS

b. Aliya stops increasing the voltage when it reaches 5.0 V as no photocurrent is detected. Calculate the maximum kinetic energy of photoelectrons being ejected in J. 2 MARKS

c. Calculate the minimum frequency of light that Aliya needs to shine in order to release an electron. 2 MARKS

d. Calculate the frequency of light for which Aliya measured a stopping voltage of 5.0 V. 2 MARKS

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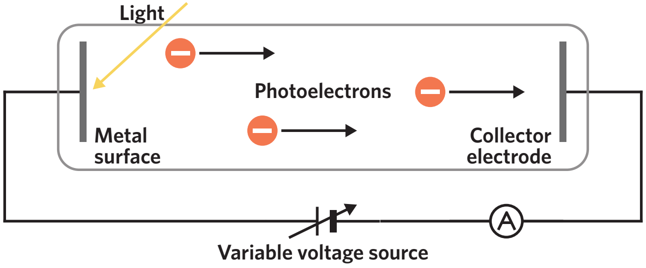
Question 8 (10 MARKS)

Amelia, Lara and Zadie are conducting the photoelectric experiment to determine how changing the frequency of a light source affects the maximum kinetic energy of the photoelectrons emitted.



a. *Key science skill*

For the first part of the experiment, the students use a potassium metal surface. The students placed their results in a table.

Frequency (Hz)	Stopping Voltage (V)
5.8×10^{14}	0.1
6.5×10^{14}	0.5
7.5×10^{14}	0.7
8.0×10^{14}	1.1
9.5×10^{14}	1.5

Use the data to plot a graph of the stopping voltage on the vertical axis against the frequency on the horizontal axis. Be sure to include: 5 MARKS

- axis labels and units
- an appropriate scale
- a straight line of best fit, extrapolated to show the y-intercept of the line

Adapted from VCAA 2011 Exam 2 Area of Study 2 Section A Q6

FROM LESSON 12D

b. Use the graph to find the work function for potassium that the students would obtain. 1 MARK

c. *Key science skill*

Use the graph to calculate the value of Planck's constant that the students would obtain from this data. 2 MARKS

FROM LESSON 12D

d. The students replace the potassium with a metal that has a work function of 1.8 eV. A photoelectron is ejected from this new metal with a kinetic energy of 6.56×10^{-19} J. Calculate the energy (in electron-volts) of the photon that was absorbed by the electron. Assume the electron emitted was the most loosely bound electron in the metal. Assume the electron emitted was the most loosely bound electron in the metal. 2 MARKS

Question 9 (6 MARKS)

A group of very interested students are studying the photoelectric effect experiment.

a. Legolas and Gimli are conducting a photoelectric experiment with a negatively charged collector electrode. They use a metal with a work function of 7.36×10^{-19} J and determine the stopping voltage to be 1.4 V. Their friend Aragorn helps them calculate the energy of the light used and obtains a photon energy of 3.2 eV. Is Aragorn's answer correct? Show your working. 3 MARKS

b. Tauriel conducts a photoelectric experiment using a zinc plate. She initially uses a high frequency of light and manages to measure a photocurrent. She decreases the frequency of the light and shines it on the surface for an extended period of time but still doesn't measure a photocurrent. Explain how Tauriel's observations support a particle model of light but not a wave model. 3 MARKS

Adapted from 2019 VCAA NHT Exam Section B Q16c

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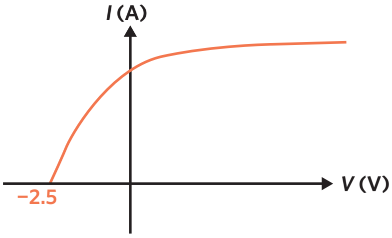
Question 10 (11 MARKS)

The photocurrent-electrode potential curve for a photoelectric experiment is shown. The work function of the metal surface is 1.8×10^{-19} J.



a. On the same axes, draw the resultant curve if the experiment was repeated with light of the same frequency but lower intensity. Use a dashed line for the new curve. 2 MARKS

b. Identify which feature of both curves from part **a** provides evidence for the particle model of light but not the wave model. Explain your answer. 4 MARKS

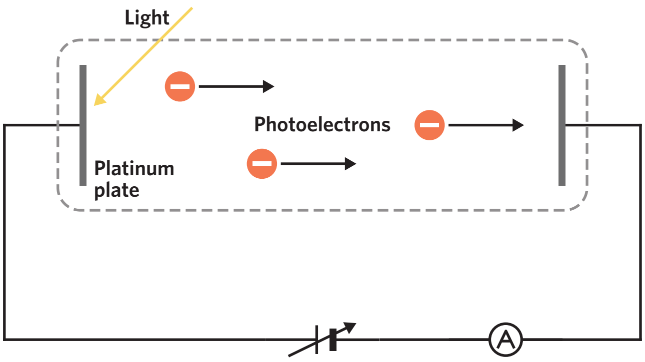
c. Explain why the graph is a flat, straight line for large positive values of electrode potential. 2 MARKS

Adapted from 2017 VCAA NHT Exam Section A Q18d

d. Calculate the wavelength of the incident light. 3 MARKS

Question 11 (7 MARKS)

Lily has set up the following photoelectric experiment. She measures the speeds of the electrons being ejected from the metal surface with zero electrode potential applied across the plates. The greatest speed was 1.22×10^{6} m s^{-1} when using incident light with a frequency of 1.96×10^{15} Hz.



a. Find the magnitude of the voltage that would need to be applied to the circuit to stop the photocurrent. 2 MARKS

b. Calculate the work function of platinum, in J. 2 MARKS

c. They repeat the experiment with a zinc plate which has a work function of 4.33 eV. Find the longest wavelength of a photon that can be used to release a photoelectron. 3 MARKS

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10

CHAPTER 10

The wave-particle duality of light and matter

STUDY DESIGN DOT POINTS

- interpret electron diffraction patterns as evidence for the wave-like nature of matter
- distinguish between the diffraction patterns produced by photons and electrons
- calculate the de Broglie wavelength of matter: $\lambda = \frac{h}{p}$
- discuss the importance of the idea of quantisation in the development of knowledge about light and in explaining the nature of atoms
- compare the momentum of photons and of matter of the same wavelength including calculations using: $p = \frac{h}{\lambda}$
- explain the production of atomic absorption and emission line spectra, including those from metal vapour lamps
- interpret spectra and calculate the energy of absorbed or emitted photons: $E = hf$
- analyse the emission or absorption of a photon by an atom in terms of a change in the electron energy state of the atom, with the difference in the states' energies being equal to the photon energy: $E = hf = \frac{hc}{\lambda}$
- describe the quantised states of the atom with reference to electrons forming standing waves, and explain this as evidence for the dual nature of matter
- interpret the single photon and the electron double slit experiment as evidence for the dual nature of light and matter

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LESSONS

Image: Procy/Shutterstock.com

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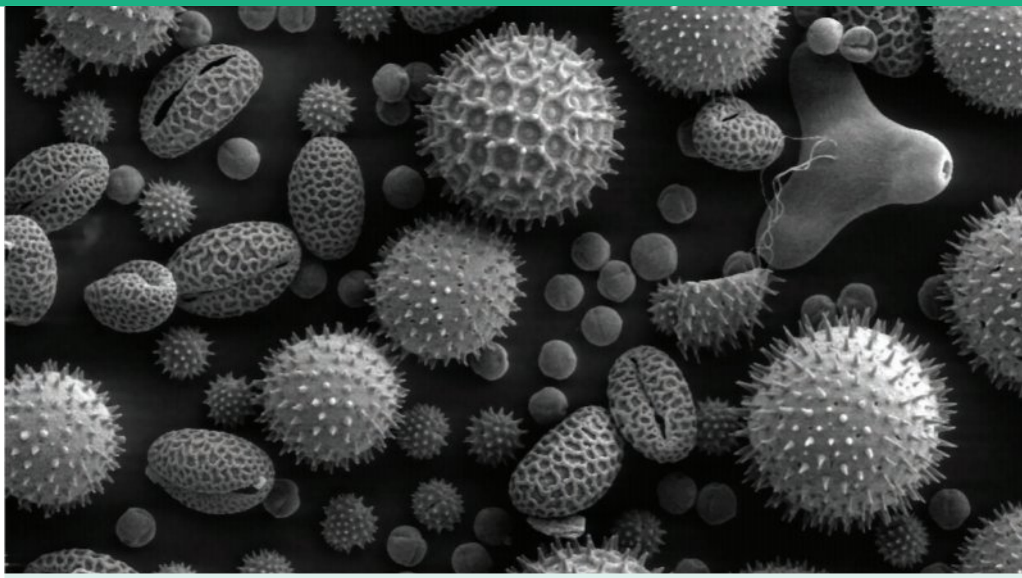
10A Comparing light and matter



STUDY DESIGN DOT POINTS

- interpret electron diffraction patterns as evidence for the wave-like nature of matter
- distinguish between the diffraction patterns produced by photons and electrons
- calculate the de Broglie wavelength of matter: $\lambda = \frac{h}{p}$
- compare the momentum of photons and of matter of the same wavelength including calculations using: $p = \frac{h}{\lambda}$
- interpret the single photon and the electron double slit experiment as evidence for the dual nature of light and matter
- investigate and explain theoretically and practically diffraction as the directional spread of various frequencies with reference to different gap width or obstacle size, including the qualitative effect of changing the ratio, and apply this to limitations of imaging using electromagnetic waves

10A 10B

4.1.10.1 & 4.1.12.1 Matter as a wave

4.1.11.1 & 4.1.14.1 & 4.1.5.3 Comparing photons and matter

4.1.19.1 Photons and electrons in the double slit experiment

ESSENTIAL PRIOR KNOWLEDGE

7D Diffraction
8B Young's double slit experiment
9D Photon energy

See questions 90–92.

Can electrons be better for imaging than light?

From X-rays to synchrotrons, light has been used to create increasingly detailed images. However at very small scales, the diffraction of light starts to limit how clear the images it produces are. In certain cases, electrons can be used instead of light to produce clear images of microscopic objects, like the image of the plant pollen shown. This lesson introduces the de Broglie wavelength for matter, and explores the dual wave-particle nature of both light and matter.

KEY TERMS AND DEFINITIONS

de Broglie wavelength the wavelength associated with objects made of matter due to their momentum

wave-particle duality the concept that light and matter can demonstrate both wave and particle properties

FORMULAS

- **de Broglie wavelength**
  $\lambda = \frac{h}{p}$
- **photon energy and momentum**
  $E_{ph} = pc$

Matter as a wave 4.1.10.1 & 4.1.12.1

Lesson 9D introduced the photon model of light, in which light has both particle and wave-like properties. Although electrons are typically modelled as particles, when they pass through small gaps, wave-like diffraction patterns emerge. This observation led to the discovery of the **de Broglie wavelength** for matter, which demonstrates the wave-like nature of particles.

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How does matter behave like a wave?

In 1924, a physicist named Louis de Broglie hypothesised that electrons, and all matter, must have wave-like properties and an associated wavelength – called the de Broglie wavelength. In 1927, the diffraction of electrons was experimentally demonstrated, earning de Broglie the Nobel Prize for Physics.

When electrons travel through a small gap, like the space between atoms in a crystal lattice, they diffract, forming an interference pattern (Figure 1). Since diffraction is a property of waves, this shows that matter can behave like waves at very small scales. This is called **wave-particle duality**.

The de Broglie wavelength can be calculated using:

FORMULA

$$\lambda = \frac{h}{p}$$

λ = de Broglie wavelength (m)
p = momentum of object (kg m s^{-1})
h = Planck's constant (6.63×10^{-34} J s)

Substituting $p = mv$ into the de Broglie wavelength formula provides another useful formula:

$$\lambda = \frac{h}{mv}$$

A de Broglie wavelength can be calculated for all objects with mass, even though larger objects do not exhibit wave-like properties that we can measure. This is because their de Broglie wavelength will be so small that any wave-like behaviour is too small for us to measure.

USEFUL TIP

In this formula make sure to use Planck's constant in joule seconds (J s), not electron-volt seconds (eV s). Wavelength and momentum will both be in SI units, so Planck's constant must be as well.

MISCONCEPTION

'Matter will move up and down as it travels, which is why it is a wave.'

The wave-nature of matter means that matter will exhibit wave-like behaviour, such as diffraction and interference. It does not imply that particles of matter must follow the path of a wave as they move.

USEFUL TIP

The concepts of waves and particles are examples of models, so it is best to think of matter as demonstrating properties of waves and of particles, rather than "being" a wave or a particle.

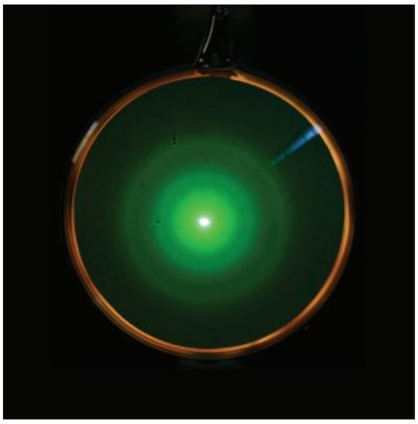

Figure 1 Diffraction pattern of electrons in a diffraction tube.

USEFUL TIP

When calculating the de Broglie wavelength using $\lambda = \frac{h}{p}$, only the magnitude of the momentum needs to be considered, not the direction.

WORKED EXAMPLE 1

Eliud is running his first lap of a marathon. He has a mass of 80 kg and is running at a speed of 4.0 m s^{-1}.

a. Calculate the de Broglie wavelength of Eliud.

Step 1

Identify known and unknown variables and write down the formula that relates these variables.

Note to find the de Broglie wavelength of Eliud, the magnitude of his momentum must be found.

$m = 80$ kg, $v = 4.0$ m s^{-1}, $p = ?$

$p = mv$

Step 2

Substitute values into the formula and solve for Eliud's momentum.

$p = 80 \times 4.0 = 320$ kg m s^{-1}

Continues →

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Step 3

Identify known and unknown variables and write down the formula that relates these variables.

$p = 320$ kg m s^{-1}, $h = 6.63 \times 10^{-34}$ J s, $\lambda = ?$

$\lambda = \frac{h}{p}$

Step 4

Substitute values into the formula and solve for Eliud's de Broglie wavelength.

$\lambda = \frac{6.63 \times 10^{-34}}{320} = 2.07 \times 10^{-36} = 2.1 \times 10^{-36}$ m

---

b. Explain why Eliud does not exhibit significant diffraction as he runs through a doorway.

Breakdown	Answer
Identify that significant diffraction only occurs when $\frac{\lambda}{w} \gtrsim 1$.	Significant diffraction only occurs when $\frac{\lambda}{w} \gtrsim 1$.
Explain that Eliud's de Broglie wavelength is so small that his diffraction will not be significant.	As Eliud's de Broglie wavelength is much smaller than the width of the doorway, $\frac{\lambda}{w}$ will be close to zero and his diffraction will not be significant.

PROGRESS QUESTIONS

Question 1

Although a de Broglie wavelength can be calculated for all objects with mass, not all objects with mass will exhibit measurable wave-like properties. Which of the following is most likely to exhibit measurable wave-like behaviour?

A. a person

B. electrons

C. a tennis ball

D. a human skin cell

Question 2

Electrons of mass 9.1×10^{-31} kg are accelerated in an electron gun to a speed of 1.0×10^{7} m s^{-1}. The best estimate of the de Broglie wavelength of these electrons is

A. 4.5×10^{-6} m.

B. 7.3×10^{-8} m.

C. 7.3×10^{-11} m.

D. 4.5×10^{-12} m.

Taken from VCAA 2019 exam Multiple choice Q14

Comparing photons and matter 4.1.11.1 & 4.1.14.1 & 4.1.5.3

Although photons don't have mass, they still have momentum, but it has to be calculated differently. To compare the diffraction patterns produced by photons and by matter, we can compare their wavelengths or their momentums.

How can we compare the momentum of photons and matter?

Experiments have shown that photons have momentum even though they do not have mass, since objects rebound in collisions with them.[1] As they don't have mass, photon momentum can't be calculated using the normal formula $p = mv$.

KEEN TO INVESTIGATE?

[1] **How do solar sails work?**
Search YouTube: How do solar sails work? Bill Nye explains.

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The formula showing how photon energy relates to its momentum is:[2]

FORMULA

$E_{ph} = pc$

E_{ph} = photon energy (J)
p = momentum (kg m s^{-1})
c = speed of light in a vacuum (3.0×10^8 m s^{-1})

KEEN TO INVESTIGATE?

[2] **How is the formula for photon momentum derived?**
Search: Hyperphysics relativistic momentum

Since the momentum and wavelength of photons and matter are both related by $\lambda = \frac{h}{p}$, we can say that a photon and an object with mass will have:

- the same de Broglie wavelength, λ, if they have the same momentum, *p*
- the same momentum, *p*, if they have the same de Broglie wavelength, λ.

How can we compare the diffraction of photons and matter?

As introduced in Lesson 7E, the amount a wave diffracts when it passes through a gap is determined by the ratio of its wavelength to the gap width ($diffraction \propto \frac{\lambda}{w}$). When matter and photons with the same wavelength diffract through the gaps of the same width, they create identically spaced diffraction patterns (Figure 2).

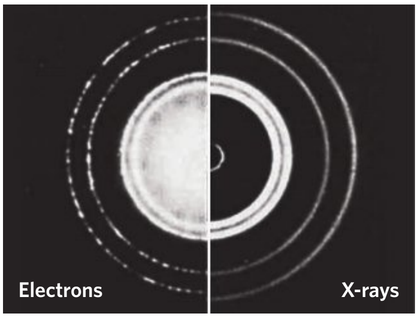

Figure 2 Electrons and X-rays with the same fringe spacing

When comparing the diffraction patterns of photons and matter, it's important to note that:

- If the spacing of the bright bands in the diffraction patterns are the same, then the wavelengths (and momentums) of the photons and the matter used to make them are also the same.
- If the spacing of bright bands in the diffraction patterns are different, then the wavelengths (and momentums) of the photons and the matter used to make them are also different.

USEFUL TIP

The centre of the electron diffraction pattern is brighter due to the higher probability of inelastic collisions when passing through the diffraction grating. When comparing diffraction patterns, this can be ignored as long as the radius of the circles and the spacing between bright bands is the same, meaning the electrons and photons have the same wavelength.

USEFUL TIP

When comparing diffraction patterns for photons and matter in VCE, you should focus on whether or not the wavelengths (and hence the momentums) are the same or different. You don't need to talk about the energies or draw any other conclusions unless specifically asked.

Table 1 gives equations for energy, wavelength, and momentum that can be used for photons, matter, or both. These can be used to calculate and compare the wavelengths and hence the diffraction patterns of photons and matter.

Table 1 A table of equations sorted by the types of particles that can be used with them.

	Only photons	Both photons and matter	Only matter
Momentum	$p = \frac{E_{ph}}{c}$	$p = \frac{h}{\lambda}$	$p = mv = \sqrt{2m \times KE}$
Wavelength	$\lambda = \frac{hc}{E_{ph}}$	$\lambda = \frac{h}{p}$	$\lambda = \frac{h}{mv} = \frac{h}{\sqrt{2m \times KE}}$
Energy	$E_{ph} = pc = \frac{hc}{\lambda}$		$KE = \frac{1}{2}mv^2 = \frac{p^2}{2m}$

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WORKED EXAMPLE 2

A ray of X-rays and a beam of electrons are directed through a lattice, and the resulting diffraction patterns have the same fringe spacing.

---

a. Given that each electron has a momentum of 2.50×10^{-23} kg m s^{-1}, calculate the energy of each X-ray photon.

Step 1

Identify known and unknown variables and the formula that relates these variables.

Note that since the diffraction patterns have the same fringe spacing, the electron and X-ray momentum will be the same, $p_{ph} = p_e$.

$p = 2.50 \times 10^{-23}$ kg m s^{-1}, $c = 3.0 \times 10^{8}$ m s^{-1}, $E_{ph} = ?$

$E_{ph} = pc$

Step 2

Substitute values into the formula and solve for the X-ray photon energy.

$E_{ph} = 2.50 \times 10^{-23} \times 3.0 \times 10^{8} = 7.5 \times 10^{-15}$ J

---

b. The X-ray is changed so that each photon has an energy of 6.00×10^{-16} J. Calculate the speed of electrons which would produce the same pattern.

Step 1

Identify known and unknown variables and the formula that relates these variables.

$c = 3.0 \times 10^{8}$ m s^{-1}, $E_{ph} = 6.00 \times 10^{-16}$ J, $p_{ph} = ?$

$E_{ph} = p_{ph}c$

Step 2

Substitute values into the formula and solve for the X-ray photon momentum.

$6.00 \times 10^{-16} = p_{ph} \times 3.0 \times 10^{8}$

$p_{ph} = 2.0 \times 10^{-24}$ kg m s^{-1}

Step 3

Identify known and unknown variables and the formula that relates these variables.

Note that to produce the same pattern, the electrons and X-rays must have the same momentum, $p_{ph} = p_e$.

$p_e = 2.0 \times 10^{-24}$ kg m s^{-1}, $m = 9.1 \times 10^{-31}$ kg, $v = ?$

$p_e = mv$

Step 4

Substitute values into the formula and solve for the speed of the electrons.

$2.0 \times 10^{-24} = 9.1 \times 10^{-31} \times v$

$v = 2.20 \times 10^{6} = 2.2 \times 10^{6}$ m s^{-1}

---

c. Calculate the de Broglie wavelength of the electrons emitted by the electron gun from part **b**.

Step 1

Identify known and unknown variables and the formula that relates these variables.

$p = 2.0 \times 10^{-24}$ kg m s^{-1}, $h = 6.63 \times 10^{-34}$ J s, $\lambda = ?$

$\lambda = \frac{h}{p}$

Step 2

Substitute values into the formula and solve for the de Broglie wavelength of the electrons.

$\lambda = \frac{6.63 \times 10^{-34}}{2.0 \times 10^{-24}}$

$\lambda = 3.32 \times 10^{-10} = 3.3 \times 10^{-10}$ m

PROGRESS QUESTIONS

Question 3

An electron and a photon will have the same momentum if

A. they have equal mass.

B. they have equal wavelength.

C. the photon's energy is equal to the electron's potential energy.

D. They cannot have the same momentum because photons don't have mass.

Question 4

A beam of electrons and a beam of photons travelling through identical gaps will produce the same diffraction pattern if the particles from each beam

A. have the same wavelength and momentum.

B. have different wavelengths and momentum.

C. have the same wavelength but different energy.

D. have the same amplitude but different momentum.

Why is there a limit to imaging using electromagnetic waves?

Light microscopes use visible light with a wavelength between 400 and 700 nm and have traditionally been used to generate magnified images of small objects. However, imaging using electromagnetic waves, such as light microscopes, is limited by the diffraction of the wave around the object being imaged ($diffraction \propto \frac{\lambda}{w}$):

- If the wavelength of light is much smaller than the object being imaged ($\frac{\lambda}{w} < 1$), limited diffraction occurs and the images are clear.
- If the object being imaged is a similar size or smaller than the wavelength of light ($\frac{\lambda}{w} \geq 1$), more significant diffraction occurs and the image becomes unclear.
- This limits the size of objects that can be imaged using electromagnetic waves to around the size of a human cell, bacteria, and large cell organelles (a cell's organs)(Figure 3).

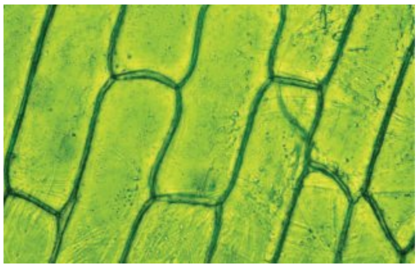

Image: Barbol/Shutterstock.com

Figure 3 Plant cells imaged using light microscopy

Although electromagnetic waves with smaller wavelengths, such as X-rays, can be used to image smaller objects, they also transmit more energy. This means they can damage or degrade the samples that scientists are attempting to image. This limits their use to imaging crystalline materials, for example silicone or glass.

Instead of using electromagnetic waves, electrons can be used as they have a small de Broglie wavelength (3.88×10^{-12} m). This means that they can be used to image small objects such as viruses, proteins, and small parts of cells without damaging them. However, images produced by electron microscopes are black and white unless given artificial colour (Figure 4).

Figure 4 Snowflake imaged using electron microscopy

Table 2 Microscopy and relative size of objects

Size of object	1 mm	100 µm	10 µm	1 µm	100 nm	10 nm	1 nm
Example	mites	strand of hair	yeast	bacterium	virus	carbon nanotubes	DNA
Type of imaging available	Human eye (1 mm)						
	Light microscopy (1 mm – 1 µm)						
	Electron microscopy (1 mm – 10 nm)						

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PROGRESS QUESTIONS

Question 5

Light microscopes are limited in their ability to image viruses clearly. What property of visible light creates this limitation?

A. speed **B.** width **C.** colour **D.** diffraction

Question 6

Why are X-ray microscopes a poor choice of imaging technology when compared to electron microscopes for imaging organic matter smaller than a cell?

A. X-rays can only be used to image bones.

B. X-rays can damage organic matter so electron microscopes are safer.

C. Electrons can damage organic matter so electromagnetic waves are safer.

D. Electrons don't diffract because they are matter. They are better suited for imaging.

Photons and electrons in the double slit experiment 4.1.19.1

If we set up a double slit experiment using individual photons or electrons instead of a beam of light, an interference pattern is observed. This provides strong evidence for the dual wave-particle nature of small objects.

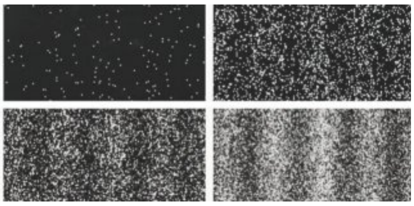

Figure 5 An electron interference pattern forms as the number of spots on the screen increases.

MISCONCEPTION

'Matter/light is either a wave or a particle at any given moment.'

The interference patterns observed for matter and light with this method have both wave and particle properties, showing that the matter/light used to make them is acting as both a wave and a particle at the same time.

MISCONCEPTION

'Young's double slit experiment shows the dual wave-particle nature of light and matter.'

Young's double slit experiment only shows the wave nature of light, since it shows the interference pattern for a continuous beam of light. A double slit experiment can be conducted using the method described earlier in this lesson, but that is not Young's double slit experiment. Therefore, Young's double slit experiment doesn't show anything about the particle nature of light, nor the wave or particle nature of matter.

How do we know that light and matter have a dual wave-particle nature?

Interference patterns for photons and electrons are constructed in a different way to the wave interference patterns we've seen before.

- Single photons or electrons are sent one at a time through tiny gaps in a diffraction grating; each creating a single spot on the detector screen.
- Over time, the spots on the screen form an interference pattern (Figure 5).

Conducting the double slit experiment using a single stream of photons or electrons results in a similar interference pattern formed to conducting the experiment using waves (Figure 6). As interference is a wave phenomenon, this experiment provides evidence for the dual-wave nature of light and matter:

- Since only one particle is travelling through one slit at a time, the interference pattern is not formed from particles interfering with each other.
- Hence, each individual particle can be considered to be demonstrating wave properties by diffracting through the gap and contributing to the interference pattern.
- This implies that each particle is interfering with itself, however, the interference pattern is still formed from many particles. No single particle can form an interference pattern, since it would only produce a single spot on the screen.

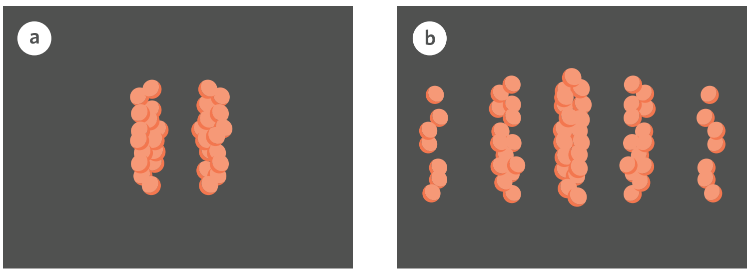

Figure 6 The results of the double slit experiment for matter or photons if **(a)** they only demonstrate particle properties, or **(b)** they demonstrate particle and wave properties, as observed.

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PROGRESS QUESTIONS

Question 7

Which of the following best explains whether light and matter are considered to be particles or waves?

A. They're both waves.

B. They're both particles.

C. They can be either a particle or a wave.

D. They have properties of both particles and waves.

Question 8

Which of the following best describes the results of the double slit experiment conducted with a single stream of electrons?

A. Each electron creates a diffraction pattern.

B. All the electrons land on the same spot on the screen.

C. Over time, the electrons land in two distinct bands corresponding to the two slits.

D. Each electron creates a single spot on the screen but, over time, these spots form an interference pattern.

Theory summary

- Objects made of matter have a wavelength called a de Broglie wavelength which can be calculated using $\lambda = \frac{h}{p}$.
- Even though they don't have mass, photons have momentum which can be calculated using $E_{ph} = pc$.
- The de Broglie wavelength of matter and the wavelength of a photon will be the same if they have the same momentum, p.
- The diffraction pattern of light and matter passing through a gap will have the same diffraction pattern if (and only if) they have the same wavelength.
- The double slit experiment with single electrons and photons supports wave-particle duality.
  - It demonstrates the wave properties of diffraction and interference.
  - It demonstrates the particle property of discreteness as each photon or electron produces a single spot on the screen.

10A Questions

Mild 🌶 Medium 🌶🌶 Spicy 🌶🌶🌶

Deconstructed exam-style

Use the following information to answer questions 9-12.

Vishal and Ho Man conduct an experiment to observe an electron diffraction pattern. 5000 eV electrons are fired through a diffraction grid and the resulting pattern is observed on a screen. Vishal and Ho Man want to calculate the wavelength of X-rays that would produce a similarly spaced diffraction pattern. Vishal says that they will need X-rays of 5000 eV. Ho Man says that X-rays of a different energy will be needed.

Question 9 🌶 (1 MARK)

Identify one requirement for the electrons and the X-rays to have the same diffraction pattern.

Question 10 (1 MARK)

Which of the following formulae can be used to determine the kinetic energy of an electron?

A. $KE = \frac{h}{\lambda}$

B. $KE = \frac{h}{p}$

C. $KE = pc$

D. $KE = \frac{p^2}{2m}$

Question 11 (1 MARK)

Which of the following is the correct equation relating photon energy to wavelength?

A. $E_{ph} = pc$

B. $E_{ph} = \frac{c}{p}$

C. $E_{ph} = \frac{hc}{\lambda}$

D. $E_{ph} = hc\lambda$

Question 12 (4 MARKS)

Calculate the energy of X-rays (in eV) that would be needed to produce a similarly spaced diffraction pattern as the electrons. Use this to identify who is correct.

Adapted from VCAA 2019 NHT exam Short answer Q11b

Exam-style

Question 13 (1 MARK)

Which one of the following does not provide evidence of electrons behaving as waves?

A. photoelectric effect

B. electron double slit experiment

C. diffraction of electrons through a crystal

D. diffraction of electrons through a sheet of foil

Question 14 (1 MARK)

Which one of the following is closest to the de Broglie wavelength of a 663 kg motor car moving at 10 m s^{-1}?

A. 10^{-37} m

B. 10^{-36} m

C. 10^{-35} m

D. 10^{-34} m

Taken from VCAA 2021 exam Multiple choice Q17

Question 15 (4 MARKS)

X-rays of wavelength 0.20 nm are directed at a crystal and a diffraction pattern is observed.

a. The X-ray beam is replaced by a beam of electrons, which produces a diffraction pattern with similar spacing. What must be the kinetic energy, in eV, of each electron in the beam? 2 MARKS

Adapted from 2011 exam 2 AOS 2 Section A Q11

b. Explain why these electrons also produce a diffraction pattern with the same spacing as the X-rays. 2 MARKS

Taken from 2011 exam 2 AOS 2 Section A Q12

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Question 16 (3 MARKS)

When electrons from a particular electron gun are diffracted through a silicon lattice, the same diffraction pattern occurs as when X-ray photons of 1.38×10^{-14} J pass through through the same lattice. At what speed are the electrons leaving the gun?

Question 17 (1 MARK)

Which of the following best show the wave-particle duality of light and matter?

A. Young's double slit experiment.

B. Only photons have wave-particle duality.

C. The electron and photon double slit experiments.

D. Only objects made of matter have wave-particle duality.

Question 18 (3 MARKS)

Explain the limitations of imaging using electromagnetic waves. Justify your answer with reference to diffraction.

Question 19 (7 MARKS)

Your class has just recorded an experiment mapping the velocity of electrons, v, incident on a metal lattice to the size of the fringe spacing, Δx, in the diffraction pattern created.

Experiment	v (10^6 m s^{-1})	Δx (10^{-3} m)
1	1.00	3.64
2	1.50	2.43
3	2.00	1.82
4	2.50	1.46
5	3.00	1.21

a. *Key science skill*

Plot a graph of the fringe spacing, Δx, on the vertical axis against $\frac{1}{v}$ on the horizontal axis.

Make sure you include: 5 MARKS

- Axis titles and units
- An appropriate scale on each axis
- A line of best fit

FROM LESSON 12D

b. *Key science skill*

Find the gradient of the line of best fit. 2 MARKS

FROM LESSON 12D

Question 20 (3 MARKS)

A stream of dust particles, which each have energy 2.0×10^{-5} J and mass 1.0 g, are passing through a gap. At the same time, a beam of photons which each have energy 2.0×10^{-5} J are passing through an identical gap. Will these produce the same diffraction pattern? Justify your answer with calculations.

Question 21 (4 MARKS)

Alexis and Dominik are discussing diffraction. Dominik says electrons produce a diffraction pattern. Alexis says this is impossible as diffraction is a wave phenomenon and electrons are particles; diffraction can only be observed with waves, as with electromagnetic waves, such as light and X-rays. Evaluate Dominik's and Alexis's statements in light of the current understanding of light and matter and identify two experiments that show the difference between Dominik's and Alexis's views.

Adapted from VCAA 2017 exam Short answer Q19

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Previous lessons

Question 22 (5 MARKS)

Electrons are accelerated from rest between two charged plates in an arm of a particle accelerator. The final speed of the electrons is 5.0×10^7 m s^{-1}. Ignore relativistic effects.

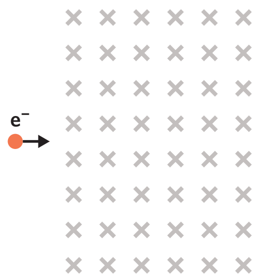
a. What is the potential difference between the plates? 2 MARKS

FROM LESSON 4C

b. The electrons then pass through a perpendicular magnetic field of strength 350 T. What is the radius of curvature of the electrons? 2 MARKS

FROM LESSON 4C

c. Sketch the path of electrons moving through the magnetic field in the diagram. 1 MARK



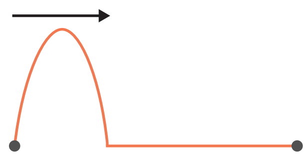
FROM LESSON 4C

Question 23 (1 MARK)

The string shown below has fixed ends.

Sketch the wave after it has been reflected once and indicate the direction of travel.

FROM LESSON 7D



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10B Absorption and emission spectra

How do we determine what stars are made of?

In order to tell what atomic elements stars are made of, scientists analyse the wavelengths of light they absorb and emit. This lesson explores the quantised states of the atom using electron standing waves, and uses this to introduce the concepts of absorption and emission spectra.

STUDY DESIGN DOT POINTS

- apply the quantised energy of photons: $E = hf = \frac{hc}{\lambda}$
- discuss the importance of the idea of quantisation in the development of knowledge about light and in explaining the nature of atoms
- explain the production of atomic absorption and emission line spectra, including those from metal vapour lamps
- interpret spectra and calculate the energy of absorbed or emitted photons: $E = hf$
- analyse the emission or absorption of a photon by an atom in terms of a change in the electron energy state of the atom, with the difference in the states' energies being equal to the photon energy: $E = hf = \frac{hc}{\lambda}$
- describe the quantised states of the atom with reference to electrons forming standing waves, and explain this as evidence for the dual nature of matter

10A — 10B

- 4.1.18.1 Electron standing waves
- 4.1.7.2 & 4.1.13.1 Quantised photon energy
- 4.1.15.1 & 4.1.16.1 & 4.1.17.1 Absorption and emission spectra

ESSENTIAL PRIOR KNOWLEDGE

- **7C** Standing waves
- **8A** The electromagnetic spectrum
- **9D** Photon energy
- **10A** Wave-particle duality

See questions 93–96.

KEY TERMS AND DEFINITIONS

quantised see discrete

discrete limited to certain values (not continuous)

absorption spectrum the specific set of frequencies or wavelengths of light that an element or compound absorbs due to electron energy transitions

emission spectrum the specific set of frequencies or wavelengths of light that an element or compound emits due to electron energy transitions

FORMULAS

- **photon energy**
  $E_{ph} = hf = \frac{hc}{\lambda}$
- **atomic energy transitions**
  $E_{ph} = \Delta E$

Electron standing waves 4.1.18.1

In Lesson 10A, we discussed how electrons can exhibit both wave and particle properties. This dual nature can be used to explain why electron orbitals around atoms are **quantised**, which means that only specific energy levels can exist.

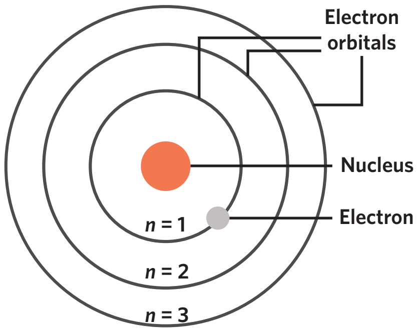

Figure 1 A diagram of a Bohr model of the atom showing the electron orbitals. Energy levels increase as the number n increases.

USEFUL TIP

The energy levels (orbitals) for an atom are commonly referred to by the value of n associated with them. The lowest energy level, $n = 1$, is known as the ground state.

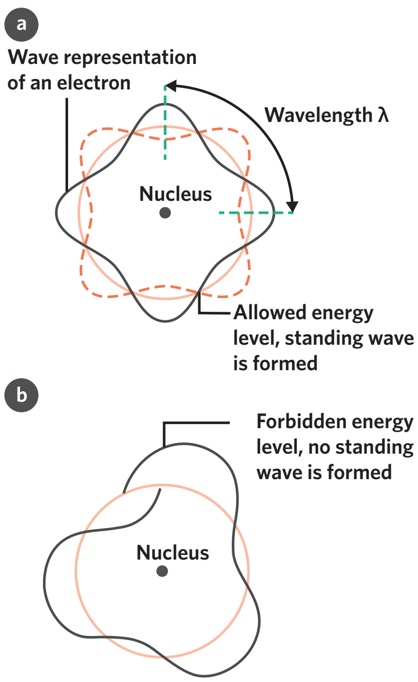

Figure 2 **(a)** An electron standing wave at the n = 4 energy level. **(b)** An example of an energy level which would result in destructive interference.

KEEN TO INVESTIGATE?

1 **How can electron standing waves be visualised?**
Search: oPhysics hydrogen energy levels

2 **What are electron orbitals?**
Search: What is the electron cloud model?

How do electrons orbit atomic nuclei?

The Bohr model of the atom shows a nucleus, containing protons and neutrons, and a number of electrons orbiting around this nucleus. The areas around the nucleus where the electrons exist are called orbitals, and each orbital has a specific energy associated with it (Figure 1). The energy levels of these orbits are **discrete** – this means that electrons will not form orbits in between these energy levels.

USEFUL TIP

The discrete energy levels correspond to discrete values of electron momentum. Since momentum and de Broglie wavelength are related by $\lambda = \frac{h}{p}$, this means that the discrete energy levels correspond to discrete de Broglie wavelengths.

De Broglie proposed that the only orbitals that can exist are ones where the circumference is the correct length for the electron to exist as a standing wave. This occurs when the orbital circumference is a whole number multiple of the electron's de Broglie wavelength. This is written mathematically as

$$n\lambda = 2\pi r \text{ where } n = 1,2,3,\ldots$$

This means that only certain electron energy levels corresponding to the electron orbitals where a standing wave is set up are allowed (Figure 2a). If an electron were to orbit in a way where it did not form a standing wave, the electron would destructively interfere with itself and drop back down to a lower energy orbital (Figure 2b).

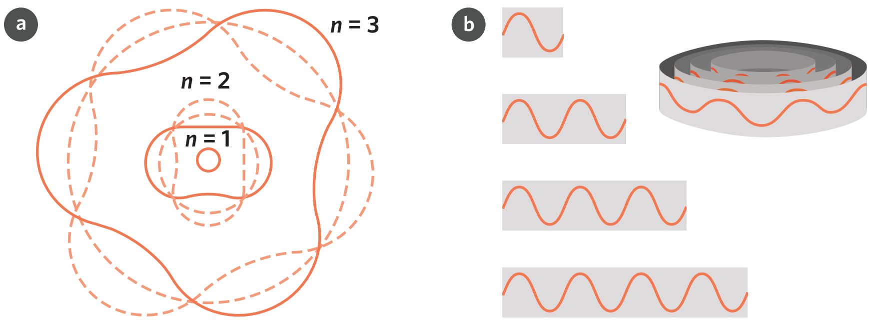

Figure 3 **(a)** A two dimensional representation of the increasing energy levels in an atom. **(b)** A representation showing how higher energy levels correspond to standing waves with a larger circumference.

Note that Figures 1 and 2 are both visual representations to help us understand the energy levels in atoms[1]. Figures 3a and 3b show two more representations of how the increasing energy levels around a nucleus correspond to a larger circumference and standing wave. It's important to note that these are all only representations, this does not mean that the electrons follow these paths or that the waves look exactly as pictured. In fact, the electrons do not travel as particles along the path of a standing wave. Instead, each individual electron exhibits wave properties with a distributed location.[2]

MISCONCEPTION

'The energy of each electron orbital is the same as the energy calculated from electron wavelength or momentum.'

The energy associated with electron orbitals depends on the atomic element being considered, the number of other electrons bound to the atom, and the orbital number n.

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STRATEGY

To draw an electron standing wave diagram for energy level n, follow these steps:

1. Draw a nucleus and a circle around it, based on where you want to draw your wave (Figure 4a).
2. Draw $2n$ dots equally spaced around the circle (Figure 4b). For this example, $2n = 2 \times 3 = 6$.
3. Each of these dots will correspond to a node. Starting at one dot, connect these dots by drawing a wave, with either a peak or a trough in between each pair of dots (Figure 4c).
4. Draw the opposite wave, that has peaks and troughs in the opposite places, with a dotted line (Figure 4d).

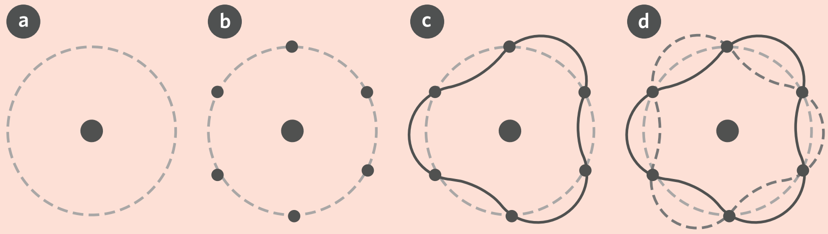

Figure 4 The process of drawing an electron standing wave diagram

USEFUL TIP

It is common to represent electrons forming standing waves using diagrams like Figure 1. To find the n value for an electron standing wave around a nucleus, count the number of full wavelengths.

The ability of electron standing waves to explain the quantisation of atomic energy levels, where only certain electron orbitals and energy levels can exist, can be viewed as evidence for the dual nature of matter.

WORKED EXAMPLE 1

Explain, with reference to the wave nature of matter, why electron energy levels in an atom are quantised.

Breakdown	Answer
State that electrons have wave properties and a de Broglie wavelength.	Electrons demonstrate wave properties, and have a de Broglie wavelength associated with them.
Explain how electrons can only exist in orbitals with a circumference that result in a standing wave being formed.	Electrons only orbit atoms when the orbital circumference is the correct length for the electron to exist as a standing wave.
Use this to justify the quantisation of electron energy levels in an atom.	Therefore electron energy levels are quantised, since electrons can only form standing waves when the orbital circumference is a whole number multiple of the electron's de Broglie wavelength.

PROGRESS QUESTIONS

Question 1

Quantised energy levels within atoms can best be explained by

A. electrons behaving as individual particles with varying energies.

B. atoms having specific energy requirements that can only be satisfied by electrons.

C. electrons behaving as waves, with each energy level representing a diffraction pattern.

D. electrons behaving as waves, with only standing waves at particular wavelengths allowed.

Taken from VCAA 2017 exam Multiple choice Q17

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Quantised photon energy 4.1.7.2 & 4.1.13.1

Since electrons only exist within discrete orbitals around a nucleus, they can only move between quantised energy levels, and therefore only absorb or emit photons with a quantised amount of energy.

Why do atoms only absorb or emit certain photons?

Atoms will only emit or absorb photons with certain energies. This occurs because of the quantised energy levels of electrons in atoms.

- The electrons can transition between these energy levels by absorbing or emitting energy in the form of photons.
- Due to the law of conservation of energy, the photon energy must equal the difference in energy between the two energy levels (orbitals).
- The electron energy levels are discrete, so the photons emitted or absorbed must also have discrete energies.

An electron must absorb a photon (gain energy) to transition to a higher energy level and it must emit a photon (lose energy) to transition to a lower energy level (Figure 5).

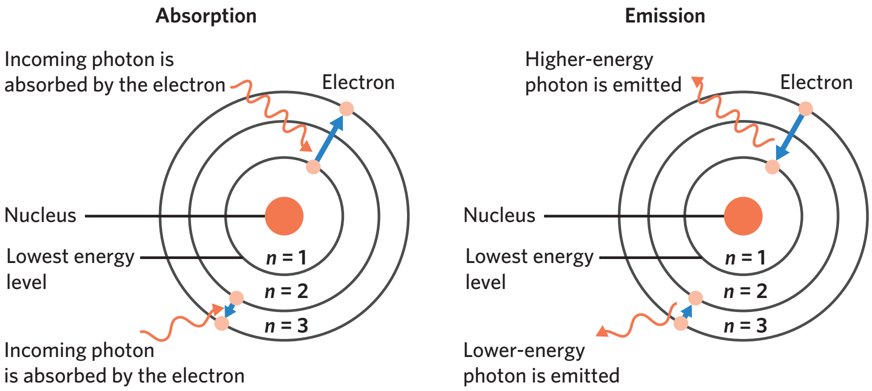

Figure 5 The absorption and emission of photons by atoms, with electron energy levels represented by n

To calculate the energy of emitted/absorbed photons, or the differences between energy levels, we use the formula:

USEFUL TIP

To convert a quantity in J to eV, multiply by 1.6×10^{-19}. To convert a quantity in eV to J, divide by 1.6×10^{-19}.

FORMULA

$$E_{ph} = \Delta E$$

E_{ph}= photon energy (eV or J)

ΔE= change in energy between levels (eV or J)

MISCONCEPTION

'The wavelength of an emitted/absorbed photon is the difference in wavelength of the electron.'

For energy conservation, we require that the total energies be the same. This does not mean that the total sum of the wavelengths has to be the same.

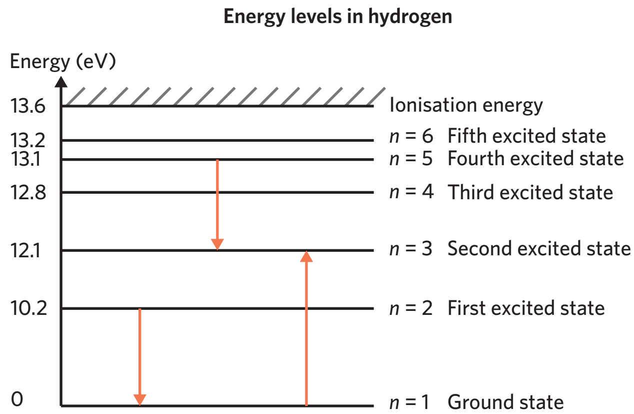

Figure 6 Electron energy levels in hydrogen

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An electron can transition between any two energy levels. Energy level diagrams depict these transitions using arrows (Figure 6). In an electron energy level diagram:

- an upwards arrow represents a photon being absorbed
- a downwards arrow represents a photon being emitted
- in both cases, the energy of the photon is given by the difference in energies between the levels, $E_{ph} = \Delta E$.

The ionisation energy in an energy level diagram represents the energy at which an electron will escape from the atom. Any incident photon with as much or more energy than the ionisation energy of an electron will eject an electron from the atom.

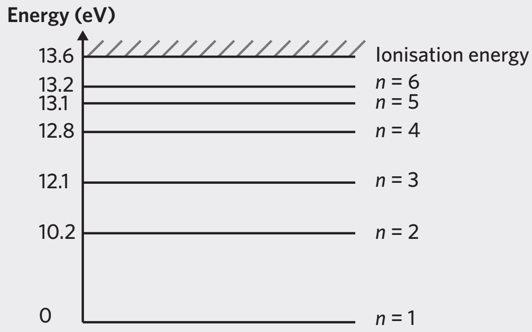
The discovery that atoms only emit or absorb photons with quantised energies helped develop our understanding of phenomena like the photoelectric effect, and provided further evidence of the dual wave-particle nature of light and matter.

USEFUL TIP

In a metal, ionisation energy is the same as the work function in the photoelectric effect.

WORKED EXAMPLE 2

The given diagram shows the atomic energy levels for a hydrogen atom.



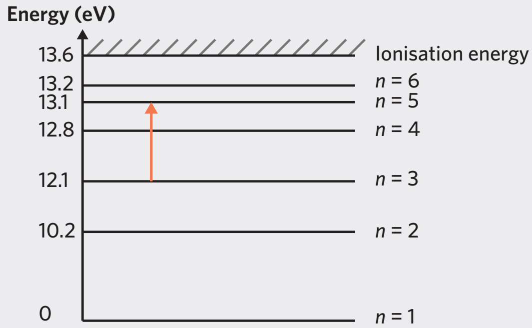
a. An electron in the $n = 3$ energy level absorbs a photon with an energy of 1.0 eV. Draw an arrow showing this transition on the electron energy level diagram.

Breakdown

I have drawn an arrow between energy levels $n = 3$ and $n = 5$, since the energy difference between these two levels is 1.0 eV.

The arrow I have drawn points upwards since a photon is being absorbed.

Answer



b. An electron orbiting a hydrogen atom transitions from the $n = 4$ to the $n = 2$ energy level. Identify whether a photon is absorbed or emitted, and calculate the energy of the photon.

Step 1

Identify whether a photon is absorbed or emitted.

Since the electron is transitioning from a higher to a lower energy level, it is losing energy, so a photon will be emitted.

Step 2

Identify known and unknown variables, and the formula that relates these variables.

$E_4 = 12.8$ eV, $E_2 = 10.2$ eV, $E_{ph} = ?$

$E_{ph} = \Delta E$

Step 3

Substitute values into the formula and solve for photon energy.

$E_{ph} = 12.8 - 10.2$

$E_{ph} = 2.6$ eV

Continues →

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c. What is the wavelength of the photon?

Step 1

Identify known and unknown variables and the formula that relates these variables.

$E_{ph} = 2.6$ eV, $h = 4.14 \times 10^{-15}$ eV s, $c = 3.0 \times 10^{8}$ m s^{-1}, $\lambda = ?$

$$E_{ph} = \frac{hc}{\lambda}$$

Step 2

Substitute values into the formula and solve for photon wavelength.

$$2.6 = \frac{4.14 \times 10^{-15} \times 3.0 \times 10^{8}}{\lambda}$$

$\lambda = 4.78 \times 10^{-7} = 4.8 \times 10^{-7}$ m

PROGRESS QUESTIONS

Question 2

What will happen as a result of the given electron transition?

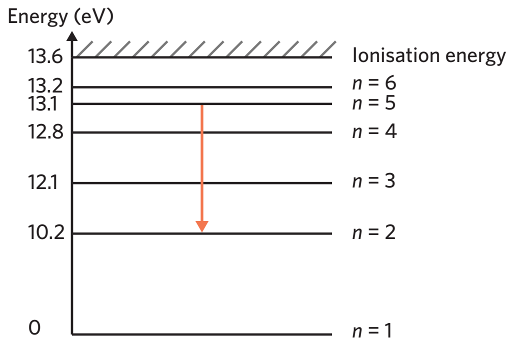
A. A photon with an energy of 2.9 eV will be emitted.

B. A photon with an energy of 2.9 eV will be absorbed.

C. A photon with an energy of 13.1 eV will be emitted.

D. A photon with an energy of 13.1 eV will be absorbed.

Energy levels in hydrogen



Question 3

An electron occupies an energy level at an energy of 12.1 eV. It absorbs a photon with frequency 1.7×10^{14} Hz. What is the energy of the energy level it transitions to?

A. 10.4 eV

B. 12.1 eV

C. 12.8 eV

D. The electron is ejected from the atom.

Absorption and emission spectra 4.1.15.1 & 4.1.16.1 & 4.1.17.1

An **absorption spectrum** shows the frequencies or wavelengths of light that a particular atom will absorb when the full spectrum of light is shone through it. An **emission spectrum** shows the frequencies or wavelengths of light that a particular atom will emit when the atoms are excited (have excess energy).

Why do emission and absorption spectra form?

An emission spectrum is the opposite of an absorption spectrum. When an atom is excited it will emit the same frequencies that it absorbs when the full spectrum of light is shone through it. Every element has a unique absorption and emission spectrum.

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As shown in Figure 7, we can see that:

- Absorption spectra consist of the continuous spectrum of light, with dark bands at the frequencies of light that the given element will absorb.
- Emission spectra consist of the same continuous spectrum that has been darkened, but with bright bands at the frequencies of light that the given element emits.

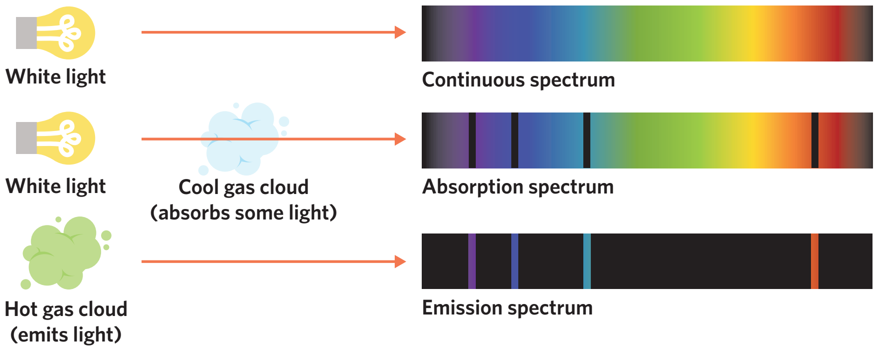

Figure 7 The production of various spectra

These specific bands exist because of the quantised electron energy levels in the atom:

- The dark bands in the absorption spectrum correspond to electrons in the element absorbing those wavelengths of light and transitioning to a higher energy level.
- The bright bands in the emission spectrum correspond to electrons in the element emitting those wavelengths of light and transitioning to a lower energy level.

The way specific photons are absorbed and emitted by atoms can be used in different ways,[3] like in metal vapour lamps. In a metal vapour lamp, a gaseous element is energised so that its electrons move into an excited state (higher energy level). They then emit photons of certain frequencies as the electrons transition to lower energy levels. Sodium vapour lamps (Figure 8) are often used as street lamps.

USEFUL TIP

For a given material, its absorption spectrum will have dark bands at the same locations its emission spectrum has bright bands.

Figure 8 A sodium vapour lamp

KEEN TO INVESTIGATE?

[3] **How does studying spectra help solve crimes?**
Search: Forensic spectroscopy

WORKED EXAMPLE 3

White light from a distant sun passes through the atmosphere of a planet before being detected by a satellite. The absorption spectrum shown is obtained.

a. What do the dark bands in the absorption spectrum correspond to?

Breakdown

Identify that the dark bands correspond to the frequencies of light being absorbed by the planet's atmosphere.

Answer

The frequencies of light absorbed by the planet's atmosphere.

b. The line furthest to the right is at a frequency of 4.57×10^{14} Hz. What is the energy (in eV) of the photon it corresponds to?

Step 1

Identify known and unknown variables, and the formula that relates these variables.

$h = 4.14 \times 10^{-15}$ eV s, $f = 4.57 \times 10^{14}$ Hz, $E_{ph} = ?$

$E_{ph} = hf$

Step 2

Substitute values into the formula and solve for photon energy.

$E_{ph} = 4.14 \times 10^{-15} \times 4.57 \times 10^{14}$

$E_{ph} = 1.892 = 1.89$ eV

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PROGRESS QUESTIONS

Question 4

Which of the following statements are incorrect regarding absorption and emission spectra?
(Select all that apply)

A. They are the same thing.

B. They are often the same for different atoms.

C. They are a result of quantised electron energy levels.

D. Absorption spectra have dark bands at the same locations emission spectra have bright bands.

Question 5

A car's xenon headlight uses xenon gas to emit light. A line spectrum for the light is obtained. Which of the following are true?
(Select all that apply)

Xenon

A. The dark bands represent the wavelengths of light emitted by xenon.

B. The coloured bands represent the wavelengths of light emitted by xenon.

C. The line spectrum shown is an emission spectrum which is unique to xenon.

D. The line spectrum shown is an absorption spectrum which is unique to xenon.

Question 6

An absorption spectrum that shows a dark line at 410 nm is obtained for a gaseous cloud in deep space. What is the energy (in eV) of the photon it corresponds to?

A. 3.0 eV **B.** 6.0 eV **C.** 9.0 eV **D.** 12.0 eV

Theory summary

- Electrons can only exist in discrete energy levels where the circumference is an integer multiple of the electron's de Broglie wavelength. This forms a standing wave where constructive interference can occur.
- The discrete electron energy levels in atoms is evidence of the dual nature of matter.
- Atoms emit and absorb specific photon energies corresponding to the difference between their electron energy levels, $E_{ph} = \Delta E$.
  - When a photon is absorbed, the electron transitions to a higher energy level.
  - When a photon is emitted, the electron transitions to a lower energy level.
- Elements have unique absorption and emission spectra.
  - Absorption spectra show the frequencies/wavelengths of photons an element can absorb.
  - Emission spectra show the frequencies/wavelengths of photons an element can emit.
- Metal vapour lamps use the emission spectra of an energised gas to produce light.

KEEN TO INVESTIGATE?

How can electron standing waves be visualised?
Search YouTube: Limitations of Bohr's model chemistry

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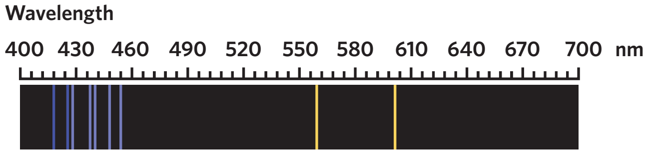
10B Questions

Mild 🌶 Medium 🌶🌶 Spicy 🌶🌶🌶

Deconstructed exam-style

Use the following information to answer questions 7–10.

The given figure shows the spectrum of light emitted from a sodium vapour lamp.



Question 7 🌶 (1 MARK)

Which of the following best describes how electrons orbit a nucleus?

A. They can orbit at any distance and in any path.

B. They can orbit with any energy within a specific range.

C. They only exist in certain orbitals, each corresponding to a certain energy level.

D. Electrons don't orbit atomic nuclei, they are captured by them and remain stationary.

Question 8 🌶 (1 MARK)

Describe how photons with a discrete amount of energy are emitted from an atom.

Question 9 🌶 (1 MARK)

Why do discrete photon energies correspond to discrete photon wavelengths?

A. Photon wavelength is always discrete.

B. Photon energy and photon wavelengths are related, $E = \frac{hc}{\lambda}$.

C. Discrete photon energies correspond to discrete changes in electron wavelength.

D. Discrete energies do not correspond to discrete wavelengths, only discrete frequencies.

Question 10 🌶🌶🌶 (3 MARKS)

Explain why a sodium vapour lamp emits discrete wavelengths of light.

Adapted from 2018 VCAA exam Short answer Q19b

Exam-style

Question 11 🌶 (1 MARK)

What physical phenomenon do metal vapour lamps utilise to produce light?

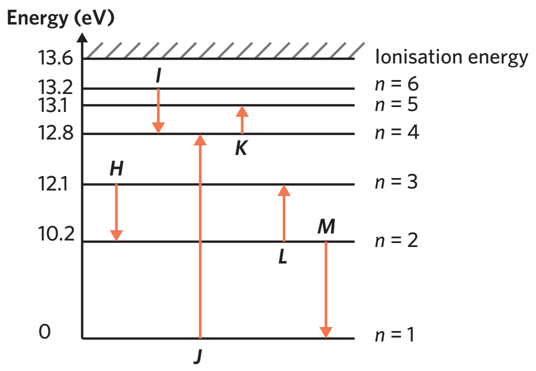
A. interference patterns

B. conversion of nuclear matter to pure energy

C. production of light in random thermal collisions

D. electrons moving between energy levels in an energised gas

Use the following diagram to answer questions 12–14.



Question 12 (1 MARK)

Which two electron transitions correspond to one emission and one absorption of a photon with the same energy?

A. *H* and *L*

B. *I* and *J*

C. *I* and *K*

D. *J* and *M*

Question 13 (1 MARK)

Which of the following lists only transitions that are a result of an electron absorbing a photon?

A. *J*, *M*

B. *H*, *I*, *M*

C. *J*, *K*, *H*

D. *J*, *K*, *L*

Question 14 (1 MARK)

Which electron transition involves the absorption of the smallest wavelength of light?

A. *I*

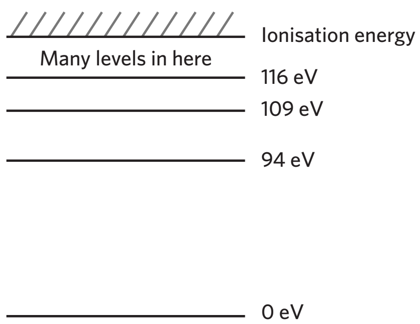
B. *J*

C. *K*

D. *M*

Question 15 (7 MARKS)

The energy level diagram for a certain atom is given.



a. An electron is at the 116 eV energy level. Calculate the smallest frequency of light it could emit. 2 MARKS

Adapted from VCAA 2013 exam Short answer Q20a

b. Using a calculation, explain why the emission spectrum of this atom includes a line at 13.2 nm. 3 MARKS

Adapted from VCAA 2013 exam Short answer Q20b

c. Draw an electron standing wave diagram of the $n = 3$ state. 2 MARKS

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Question 16 🌶🌶 (1 MARK)

What happens if an electron absorbs a photon with a greater energy than its ionisation energy?

A. The electron will be ejected from the atom.

B. The electron will go to a higher energy level.

C. The electron will spiral down into the nucleus.

D. This is impossible, the electron will not absorb a photon greater than its ionisation energy.

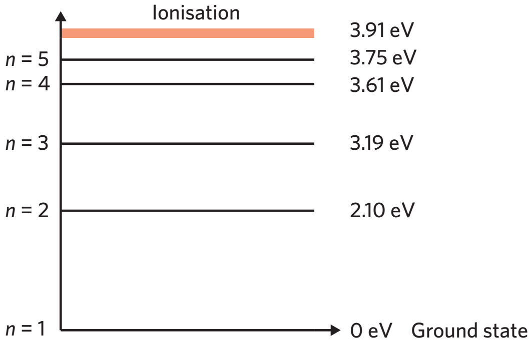
Question 17 🌶🌶 (3 MARKS)

How do wave-like properties of electrons explain the quantisation of electron energy levels?

Adapted from VCAA 2014 exam Short answer Q23b

Question 18 (10 MARKS)

The given diagram shows the electron energy levels in a sodium atom.



a. List all the different photon energies that the electron can emit as it returns to the ground state from the third excited state ($n = 3$). 🌶🌶 3 MARKS

Adapted from VCAA 2016 exam Short answer Q21c

b. A scientist reports detecting a photon with an energy of 2.3 eV being emitted from the sodium atom. Is this possible? State a reason why. 🌶 2 MARKS

c. A sodium atom emits a photon of 1.353×10^{14} Hz. Calculate the energy of this photon in eV. 🌶 1 MARK

d. Draw an arrow to show the electron's change in energy levels when a 1.353×10^{14} Hz photon is emitted. 🌶🌶 2 MARKS

e. ***Key science skill***

A scientist wants to calculate the wavelength of an emitted photon using the energy levels in the given diagram. What value for Planck's constant, h, is it best for them to use? Justify your response. 🌶 2 MARKS

Question 19 🌶🌶 (1 MARK)

Why can electrons only exist in atoms at certain energy levels?

A. Electrons are waves and waves are always discrete.

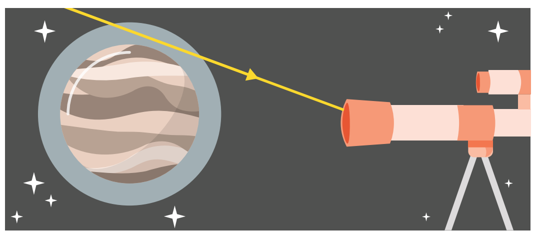
B. Electrons have wave-like properties and only exist when a standing wave can form.

C. Electrons are particles, meaning that all their quantities, including orbit, must be discrete.

D. This is not true. When an electron goes from one orbit to another it exists between discrete orbits.

Question 20 🌶🌶 (2 MARKS)

Jenn wants to determine if there is the element mercury in the planet Mercury's exosphere by analysing the spectrum of light passing through it and reaching a telescope. Using your understanding of absorption spectra, explain how Jenn will be able to determine the presence of mercury in this exosphere.



Question 21 (5 MARKS)

Eimear and Dhilan are independently measuring the emission spectra of an element.

a. *Key science skill*

Eimear's measurements of a particular spectral line are: 124 nm, 120 nm, 127 nm (average 124 nm).
Dhilan's measurements of the same spectral line are: 116 nm, 130 nm, 117 nm (average 121 nm).
The emission line is known to be at 122 nm.

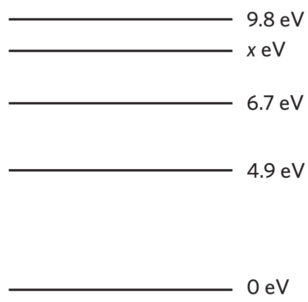
Comment on whose results were more precise. Justify your answer. 2 MARKS

FROM LESSON 12C

b. They measure a spectral line corresponding to a frequency of 3.1×10^{14} Hz. They believe this to be a transition from an energy level of 5.6 eV. What is the energy, E_n, of the other energy level in the transition? 3 MARKS

Use the following information to answer questions 22 and 23.

In a sample of excited mercury atoms, all of the energy levels shown in the given energy level diagram are occupied, but no higher levels are. One of the energy levels is labelled x eV. The emission spectrum of mercury shows lines at approximately 2.2 eV and 4.0 eV.



Question 22 (1 MARK)

For a transition to or from x to have an energy difference of $\Delta E = 2.2$ eV, which of the following are possible values for x? **(Select all that apply)**

A. 2.2 eV

B. 7.6 eV

C. 8.0 eV

D. 8.9 eV

Question 23 (3 MARKS)

Use this information and the diagram to calculate x. Give your reasoning.

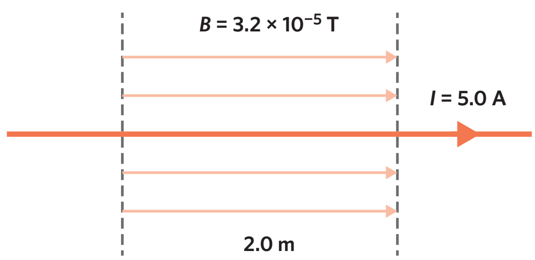
Adapted from VCAA 2014 exam Short answer Q22b

Previous lessons

Question 24 (1 MARK)

A wire carrying a current of $I = 5.0$ A passes through a magnetic field with a strength of 3.2×10^{-5} T, as shown in the diagram. The magnetic field is 2.0 m wide. What is the magnitude of the force on the wire?

FROM LESSON 4C



Question 25 (3 MARKS)

A beam of light with wavelength 1.5 nm is incident on a single slit with width 6.0×10^{-8} m. Will significant diffraction occur? Justify your answer.

FROM LESSON 7D

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Chapter 10 review

Mild 🌶 Medium 🌶🌶 Spicy 🌶🌶🌶

These questions are typical of one hour's worth of questions on the VCE Physics Exam.

Total marks: 50

Section A

All questions in this section are worth one mark.

Unless otherwise indicated, the diagrams in this book are not drawn to scale.

Question 1 🌶

Protons of mass 1.67×10^{-27} kg are accelerated to a speed of 2.0×10^{3} m s^{-1}. The best estimate of the de Broglie wavelength of these protons is

A. 1.2×10^{-10} m.

B. 2.0×10^{-10} m.

C. 1.2×10^{-7} m.

D. 2.0×10^{-7} m.

Taken from 2021 NHT exam Multiple choice Q17

Question 2 🌶

Which of the following provides the best evidence of the dual wave-particle nature of light and matter?

A. the photoelectric effect

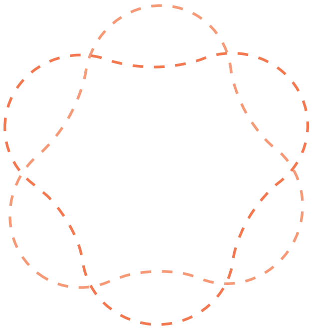
B. Young's double slit experiment

C. the photon/electron double slit experiment

D. light and matter do not have a dual wave-particle nature

Question 3 🌶🌶

The diagram below shows one representation of a de Broglie standing wave for an electron in orbit around a hydrogen atom.



Which one of the following values of n, the number of whole wavelengths, best depicts the standing wave pattern shown in the diagram?

A. 2

B. 3

C. 4

D. 6

Adapted from VCAA 2021 exam Multiple choice Q19

Question 4 🌶🌶

Spectral lines in the emission and absorption spectra of an atom can be best explained by

A. electrons behaving as discrete particles.

B. electrons having the same energy as the photons corresponding to the spectral lines.

C. electrons having the same wavelength as the photons corresponding to the spectral lines.

D. electrons behaving as waves, only allowing them to form standing waves around a nucleus.

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Question 5

For certain applications, using light to create images becomes very difficult. Which of the following is the reason for this limitation?

A. Light diffracts less around smaller objects.

B. Light has a longer wavelength than electrons.

C. Imaging small objects requires a larger amount of light.

D. Shorter wavelengths of light carry more energy than longer wavelengths.

Section B

In questions where more than one mark is available, appropriate working must be shown.

Unless otherwise indicated, the diagrams in this book are not drawn to scale.

Question 6 (6 MARKS)

Three scientists, Eva, Hayden, and Leo, are conducting experiments to study the properties of photons.

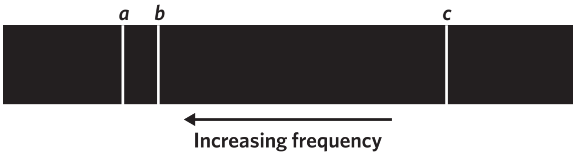
a. Eva uses photons with an energy of 12.5 eV in her experiment. Calculate the momentum of these photons. 2 MARKS

b. Hayden uses photons with an energy of 10.2 eV in his experiment. Calculate the frequency of these photons. 2 MARKS

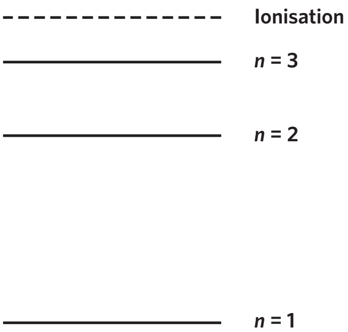
c. Leo finds that the photons he has been using have a momentum of 9.2×10^{-28} kg m s^{-1}. Calculate the wavelength of these photons. 2 MARKS

Question 7 (6 MARKS)

An atom has a single electron in the second excited state ($n = 3$). When it returns to the ground state ($n = 1$), the emission spectrum has lines at $a = 2.63 \times 10^{16}$ Hz, $b = 2.22 \times 10^{16}$ Hz and $c = 0.41 \times 10^{16}$ Hz, as shown in the diagram.



The electron energy level diagram is also provided.



a. Use this information to show that the energies of the $n = 3$ and $n = 2$ states are 109 eV and 91.9 eV respectively. 4 MARKS

Adapted from VCAA 2015 exam Short Answer Q19a

b. Explain why an atom of this kind, while in the first excited state, is able to absorb a 17.1 eV photon, but cannot emit a photon of this energy. 2 MARKS

Adapted from VCAA 2014 exam Short Answer Q22a

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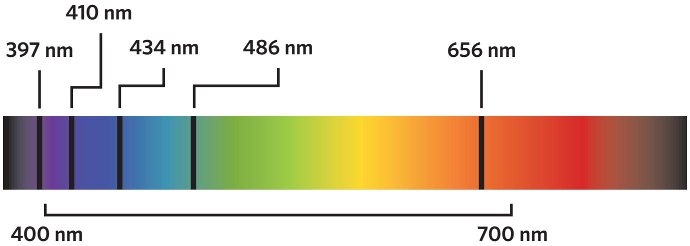
Question 8 (6 MARKS)

A group of astronomers obtain the following absorption spectra while studying a cloud of cool gas in outer space.



a. Calculate the energy of the photon corresponding to the line at 656 nm. Give your final answer in eV. 2 MARKS

b. The absorption of a photon will cause an atom to transition between two energy levels. or the absorption of the 656 nm photon, what is the difference in energy between these two atomic energy levels? 1 MARK

c. The scientists have the following table, which shows the location of two dark bands in the absorption spectra of various elements.

Element	Wavelength of dark band one (nm)	Wavelength of dark band two (nm)
Hydrogen	434	486
Helium	588	668
Mercury	436	579
Oxygen	558	630

Which of the given elements can they conclude is present in the gas cloud? Justify your response. 3 MARKS

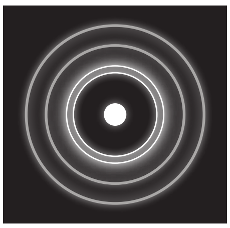
Question 9 (7 MARKS)

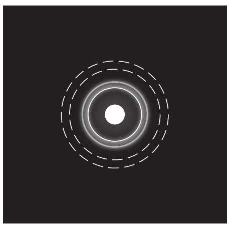
Thuy is doing some experiments on the diffraction of photons. She is using a beam of photons with an energy of 4.1 eV.

a. Calculate the wavelength of a photon in this light beam. 2 MARKS

Adapted from VCAA 2014 exam Short answer Q21a

Thuy now carries out another experiment, comparing the diffraction of X-ray photons and electrons. A beam of X-ray photons is incident on a small circular aperture. The experiment is then performed with a beam of electrons incident on the same aperture. The X-ray photons and electrons have the same energy. The diffraction patterns, as given here, have the same general shape, but very different spacings.


X-ray photon diffraction


Electron diffraction

b. Explain why the electron diffraction pattern has a different spacing from the X-ray diffraction pattern, even though the electrons and the photons have the same energy. 3 MARKS

Adapted from VCAA 2014 exam Short answer Q21d

c. Calculate the de Broglie wavelength of the electrons, which have mass 9.1×10^{-31} kg. 2 MARKS

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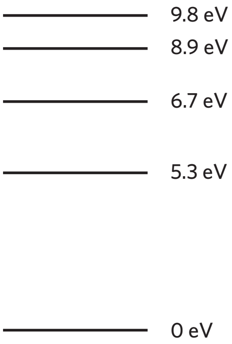
Question 10 (9 MARKS)

A simplified diagram of some of the energy levels of an atom is shown in the figure.



a. Show that the energy of a photon with a wavelength of 565 nm is 2.2 eV. — 1 MARK

b. Draw the transition on the energy level diagram that would result in the emission of the photon with wavelength 565 nm. — 1 MARK

Adapted from VCAA 2021 exam Short answer Q19a

c. A sample of the atoms have their electrons excited into the 9.8 eV state and a spectrum is observed as the states decay. Assume that all possible transitions occur. What is the total number of lines in the spectrum? Explain your answer. — 2 MARKS

Adapted from VCAA 2021 exam Short answer Q19b

d. An electron in the ground state is excited to the $n = 4$ state in one step. Explain how this could happen. — 2 MARKS

Adapted from VCAA 2019 exam Short answer Q18a

e. Calculate the lowest frequency in this atom's emission spectrum. — 3 MARKS

Question 11 (4 MARKS)

The single photon double slit experiment is performed to display the wave-particle duality of light. Identify one result of the experiment which supports the particle model and a second result which does not. Explain your answers.

Question 12 (7 MARKS)

Wave-particle duality is a term used to describe objects, such as light and electrons, that demonstrate both wave and particle behaviour.

a. Identify one piece of evidence that supports electrons behaving like waves. Explain how this evidence supports a wave model of electrons. — 2 MARKS

Adapted from VCAA 2015 exam Short answer Q20b

b. Use the model of quantised states of the atom to explain why only certain energy levels are allowed. — 3 MARKS

Adapted from VCAA 2015 exam Short answer Q21a

c. Draw the standing wave that corresponds to an electron orbital with four whole wavelengths. — 2 MARKS

Adapted from VCAA 2015 exam Short answer Q21b

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11

CHAPTER 11

Special relativity and mass-energy equivalence

STUDY DESIGN DOT POINTS

- describe the limitation of classical mechanics when considering motion approaching the speed of light
- describe Einstein's two postulates for his special theory of relativity that:
  - the laws of physics are the same in all inertial (non-accelerated) frames of reference
  - the speed of light has a constant value for all observers regardless of their motion or the motion of the source
- interpret the null result of the Michelson-Morley experiment as evidence in support of Einstein's special theory of relativity
- compare Einstein's special theory of relativity with the principles of classical physics
- describe proper time (t_0) as the time interval between two events in a reference frame where the two events occur at the same point in space
- describe proper length (L_0) as the length that is measured in the frame of reference in which objects are at rest
- model mathematically time dilation and length contraction at speeds approaching c using the equations: $t = \gamma t_0$ and $L = \frac{L_0}{\gamma}$ where $\gamma = \frac{1}{\sqrt{\left(1 - \frac{v^2}{c^2}\right)}}$
- explain and analyse examples of special relativity including that:
  - muons can reach Earth even though their half-lives would suggest that they should decay in the upper atmosphere
  - particle accelerator lengths must be designed to take the effects of special relativity into account
  - time signals from GPS satellites must be corrected for the effects of special relativity due to their orbital velocity
- interpret Einstein's prediction by showing that the total 'mass-energy' of an object is given by: $E_{tot} = E_k + E_0 = \gamma mc^2$ where $E_0 = mc^2$, and where kinetic energy can be calculated by: $E_k = (\gamma - 1)mc^2$
  - apply the energy-mass relationship to mass conversion in the Sun, to positron-electron annihilation and to nuclear transformations in particle accelerators (details of the particular nuclear processes are not required).

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LESSONS

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11A Special relativity concepts

Image: photocritical/Shutterstock.com

How could someone on board tell if the train is moving?

Unless the train was accelerating, it would be impossible for someone on board the train to determine whether it is moving. This is a consequence of Einstein's postulates of special relativity, which have implications for our understanding of space and time. This lesson will lay the foundations for understanding Einstein's theory of special relativity which applies to relative motion at a constant speed in a straight line, and compare them to the predictions of classical physics.

STUDY DESIGN DOT POINTS

- describe the limitation of classical mechanics when considering motion approaching the speed of light
- describe Einstein's two postulates for his special theory of relativity that:
  - the laws of physics are the same in all inertial (non-accelerated) frames of reference
  - the speed of light has a constant value for all observers regardless of their motion or the motion of the source
- interpret the null result of the Michelson-Morley experiment as evidence in support of Einstein's special theory of relativity
- compare Einstein's special theory of relativity with the principles of classical physics

11A 11B 11C 11D

- 4.1.21.1 Einstein's first postulate
- 4.1.21.2 Einstein's second postulate
- 4.1.22.1 Michelson-Morley experiment
- 4.1.20.1 & 4.1.23.1 Special relativity and classical physics

ESSENTIAL PRIOR KNOWLEDGE

1A Acceleration

See question 97.

KEY TERMS AND DEFINITIONS

frame of reference a perspective from which we measure the relative location and motion of objects

inertial frame of reference a non-accelerating frame of reference

postulate a statement which is accepted to be true as a basis for reasoning

ether a hypothetical medium that light travels through

Einstein's first postulate 4.1.21.1

A **frame of reference** is a perspective from which we measure the relative location and motion of objects. An **inertial frame of reference** is one which is considered stationary or moving at a constant velocity (not accelerating). Einstein's first postulate states that the laws of physics are the same for all inertial frames of reference.

What is a frame of reference?

Every object can be considered to be in its own frame of reference. This means the relative location and motion of all other objects depends on the frame of reference in which the measurements are made.

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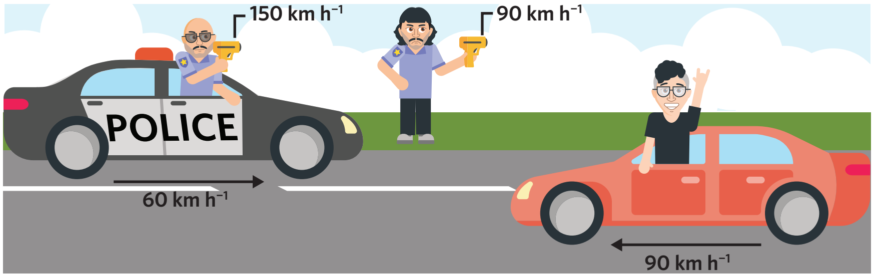

Figure 1 Two officers measure different speeds for the red car.

When measured from the frame of reference of the stationary police officer, the red car in Figure 1 travels at 90 km h^{-1}. However, when measured from the frame of reference of the moving police car, the red car travels at 90 + 60 = 150 km h^{-1}.

This supports our observations in everyday life. Both measurements are correct and indicate all motion is relative: measurements of motion are made in relation to a frame of reference.

When we travel along a road, the cars next to us travelling at the same velocity may appear to be stationary as they are not moving with respect to our frame of reference. An inertial frame of reference is one which is not accelerating (has a constant velocity). Examples of inertial frames of reference include:

- A person's frame of reference when they are sitting still.
- A car's frame of reference when it is travelling at a constant speed in a constant direction.
- An aeroplane's frame of reference while it is flying in a straight line at a constant speed of 900 km h^{-1}.

Examples of non-inertial frames of reference include:

- A person's frame of reference as they speed up from a walk to a run.
- A car's frame of reference when it is travelling at a constant speed around a corner.
- An aeroplane's frame of reference while it is slowing down.

MISCONCEPTION

'Any reference frame travelling at a constant speed is an inertial frame of reference.'

Constant speed is not a sufficient condition to describe an inertial frame of reference. Constant velocity (speed and direction) is required for an inertial frame of reference.

USEFUL TIP

Due to the Earth's rotation and curvature, a reference frame which is at rest on the surface of the Earth is not technically an inertial frame of reference. For the purposes of VCE Physics and our discussion in this book, we will treat reference frames that are not accelerating with respect to the surface of the Earth as inertial reference frames.

What are the consequences of Einstein's first postulate?

A **postulate** is an assumed fact used for reasoning. Einstein's first postulate states that the laws of physics are the same in all inertial frames of reference.

This means that if we conducted physics experiments in different inertial frames of reference, we should find that the results are the same and that there is no universal 'correct' frame of reference in which to conduct experiments. In an accelerating reference frame the results of an experiment may depend on the acceleration of the frame.

Figure 2a shows a stationary tram carriage, whereas Figure 2b shows one that is moving at a constant velocity of 50 km h^{-1} to the right. If you are travelling on a tram that is not accelerating, there is no way to detect the relative motion of the tram without looking outside. We can test the laws of physics in both these inertial frames of reference and find the results of the experiments are the same.

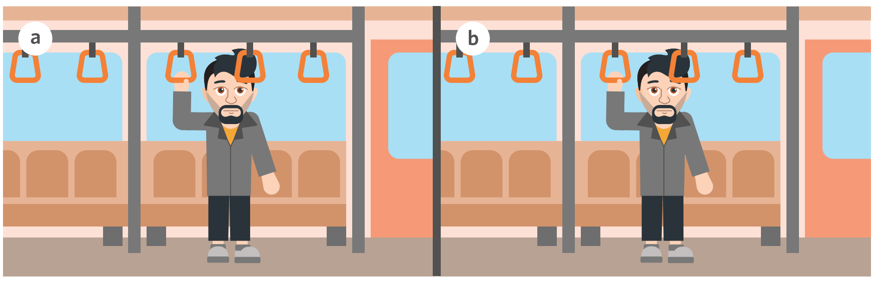

Figure 2 **(a)** A person in a tram carriage that is stationary and **(b)** moving at a constant velocity.

USEFUL TIP

The 'laws of physics' refer to the fundamental principles that describe the behaviour of the universe. This includes Newton's laws of motion, the principles of electromagnetism and the conservation of energy and momentum. Lesson 12A will discuss the formal definition of a law.

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Figure 3 A person in a tram carriage that is accelerating.

Figure 3 shows the inside of a tram carriage that is accelerating. If we were to test the laws of physics, the results of this experiment may show that the laws of physics as we understand them are different, as the tram carriage is a non-inertial frame of reference.

Suppose we drop a ball.

- In an inertial frame of reference the ball will drop straight down regardless of whether the tram is stationary or moving at a constant velocity. The results of the experiment are identical.
- If we dropped the same ball in an accelerating tram, the ball would fall backwards as the laws of physics in a non-inertial frame of reference are not the same as those in an inertial frame of reference.

Einstein's first postulate on its own agrees with the predictions of classical physics – the laws of physics discovered before the 20th century.[1]

KEEN TO INVESTIGATE?

[1] **Was relativity accounted for before Einstein?**
Search YouTube: What is Galilean relativity?

PROGRESS QUESTIONS

Question 1

Which of the following best describes Einstein's first postulate?

A. The laws of physics are the same for all frames of reference.

B. The laws of physics are the same for all inertial frames of reference.

C. The classical laws of physics are the same for all frames of reference.

D. The classical laws of physics are the same for all inertial frames of reference.

Question 2

Which of the following best describes an inertial frame of reference?

A. A point in space from which the location of other objects can be measured.

B. A point in space from which the relative location and motion of objects can be measured.

C. A non-accelerating point in space from which the relative location and motion of objects can be measured.

D. A point in space with a changing velocity from which the relative location and motion of objects can be measured.

Question 3

A student sits inside a windowless box that has been placed on a smooth-riding train carriage. He conducts a series of motion experiments to investigate frames of reference. Which one of the following observations is correct?

A. The results when the train accelerates are identical to the results when the train is at rest.

B. The results when the train accelerates are different from the results when the train is in uniform straight line motion.

C. The results when the train is at rest are different from the results when the train is in uniform straight line motion.

D. The results when the train accelerates are identical to the results when the train is in uniform straight line motion.

Adapted from VCAA 2017 exam Multiple choice Q10

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Einstein's second postulate 4.1.21.2

Einstein's second postulate states that the speed of light in a vacuum is the same regardless of the movement of the source or the detector. The speed of light in a vacuum, c, is 3.0×10^8 m s^{-1}.

What are the consequences of Einstein's second postulate?

The speed of most objects (such as the red car in Figure 1) is a relative measurement: different reference frames will measure different speeds of the same object. The exception to this is light.

- The stationary police officer in Figure 4 will measure the speed of a beam of light travelling towards them as c.
- The moving police officer, who is travelling at $0.4c$ towards the beam of light relative to the stationary police officer, will also measure the speed of the beam as c.

This is a consequence of Einstein's second postulate: the speed of light is c, regardless of the motion of an observer or the motion of the source of light.[2]

These results disagree with the predictions of classical physics – that the moving police officer will measure the speed of the beam of light as $c + 0.4c = 1.4c$. However, experimental results, like the Michelson-Morley experiment, support Einstein's second postulate and dispute the predictions of classical physics.

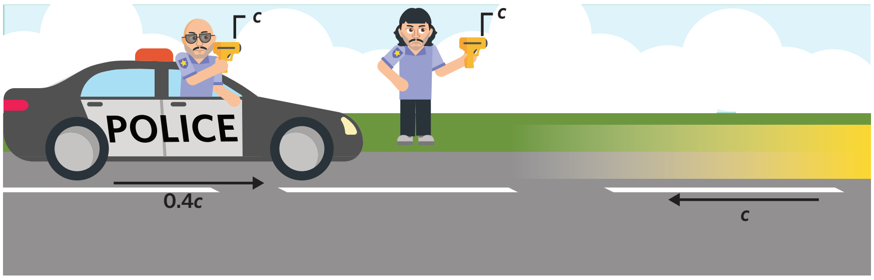

Figure 4 Two officers measure the same speed for the beam of light.

KEEN TO INVESTIGATE?

[2] **Why is the speed of light c?**
Search YouTube: The speed of light is not about light

USEFUL TIP

Only things with no mass can travel at the speed of light, $v = 3.0 \times 10^8$ m s^{-1}, including all electromagnetic waves.

PROGRESS QUESTIONS

Question 4

Which of the following best describes Einstein's second postulate?

A. The speed of light in a vacuum is the same for all observers.

B. The speed of all waves is the same for all frames of reference.

C. The speed of light in a vacuum is the same for all stationary observers.

D. The speed of light in a vacuum depends on the motion of the source of light.

Question 5

A person is travelling in spaceship A at 1.0×10^8 m s^{-1} relative to the nearby planet of Mars. They fire a laser towards a person on spaceship B, which is stationary relative to Mars. Which of the following correctly shows the measurements made for the speed of the laser beam by each person?

	Person on spaceship A	Person on spaceship B
A.	2.0×10^8 m s^{-1}	2.0×10^8 m s^{-1}
B.	2.0×10^8 m s^{-1}	3.0×10^8 m s^{-1}
C.	3.0×10^8 m s^{-1}	3.0×10^8 m s^{-1}
D.	3.0×10^8 m s^{-1}	4.0×10^8 m s^{-1}

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Michelson-Morely experiment 4.1.22.1

Up until the late 19th century it was thought that light required a medium to travel through, just like sound waves. Two scientists, Albert A. Michelson and Edward W. Morely, attempted to observe light travelling through this hypothetical medium, called the **ether**.

How can we interpret the results of the Michelson-Morley experiment?

The purpose of the Michelson-Morely experiment was to measure a change in the speed of light. They hypothesised that if light travelled through the ether, the Earth must too. So, as the motion of the Earth changed along its orbital path around the Sun, its movement relative to the ether would also change. The experimental design involved splitting a beam of light into two perpendicular arms, one parallel to the Earth's motion through the ether and one perpendicular to it (Figure 5).

By observing the diffraction pattern created at the telescope they could calculate whether the speed of each beam of light was different. If the speed of the beams were measured to be different then it confirmed the existence of the ether, as the Earth's movement through the ether altered the speed of the light beam.[3]

KEEN TO INVESTIGATE?

[3] **How does the Michelson-Morely experiment measure the speed of light?**
Search YouTube: Michelson-Morely experiment explained

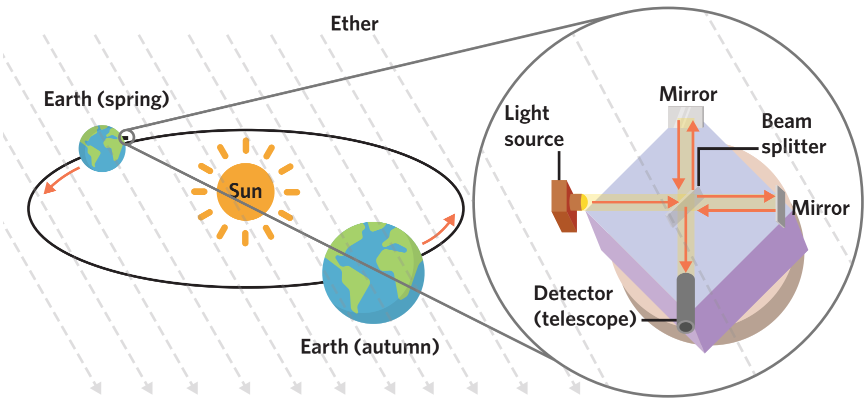

Figure 5 The Earth's movement relative to the ether at different points in its orbit around the Sun, and the experimental set-up of the Michelson-Morely experiment.

The experiment was repeated at different times of the day, and at different times during the year, to account for any changes in the Earth's motion through the ether. The results showed there was no change to the speed of light in any situation. This disproved the existence of the hypothetical ether, as there was no detectable change to the speed of light, indicating that the speed of light was constant.

This supports Einstein's theory of special relativity, specifically the second postulate which states the speed of light in a vacuum is *c*, regardless of the motion of the observer or light source.

PROGRESS QUESTIONS

Question 6

Which of the following best describes the conclusion of the Michelson-Morely experiment?

A. The speed of light depends on the motion of the Earth through the ether.

B. The ether does not exist, as the speed of light was measured to be the same.

C. The speed of light does not depend on the motion of the Earth through the ether.

D. The ether does not exist, as the speed of light varies depending on the motion of the Earth.

Continues →

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Question 7

Did the results of the Michelson-Morely experiment support or dispute Einstein's theory of special relativity?

A. They supported Einstein's theory of special relativity, as they support Einstein's first postulate.

B. They supported Einstein's theory of special relativity, as they support Einstein's second postulate.

C. They disputed Einstein's theory of special relativity, as they contradicted Einstein's first postulate.

D. They disputed Einstein's theory of special relativity, as they contradicted Einstein's second postulate.

Special relativity and classical physics 4.1.20.1 & 4.1.23.1

The principles of classical physics are different to those that underpin Einstein's theory of special relativity and are limited in their ability to describe the motion of objects approaching the speed of light.

How does the theory of special relativity compare to the principles of classical physics?

Classical physics assumes that space and time are absolute, which means that observers in different reference frames should always agree about their measurements of length and time. At low relative speeds, these assumptions are good approximations, but they are still approximations. As speeds approach the speed of light (relativistic speeds), classical physics predicts results which differ significantly from experimental measurements.

As with any speed, the speed of light is a measure of the rate of change of distance with respect to time ($c = \frac{\Delta s}{\Delta t}$). For all inertial observers to measure the same speed of light, space (in terms of length, l) and time (t) must change depending on an observer's reference frame. These changes, known as length contraction and time dilation, will be discussed in Lesson 11B and they underpin Einstein's theory of special relativity.

The predictions of the theory of special relativity have been supported by experimental measurements in inertial reference frames at all speeds. Table 1 shows the difference between predictions of classical physics and special relativity.

MISCONCEPTION

'Relativistic effects are not relevant to our everyday lives but only to high speed spaceships.'

For a phone GPS to accurately determine its location, the clocks on board GPS satellites tick at a slower rate in their rest frame than clocks on Earth. This is one of many examples of how relativity must be taken into account in everyday life.

Table 1 A comparison between the principles of classical physics and special relativity

	Classical physics prediction	Special relativity prediction
Space and time	Fixed – all observers agree on measurements of length and time	Flexible – length and time measurements change between reference frames
Relative speeds	Add linearly – all values of relative speed are possible.	Add nonlinearly – the relative speed of objects with mass can never reach the speed of light (Note that this is outside the scope of VCE physics).
Kinetic energy	$KE = \frac{1}{2}mv^2$ regardless of the value of v	At velocities close to c, a small increase in velocity requires a large increase in KE.

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KEEN TO INVESTIGATE?

4 **Why can't objects travel as fast as light?**
Search YouTube: Cosmic speed light

KEEN TO INVESTIGATE?

5 **How are velocities combined in special relativity?**
Search YouTube: Relativistic addition of velocities

What are the limitations of classical mechanics?

Figure 6 shows two rockets travelling towards each other each at 60% of the speed of light ($0.60c$) as measured from the Earth's frame of reference. According to classical physics, Rocket 1 should measure Rocket 2's relative speed to be $0.60c + 0.60c = 1.20c$. This would mean that Rocket 2 would run into Rocket 1 before Rocket 1 could even see Rocket 2. Why objects with mass can never reach the speed of light will be explained in Lesson 11D.[4]

In reality, the relative speed of Rocket 2 in Rocket 1's frame of reference will be $0.88c$.[5] The details of this are beyond the scope of VCE Physics, but it is important to understand that the limitation of classical mechanics exists. The theory of special relativity can explain this difference as a result of the different length and time measurements taken from Rocket 1's frame of reference compared to Earth's frame of reference.

Figure 6 Two rockets travelling towards each other at 0.60c, as measured in the Earth's frame of reference.

PROGRESS QUESTIONS

Question 8

Which one of the following statements about the kinetic energy, *KE*, of a proton travelling at relativistic speed (close to c) is the most accurate?

A. The proton's relativistic *KE* is less than its classical *KE*.

B. The proton's relativistic *KE* is the same as its classical *KE*.

C. The proton's relativistic *KE* is greater than its classical *KE*.

D. The difference between the proton's relativistic *KE* and its classical *KE* cannot be determined.

Adapted from VCAA 2018 exam Multiple choice Q14

Question 9

Which of the following correctly describes a key difference in the predictions of classical physics and the predictions of special relativity?

A. The kinetic energy of objects will always be larger using the predictions of classical physics compared to the predictions of special relativity.

B. Classical physics predicts that the speed of light in a vacuum is always c, while special relativity predicts that objects can travel faster than c.

C. Classical physics predicts space and time are absolute, while special relativity predicts that measurements of space and time depend on the frame of reference of the observer.

D. Classical physics predicts measurements of space and time are relative to the frame of reference of the observer, while special relativity predicts that space and time are absolute.

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Theory summary

- An inertial frame of reference is a non-accelerating perspective from which measurements can be made.
- Einstein's first postulate states that the laws of physics are the same for all inertial frames of reference.
- Einstein's second postulate states that the speed of light is the same for all observers, regardless of their motion or the motion of the source of the light.
  - This is supported by the results of the Michelson-Morely experiment that measured light to always travel at the speed *c*, regardless of the Earth's motion.
- Special relativity makes different predictions to classical physics.
  - Measurements of space and time depend on the observer.
  - Relative speeds do not add linearly and cannot exceed *c*.
  - Kinetic energy increases drastically as the speed of an object approaches *c*.
- Classical mechanics is limited when considering motion approaching the speed of light.

11A Questions

Mild 🌶 Medium 🌶🌶 Spicy 🌶🌶🌶

Deconstructed exam-style

Question 10 🌶 (1 MARK)

State Einstein's second postulate of special relativity.

Question 11 🌶 (1 MARK)

How does the motion of an observer affect their measurement of the speed of light, according to classical physics?

Question 12 🌶 (1 MARK)

How does the motion of an observer affect their measurement of the speed of light, according to Einstein's second postulate?

Question 13 🌶🌶🌶 (3 MARKS)

Explain how Einstein's second postulate of special relativity is different from the concept of the speed of light in classical physics.

Adapted from VCAA 2019 exam Short answer Q11

Exam-style

Question 14 🌶 (1 MARK)

Which one of the following is an example of an inertial frame of reference?

A. a bus travelling at constant velocity

B. an express train that is accelerating

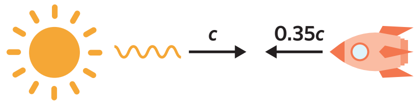
C. a car turning a corner at a constant speed

D. a roller-coaster speeding up while heading down a slope

Adapted from VCAA 2022 exam Multiple choice Q18

Question 15 (1 MARK)

Light emitted from the Sun travels towards a spacecraft at c. The spacecraft is travelling towards the Sun at $0.35c$, when measured in the Sun's frame of reference. At what speed will an observer on the spacecraft measure the light travelling?



A. $0.35c$

B. $0.65c$

C. c

D. $1.35c$

Question 16 (3 MARKS)

Anna believes that any object moving at a constant speed is in an inertial frame of reference. Is she correct? Justify your answer.

Adapted from 2018 VCAA Exam Section B Q14

Question 17 (3 MARKS)

Key science skill

Which of the following statements best describes what the Michelson–Morley experiment attempted to measure?

A. the speed of Earth through space

B. changes in the speed of Earth through space

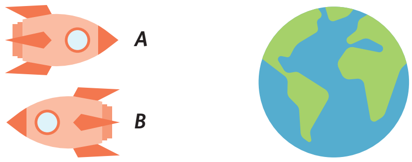
C. accuracy obtainable with an optical interferometer

D. differences in the speed of light in different directions

Adapted from VCAA 2011 Exam 1 Detailed Study 1 Q7

Use the following information to answer questions 18–19.

In deep space, a spaceship, A, is travelling towards the Earth when it passes a second spaceship, B, travelling in the opposite direction with a relative speed of $0.8c$. At this instant, each spaceship sends a light pulse back towards the Earth, which is the same distance from each spaceship.



Question 18 (1 MARK)

Which of the following statements about the arrival time of the light pulse at the Earth is true?

A. Both light pulses arrive at the same time.

B. The light pulse from A arrives before the light pulse from B.

C. The light pulse from B arrives before the light pulse from A.

D. The order of the light pulses arriving at the Earth depends on which reference frame is taking the measurements.

Adapted from VCAA 2011 Exam 1 Detailed Study 1 Q5

Question 19 (2 MARKS)

Given that the spaceships are 6.01×10^{11} m from the Earth (as measured by an observer on Earth) when they send the light pulses, calculate how long the light pulse from spaceship A takes to reach the Earth as measured by an observer on Earth. Give your answer in seconds.

Adapted from VCAA 2010 Exam 1 Detailed Study 1 Q1

Question 20 (3 MARKS)

Key science skill

Explain the result of the Michelson-Morely experiment, and how this supports Einstein's theory of special relativity.

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Question 21 (4 MARKS)

A Year 12 physics class is studying Einstein's theory of special relativity. The teacher provides a thought experiment: Imagine you are travelling at a speed of 2.9×10^8 m s^{-1} alongside a beam of light. What would you measure the speed of the beam of light to be?

Two students put up their hands to offer an answer. Hilary says that you would measure the speed of the beam of light to be 3.0×10^8 m s^{-1}. Ryan says that you would measure the speed of the beam of light to be 0.1×10^8 m s^{-1}.

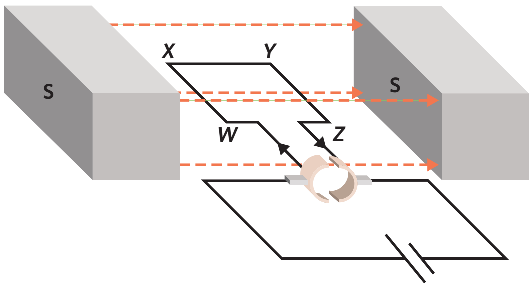
Describe the possible basis of each student's response, and which student is correct.

Adapted from VCAA 2005 Exam 1 Detailed Study 1 Q2

Previous lessons

Question 22 (3 MARKS)

A DC motor is set up using permanent magnets and a split ring commutator. Before the motor is switched on, the coil of the motor is stationary and horizontal (as in the diagram). Explain why the coil begins to rotate when the motor is turned on.



Adapted from VCAA 2014 exam Short answer Q17c

FROM LESSON 4D

Question 23 (3 MARKS)

Ariel walks down a hallway and hears a song coming from an open door on the side of the hallway, but can only hear the bass. As she gets closer to the door, she starts to hear the higher frequencies as well. Use relevant physics to explain what Ariel hears.

FROM LESSON 7E

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11B Length contraction and time dilation

STUDY DESIGN DOT POINTS

- describe proper time (t_0) as the time interval between two events in a reference frame where the two events occur at the same point in space
- describe proper length (L_0) as the length that is measured in the frame of reference in which objects are at rest
- model mathematically time dilation and length contraction at speeds approaching c using the equations: $t = t_0\gamma$ and $L = \frac{L_0}{\gamma}$ where $\gamma = \frac{1}{\sqrt{1 - \frac{v^2}{c^2}}}$

11A 11B 11C 11D

4.1.26.1 The Lorentz factor

4.1.25.1 & 4.1.26.2 Length contraction

4.1.24.1 & 4.1.26.3 Time dilation

ESSENTIAL PRIOR KNOWLEDGE

11A Einstein's postulates

See question 98.

What happens as we approach the speed of light?

As we approach the speed of light, weird things occur to measurements of length and time. This lesson will build on our knowledge of Einstein's postulates, exploring the phenomena of length contraction and time dilation and their effects on the measurement of objects approaching the speed of light.

KEY TERMS AND DEFINITIONS

proper length the length of an object measured in a reference frame where the object is at rest

contracted length the length of an object measured in a reference frame where the object is moving

event something that occurs at a particular location and time

proper time the time interval between two events measured in a reference frame where the two events occur at the same point in space

dilated time the time interval between two events measured in a reference frame where the two events occur at different points in space

FORMULAS

- **the Lorentz factor**
  $\gamma = \frac{1}{\sqrt{1 - \frac{v^2}{c^2}}}$
- **time dilation**
  $t = t_0\gamma$
- **length contraction**
  $L = \frac{L_0}{\gamma}$

The Lorentz factor 4.1.26.1

As an object approaches the speed of light (relativistic speeds), the effects of length contraction and time dilation make the predictions of classical physics less accurate. The Lorentz factor is a dimensionless quantity used to determine the magnitude of these relativistic effects.

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How can we determine the magnitude of relativistic effects?

The Lorentz factor depends on the relative speed between frames of reference. It is used to determine the magnitude of length contraction or time dilation.

The Lorentz factor is calculated using the following formula.

FORMULA

$$\gamma = \frac{1}{\sqrt{1 - \frac{v^2}{c^2}}}$$

γ = Lorentz factor (no units)
v = relative velocity (m s^{-1})
c = speed of light (3.0×10^8 m s^{-1})

USEFUL TIP

The speeds used to calculate the Lorentz factor are often written as a multiple of c (the speed of light). To convert from m s^{-1} to a multiple of c, the value must be divided by 3.0×10^8 (Figure 1). For example, for an object moving at 1.5×10^8 m s^{-1}, its speed can also be written as $\frac{1.5 \times 10^8}{3.0 \times 10^8} = 0.5c$.

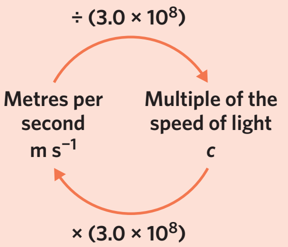

Figure 1 Converting between m s^{-1} and multiples of c

As the relative speed approaches the speed of light, the Lorentz factor approaches infinity (Figure 2). This is why an object with mass can never travel at the speed of light.[1]

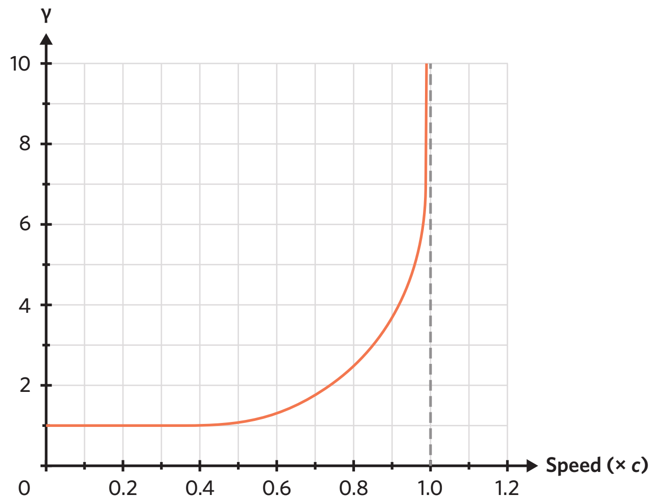

Figure 2 The Lorentz factor increases with speed and approaches infinity as speed approaches c.

For speeds we experience in everyday life, the Lorentz factor is extremely close to one, so there are no observable relativistic effects. Table 1 shows values for the Lorentz factor for objects approaching the speed of light.

USEFUL TIP

An object that is measured to be at rest in a given reference frame has a Lorentz factor of one (in that reference frame), meaning there is no length contraction or time dilation measured.

USEFUL TIP

By rearranging the Lorentz factor formula, the relative speed of an object can be calculated from a known value of γ using $v = c\sqrt{1 - \frac{1}{\gamma^2}}$.

KEEN TO INVESTIGATE?

1 **Why can't we travel at the speed of light?**
Search YouTube: Can you go the speed of light?

USEFUL TIP

An asymptote on a graph is a line that a curve approaches but never reaches. In this case, the asymptote is the speed of light.

Table 1 A table of values showing the Lorentz factor for different speeds

Relative speed ($m\ s^{-1}$)	Relative speed (c)	Lorentz factor (γ)
0	0	1.000
1.5×10^8	0.5	1.155
1.8×10^8	0.6	1.250
2.1×10^8	0.7	1.400
2.4×10^8	0.8	1.667
2.7×10^8	0.9	2.294
2.85×10^8	0.95	3.203
2.97×10^8	0.99	7.089

USEFUL TIP

It can be helpful to have a similar table to Table 1 in your pre-written exam notes so that you can check how appropriate your calculations are for the Lorentz factor.

WORKED EXAMPLE 1

Calculate the Lorentz factor of a meteor travelling with a relative speed of 2.6×10^8 m s^{-1}.

Step 1

Identify known and unknown variables and write down the formula that relates these variables.

$v = 2.6 \times 10^8 \text{ m s}^{-1}, c = 3 \times 10^8 \text{ m s}^{-1}, \gamma = ?$

$$\gamma = \frac{1}{\sqrt{1 - \frac{v^2}{c^2}}}$$

Step 2

Substitute values into the formula and solve for the Lorentz factor.

$$\gamma = \frac{1}{\sqrt{1 - \frac{(2.6 \times 10^8)^2}{(3 \times 10^8)^2}}} = 2.00 = 2.0$$

PROGRESS QUESTIONS

Question 1

As an object with mass approaches *c*, its Lorentz factor approaches

A. 0. **B.** 1. **C.** 100. **D.** infinity.

Question 2

The Lorentz factor for an object at rest is

A. −1. **B.** 0. **C.** 1. **D.** 2.

Question 3

The Lorentz factor for an object travelling at 2.67×10^8 m s^{-1} is closest to

A. 2.1. **B.** 2.2. **C.** 9.1. **D.** 9.2.

Length contraction 4.1.25.1 & 4.1.26.2

Due to the effects of special relativity, observers in reference frames which are moving relative to each other will measure different lengths for the same object.

How is our measurement of length affected as we approach the speed of light?

The **proper length**, or rest length, L_0, describes the length of an object measured by an observer who is at rest relative to the object. This is the length measured by an observer who is in the same reference frame as the object being measured.

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The **contracted length** describes the length of an object as measured by an observer who is moving relative to the object. This observer will measure the object to be shorter in its relative direction of motion. It is important to understand that the contracted length is still a correct measurement – in this sense the term 'proper length' can be misleading.

Consider the relative motion of a train moving past a stationary platform shown in Figure 3. Remember that speed is relative, and so a person on the train and a person on the platform (who are both in inertial frames of reference) can both claim to be at rest while the other is in motion:

- A person on the train would see the platform moving past them.
- A person on the platform would see the train moving past them.

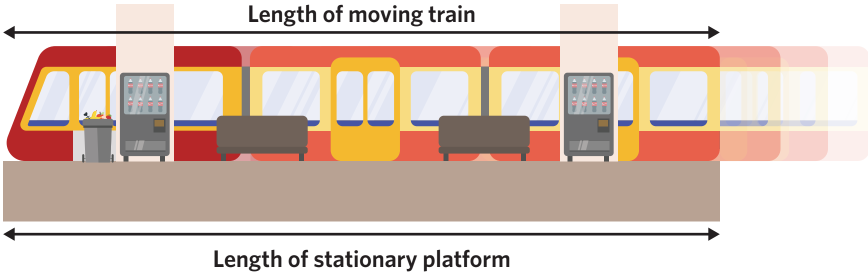


Figure 3 A person on the platform would measure the contracted length of the train moving past them.

For measurements of the length of the train:

- A person on the train measures the proper length, L_0, because the front and back of the train are at rest relative to them – they are measuring the length of the train from a frame of reference in which the train is stationary.
- A person on the platform measures a contracted length, L, because the front and back of the train are moving relative to them– they are measuring the length of the train from a frame of reference in which the train is moving.

Now compare this with measurements of the length of the platform:

- A person on the train measures a contracted length, L, because the front and back of the platform are moving relative to them – they are measuring the length of the platform from a frame of reference in which the platform is moving.
- A person on the platform measures the proper length, L_0, because the front and back of the platform are at rest relative to them – they are in a frame of reference in which the platform is stationary.

The relationship between proper length and the contracted length measured by an observer in a different reference frame is given by the following formula.

FORMULA

$$L = \frac{L_0}{\gamma}$$

L = contracted length (m)
L_0 = proper length (m)
γ = Lorentz factor (no units)

There are some important points to emphasise here:

- Length contraction occurs only in the direction of motion (Figure 4).
- The contracted length, L, is always shorter than the proper length, L_0.
- The proper length is measured if the object is at rest relative to the observer, while the contracted length is measured if the object is in motion relative to the observer.
- Two observers in frames of reference moving relative to each other agree on the relative speed, v, but they may disagree about which reference frame is moving.

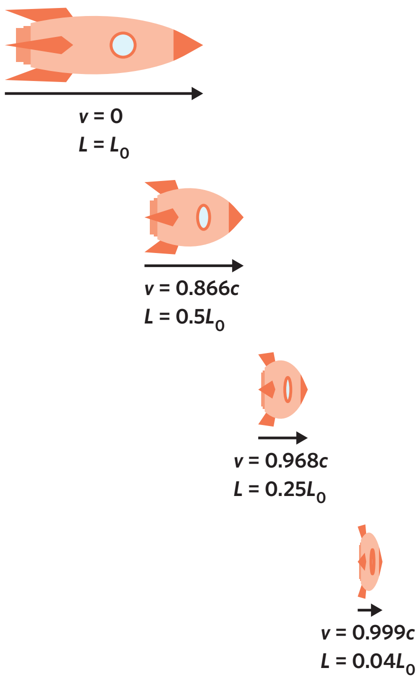
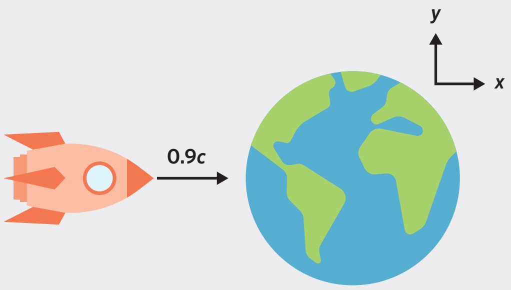


Figure 4 As the relative velocity of the rocket increases, the length of the rocket, as measured by a stationary observer, decreases in the direction of motion. Its measured height, in this case, remains the same.

WORKED EXAMPLE 2

A spaceship is travelling towards Earth at 0.9c, as shown in the diagram. An astronaut on board the spaceship and an observer on Earth both measure the length of the spaceship and the diameter of the Earth in the x-direction.

Take the Earth's diameter to be 1.3×10^7 m as measured by the observer on Earth.



a. Does the astronaut or the observer measure the proper length of the spaceship?

Breakdown

State whose reference frame is at rest relative to spaceship.

Answer

The astronaut – the front and back of the spaceship are at rest relative to the astronaut.

b. Who measures the proper length (diameter in the x-direction) of the Earth?

Breakdown

State whose reference frame is at rest relative to the Earth.

Answer

The observer on Earth – both ends of the Earth are at rest relative to the observer.

c. What is the diameter of the Earth in the x-direction as measured by the astronaut?

Step 1

Identify known and unknown variables and write down the formula that relates these variables.

Note that the astronaut measures a contracted diameter in the x-direction because the Earth is moving relative to the astronaut.

$v = 0.9c$, $c = 3 \times 10^8$ m s^{-1}, $\gamma = ?$

$$\gamma = \frac{1}{\sqrt{1 - \frac{v^2}{c^2}}}$$

Step 2

Substitute values into the formula and solve for the Lorentz factor.

$$\gamma = \frac{1}{\sqrt{1 - \frac{(0.9c)^2}{c^2}}} = \frac{1}{\sqrt{1 - 0.9^2}} = 2.294$$

Step 3

Identify known and unknown variables and write down the formula that relates these variables.

$\gamma = 2.294$, $L_0 = 1.3 \times 10^7$ m, $L = ?$

$$L = \frac{L_0}{\gamma}$$

Step 4

Substitute values into the formula and solve for the length of the Earth as measured by the astronaut.

$$L = \frac{1.3 \times 10^7}{2.294} = 5.7 \times 10^6 \text{ m}$$

d. What is the diameter of the Earth in the y-direction as measured by the astronaut?

Breakdown

Identify that the astronaut and the observer will agree on the diameter of the Earth in the y-direction, since the astronaut and the observer are both stationary relative to the diameter of the Earth in the y-direction.

Answer

The diameter of the Earth in the y-direction will be 1.3×10^7 m.

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PROGRESS QUESTIONS

Question 4

Proper length is best defined as

A. dependent on an observer's frame of reference.

B. the length as measured by an observer in motion.

C. the shortest possible length that an observer measures an object to be.

D. the length that is measured in the frame of reference in which the object is at rest.

Question 5

A satellite and a space station are moving at relativistic speeds relative to each other. In which reference frame will the contracted length of the satellite be measured?

A. the satellite's reference frame

B. the space station's reference frame

C. There is not enough information to tell.

D. The contracted length will be measured to be the same in both reference frames.

Question 6

An astronaut on the Moon spots a comet travelling past and calculates its Lorentz factor to be 4.9. They measure the length of the comet's tail to be 2.6×10^9 m. Which option is closest to the length of the comet's tail as measured in the reference frame of the comet?

A. 1.3×10^8 m **B.** 5.3×10^8 m **C.** 2.6×10^9 m **D.** 1.3×10^{10} m

Time dilation 4.1.24.1 & 4.1.26.3

Observers in reference frames which are moving relative to each other will measure different time intervals between the same two **events**. **Proper time** refers to the time interval between two events measured by an observer for whom the two events occur at the same location in space. An observer in a reference frame moving relative to the two events will measure a dilated (greater) time interval between the same two events.

How is our measurement of time affected as we approach the speed of light?

Proper time is the time interval between two events, as measured by an observer for whom the two events occur at the same location in space. An event is something that occurs at a particular location and time. Examples of events include:

- a rocket arriving on the surface of a planet
- a clock hand striking 12
- a collision between two vehicles

Consider the relative motion of a train moving past a stationary platform shown in Figure 5. Now consider a clock at the start of the platform measuring the time between two events – the front of the train and the back of the train passing it. Similarly, two synchronised clocks, one at the front of the train and one at the back of the train, measure the same two events. For the time between the two events:

- The clock on the platform measures the proper time, t_0, because the two events occur at the same location in space – as the train moves past it, the front and back of the train are both at the start of the platform.
- The clocks on the train measure the **dilated time**, t, because the two events happen at different locations in space – as the platform moves past the train, the front of the train and back of the train are in two different locations.

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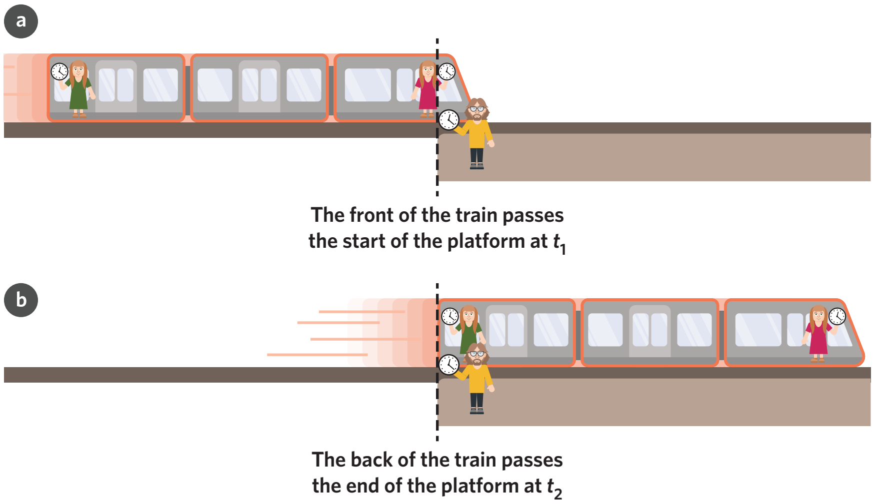

Figure 5 A person on the platform would measure the proper time between **(a)** the front of the train passing the start of the platform and **(b)** the back of the train passing the start of the platform.

Figure 6 An observer on Earth would measure the rocket's clock running slower due to time dilation.

KEEN TO INVESTIGATE?

[2] **What is the twin paradox?**
Search YouTube: Einstein's twin paradox explained

Another example to help us understand the effects of time dilation is to measure the time it takes a rocket to travel from Earth to Mars. In order to do this we need to measure the time between two events – the rocket leaving Earth and the rocket arriving on Mars. For the sake of this example we will consider Earth and Mars to be stationary relative to each other and to both have perfectly synchronised clocks (Figure 6).

- The clock on the rocket measures proper time, t_0, because the two events occur at the same location in space:
  - From the rocket's frame of reference it remains stationary while Earth and Mars move past it.
  - Therefore the rocket leaving Earth and arriving on Mars both happen at the same location in space – the rocket.
- The clocks on Earth and Mars measure the **dilated time**, t, because the two events occur at different locations in space:
  - From Earth and Mars' frame of reference they remain stationary while the rocket travels between them.
  - Therefore the rocket leaving Earth and arriving on Mars happens in two locations in space – Earth and Mars.

It's important to note that:

- All clocks are functioning normally in their respective frames of reference.
- All observers measure clocks in their frame of reference as ticking at a normal rate.
- Observers on Earth and Mars would measure the clock on the rocket as ticking slower due to time dilation.[2]
- Observers on the rocket would measure the clocks on Earth and Mars as ticking slower due to time dilation.

STRATEGY

Since either frame of reference can be considered stationary or moving, thinking about time dilation as 'moving clocks tick slower' can often lead to confusion. A convenient way to think about time dilation problems is to imagine two synchronised clocks at rest at the locations of the two events (like Earth and Mars), and compare their time to a single clock on the object moving relative to them (like the rocket). Then we can say:

- The single clock will measure proper time, t_0, as the events occur at the same location.
- The two clocks will measure dilated time, t, as the events occur at different locations.

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The relationship between proper time and the dilated time is given by the following equation.

FORMULA

$$t = t_0\gamma$$

t = dilated time (s)
t_0 = proper time (s)
γ = Lorentz factor (no units)

USEFUL TIP

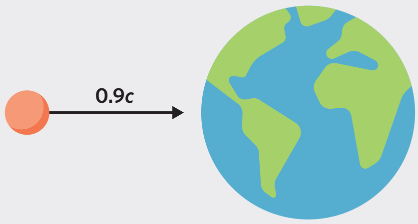
To dilate means to stretch or to make something bigger. To contract means to squeeze or make something smaller. Therefore, by associating time with dilation and length with contraction, we can remember that as the Lorentz factor increases, dilated time is measured to be greater and contracted length is measured to be shorter.

There are some important points to emphasise here:

- The dilated time is always greater than the proper time.
- Which observer measures proper time depends on the events being measured.
- The ordinary formula for calculating speed ($v = \frac{\Delta s}{\Delta t}$) still applies as long as the distance and time measurements are made in the same reference frame.

WORKED EXAMPLE 3

A particle is travelling directly towards Earth at 0.9c. In Earth's frame of reference, the particle is created and then decays within 8.1 s.



a. Explain whether observers on Earth measure the proper time for the life of the particle.

Breakdown	Answer
Identify the two time events.	The two events are creation of the particle and decay of the particle
Identify if the two events occur in the same location or not.	In the Earth's frame of reference these two events occur at different locations.
Determine whether the observers on Earth measure proper time or not.	The observers on Earth do not measure proper time.

b. Calculate the lifetime of the particle as measured in its own reference frame.

Step 1

Identify known and unknown variables and write down the formula that relates these variables.

$v = 0.9c\ \text{m s}^{-1}, c = 3 \times 10^8\ \text{m s}^{-1}, \gamma = ?$

$$\gamma = \frac{1}{\sqrt{1 - \frac{v^2}{c^2}}}$$

Step 2

Substitute values into the formula and solve for the Lorentz factor.

$$\gamma = \frac{1}{\sqrt{1 - \frac{(0.9c)^2}{c^2}}} = \frac{1}{\sqrt{1 - 0.9^2}} = 2.294$$

Step 3

Identify known and unknown variables and write down the formula that relates these variables.

$\gamma = 2.294, t = 8.1\ \text{s}, t_0 = ?$

$t = t_0\gamma$

Step 4

Substitute values into the formula and solve for the lifetime of the particle as measured in its own reference frame.

$8.1 = t_0 \times 2.294 \Rightarrow t_0 = \frac{8.1}{2.294}$

$t_0 = 3.5\ \text{s}$

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PROGRESS QUESTIONS

Question 7

Proper time is best defined as

A. the time between two events within the observer's frame of reference.

B. the time interval between two events in the reference frame of a stationary observer.

C. the longest possible time interval between two events that any observer can measure.

D. the time interval between two events, as measured in a reference frame where the two events occur at the same point in space.

Question 8

Celeste, who is in a UFO travelling at a constant velocity, and Luna, who is camped on the moon, both measure the time it takes for Celeste to fly the width of the Moon. Who would measure the proper time for the event?

A. Luna

B. Celeste

C. Both would be able to measure the proper time.

D. Neither would be able to measure the proper time.

Question 9

A mystical school bus passes Mr Frazzle at speed such that $\gamma = 1.2$. The proper time it takes for a student on the bus to throw a ball vertically up and catch it again is measured as 1.9 s. Which of the following options is closest to the dilated time as measured by Mr. Frazzle?

A. 1.2 s

B. 1.6 s

C. 1.9 s

D. 2.3 s

Theory summary

- The Lorentz factor is a dimensionless quantity that quantifies the amount of time dilation and length contraction.
  - $\gamma = \dfrac{1}{\sqrt{1 - \dfrac{v^2}{c^2}}}$
  - For an object at rest with respect to an observer, its Lorentz factor is 1.
  - The Lorentz factor approaches infinity as an object's relative velocity approaches the speed of light.
- Proper length, L_0, is the length that is measured in the frame of reference in which the object being measured is at rest.
- Contracted length is the length that is measured from a frame of reference moving relative to the object being measured, and is always shorter than the proper length.
  - It can be calculated using: $L = \dfrac{L_0}{\gamma}$.
- Proper time, t_0, is the time interval between two events in a reference frame where the two events occur at the same point in space.
- Dilated time is the time interval between two events measured from a frame of reference where the two events occur at different locations, and is always greater than the proper time.
  - It can be calculated using: $t = t_0\gamma$.

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11B Questions

Mild 🌶 Medium 🌶🌶 Spicy 🌶🌶🌶

Deconstructed exam-style

Use the following information to answer questions 10–13.

An exoplanet orbits its star five times in 24 hours as measured by scientists on Earth. The star is travelling towards Earth at 0.78*c*.

Question 10 🌶 (1 MARK)

Which of the following is the best estimate for the period of the orbit, as measured by the scientist?

A. 3.6 hours **B.** 4.8 hours **C.** 5.0 hours **D.** 24 hours

Question 11 🌶 (1 MARK)

The Lorentz factor for the star moving at this relative velocity is closest to

A. 1.2. **B.** 1.4. **C.** 1.6. **D.** 1.8.

Question 12 🌶 (1 MARK)

Identify whether the period of the planet's orbit measured by the scientists is proper time or dilated time.

Question 13 🌶🌶 (3 MARKS)

Calculate how long it takes the planet to orbit, in the star's frame of reference. Give your answer in hours.

Adapted from VCAA 2018 exam Short answer Q16

Exam-style

Question 14 (4 MARKS)

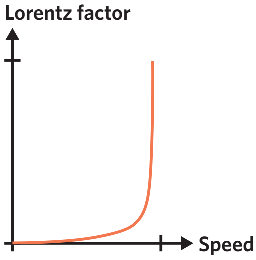
The diagram shows a train moving to the right, at close to the speed of light, past a stationary train platform. Lucy is standing at the left end of the platform.

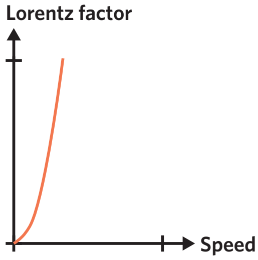
a. Does Lucy measure the proper length of the train? Why or why not? 🌶 2 MARKS

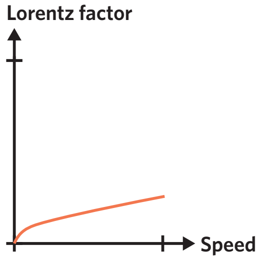
b. Lucy measures the time between the front of the train and the back of the train passing her. Does Lucy measure the proper time for the train to pass? Why or why not? 🌶🌶 2 MARKS

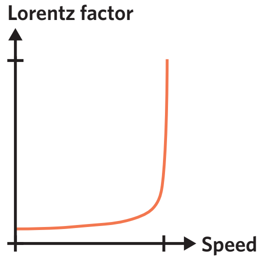
Question 15 (1 MARK)

Which of the following gives the graph of the Lorentz factor against the speed of a spacecraft approaching the speed of light?

A.


B.


C.


D.


Adapted from VCAA 2018 exam Multiple choice Q13

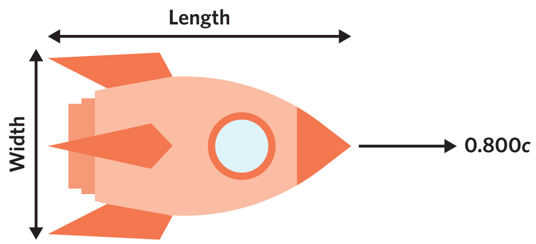
Question 16 (2 MARKS)

A rocket ship is travelling at 2.79×10^8 m s^{-1}. What is the Lorentz factor of the rocket?

Adapted from VCAA 2022 exam Multiple choice Q19

Question 17 (4 MARKS)

A technician on Earth measures the length and width of a spaceship travelling at 0.800*c* relative to Earth. The technician notices that the length of the spaceship does not match the measurements taken when the spaceship was stationary in a laboratory, but the width does.



a. Explain why the technician measures a different length of the spaceship but not a different width. 2 MARKS

b. If the technician measures the spaceship to be 122 m long while travelling at a constant 0.800*c*, calculate the length of the spaceship when it was stationary on Earth. 2 MARKS

Adapted from VCAA 2021 exam Short answer Q10

Question 18 (6 MARKS)

Jemma is attempting to experimentally verify the relationship between time dilation and speed by measuring the time for a certain particle to decay at different speeds. The particle has a lifetime of 2.18×10^{-6} s when measured in its own reference frame.

a. Calculate the lifetime of the particle, as measured by Jemma, when it is travelling at a speed of 0.92*c*. 2 MARKS

b. *Key science skill*

Her results are shown in a table.

Speed (× *c*)	Time to decay (s)
0	2.18×10^{-6}
0.2	2.28×10^{-6}
0.5	2.54×10^{-6}
0.7	2.98×10^{-6}
0.9	5.07×10^{-6}
0.95	7.03×10^{-6}

Plot a graph of time to decay vs. speed. Include an appropriate scale as well as axis labels and units 4 MARKS

FROM LESSON 12D

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Question 19 (3 MARKS)

Two spacecraft are travelling towards each other. Spacecraft 1 has a beacon which flashes once every 5.00 s. An observer on spacecraft 2 detects the pulse periodically flashing every 5.72 s.

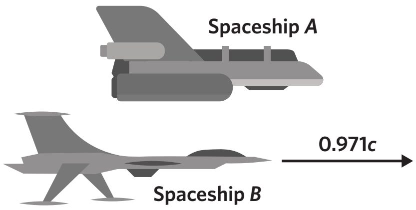
What is the relative speed of the two spacecraft? Give your answer in m s^{-1}.

Question 20 (2 MARKS)

Noor is an observer in Spaceship *A*, watching Spaceship *B* fly past at a relative speed of 0.971*c*.

She measures the length of Spaceship *B* from her frame of reference to be 24 m. Find the proper length of Spaceship *B*.

Adapted from VCAA 2019 exam Multiple choice Q13



Question 21 (3 MARKS)

A train travelling close to the speed of light passes a stationary observer standing on the side of the track. The observer measures the train's length as 114 m. A passenger on the train measures the train's length as 446 m. What is the relative speed between the train and the observer? Give your answer in m s^{-1}.

Adapted from VCAA 2017 exam Short answer Q10

Question 22 (1 MARK)

A UFO is travelling towards Earth at 0.5*c* ($\gamma = 1.155$). A rocket is travelling towards the same UFO with a speed of 0.7*c* ($\gamma = 1.400$) relative to the UFO. The rocket is 30.00 m long when measured in its own reference frame. What is the rocket's length when measured from the UFO's reference frame?

A. 11.74 m

B. 21.43 m

C. 25.97 m

D. 30.00 m

Question 23 (3 MARKS)

Scientists created a particle travelling at 0.9967*c* relative to them. They measure it travelling a distance of 1.42×10^{-2} m in a straight line before decaying. The particle is not accelerating.

a. ***Key science skill***
Identify whether the distance measured is qualitative or quantitative. 1 MARK

FROM LESSON 12A

b. Calculate the lifetime of the particle in the scientists' frame of reference. 2 MARKS

Adapted from 2017 VCAA Exam Section B Q11a

Previous lessons

Question 24 (1 MARK)

As viewed from the split ring commutator, in which direction will the force on *AB* act?

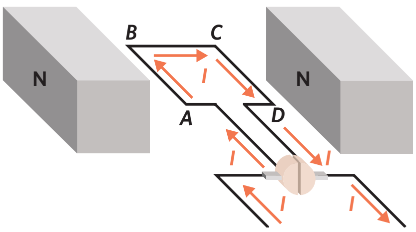
A. left

B. right

C. upwards

D. downwards

FROM LESSON 4D



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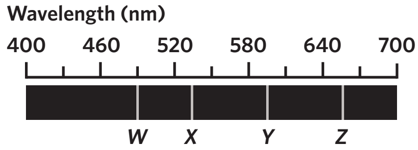
Question 25 (1 MARK)

The vertical lines in the diagram show the wavelengths of light which a carbon atom can emit. The following list are the visible colours emitted by the carbon atom.



- yellow
- red
- blue
- blue-green
- green
- green-yellow

Which band represents the yellow emission?

A. *W*

B. *X*

C. *Y*

D. *Z*

Adapted from 2018 VCAA Exam Section B Q19a

FROM LESSON 8A

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11C Relativity examples

Image: Andrei Armiagov/Shutterstock.com

How do GPS satellites account for the effects of special relativity?

Although GPS satellites do not travel at close to the speed of light, their high degree of accuracy means that the effects of special relativity need to be accounted for to correct the measurement of their time signals. The effects of special relativity must also be taken into account when designing particle accelerators and explaining the experimental observations of high speed muons.

STUDY DESIGN DOT POINT

- explain and analyse examples of special relativity including that:
  - muons can reach Earth even though their half-lives would suggest that they should decay in the upper atmosphere
  - particle accelerator lengths must be designed to take the effects of special relativity into account
  - time signals from GPS satellites must be corrected for the effects of special relativity due to their orbital velocity

11A 11B **11C** 11D

- 4.1.27.1 Muon detection as evidence of the effect of special relativity
- 4.1.27.2 The effects of special relativity in particle accelerators
- 4.1.27.3 GPS time signals

ESSENTIAL PRIOR KNOWLEDGE

11B Lorentz factor

11B Time dilation and length contraction

See questions 99–100.

KEY TERMS AND DEFINITIONS

muon an unstable subatomic particle

half-life the average time it takes for half the particles in a sample to decay

particle accelerator a machine used to accelerate charged particles

GPS satellites a group of satellites that send and receive signals to accurately determine a location on Earth

FORMULAS

- **the Lorentz factor**
  $\gamma = \frac{1}{\sqrt{1 - \frac{v^2}{c^2}}}$
- **time dilation**
  $t = t_0\gamma$
- **length contraction**
  $L = \frac{L_0}{\gamma}$

Muon detection as evidence of the effect of special relativity 4.1.27.1

Muons are subatomic particles that are created high in the Earth's atmosphere, when cosmic rays collide with atoms in the air. They travel at close to the speed of light. The detection of muons at the surface of the Earth is explained by the effects of special relativity.

KEEN TO INVESTIGATE?

[1] **Why do particles decay?**
Search: Why do most particles decay

Why do more muons reach the ground than classical physics predicts?

Muons are unstable and have a **half-life** of 1.56 μs – after 1.56 μs we would expect half of the initial number of muons present to have decayed.[1] We will examine the effects of special relativity on a muon travelling at approximately $0.99c$ ($\gamma = 7.1$), created at the top of a mountain 10 km high.

- According to classical physics it would take a muon $t = \frac{d}{v} = \frac{10 \times 10^3}{0.99 \times (3.0 \times 10^8)} = 34$ μs to reach the bottom of the mountain.
- As this is significantly greater than the half-life of a muon, classical physics predicts that the vast majority of muons would decay before they reach the bottom.

In order to analyse the effects of special relativity on the lifetime of the muon we will consider two events:

1. The muon being created at the top of the mountain.
2. The muon being detected by a scientist at the bottom of the mountain.

In the frame of reference of the scientist:

- The two events are stationary and the muon travels between them (Figure 1).
- The scientist measures the proper length, $L_0 = 10$ km, for the height of the mountain, since the two events are stationary relative to the scientist.
- The scientist measures a dilated time, $t = 11$ μs, for the lifetime of the muon, as the two events occur at different locations in space – the top and bottom of the mountain (can also be thought of as two clocks, one at the top and one at the bottom, measuring dilated time).

So in the frame of reference of the scientist at the bottom of the mountain, more muons are detected than classical physics predicts because time dilation increases their lifetime.

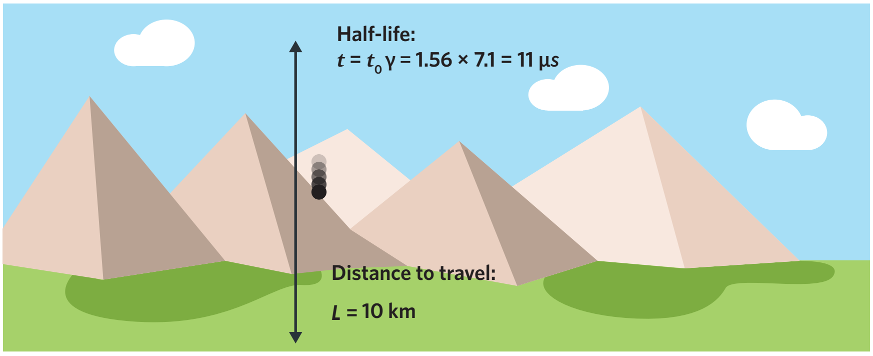

Figure 1 Muon decay, from the reference frame of an observer on Earth

In the frame of reference of the muon:

- The muon is stationary and the mountain moves past it (Figure 2).
- The muon measures a contracted length, $L = 1.4$ km, for the height of the mountain, as the mountain is moving relative to it.
- The muon measures the proper time for its own lifetime, $t_0 = 1.56$ μs, as the two events occur at the same location in space – the muon (can also be thought of as one clock measuring proper time).

So in the frame of reference of a muon, more muons are detected than classical physics predicts because the height of the mountain is contracted.

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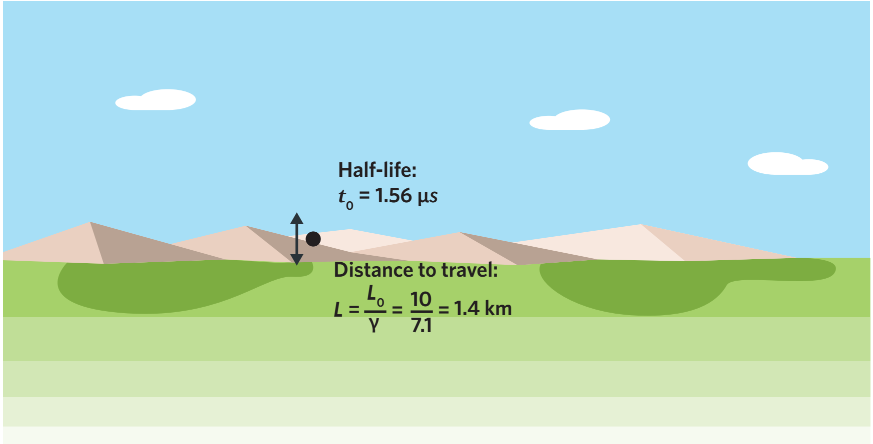

Figure 2 Muon decay, from the reference frame of a muon

Table 1 summarises the half-life of the muons travelling at 0.99c relative to Earth, the height of the mountain, and the percentage expected to survive by the time they reach the bottom of the mountain from both a classical and relativistic perspective.

Note that the number of half-lives passed is given by $\frac{\text{time to reach ground}}{\text{half-life}}$.

Table 1 Non-relativistic and relativistic predictions of the number of muons travelling with a Lorentz factor of 7.1 relative to Earth

	Classical prediction	Scientist in Earth's frame of reference	Muon's frame of reference
Height of mountain	10 km	10 km	1.4 km
Half-life	1.56 μs	11 μs	1.56 μs
Half-lives passed	22	3.0	3.0
Percentage that reach the bottom of the mountain without decaying	3.2×10^{-5} %	12%	12%

We can see that when the effects of special relativity are accounted for, a much higher percentage of muons (12%) are able to reach the surface of the Earth than classical physics predicts (3.2×10^{-5} %).

WORKED EXAMPLE 1

A scientist in a hot air balloon 14 km above another scientist on the surface of Earth, detects a muon with a half-life of 1.56 μs travelling between them. The muon travels at a speed such that its Lorentz factor is $\gamma = 8.4$ relative to the scientists.

a. Calculate the distance between the scientists, as measured from the muon's frame of reference.

Step 1

Identify known and unknown variables and write down the formula that relates these variables.

Note that the distance between the scientists is contracted in the muon's frame of reference.

$L_0 = 14$ km, $\gamma = 8.4$, $L = ?$

$$L = \frac{L_0}{\gamma}$$

Step 2

Substitute values into the formula and solve for the distance between the scientists as measured from the muon's frame of reference.

$$L = \frac{14}{8.4}$$

$L = 1.67 = 1.7$ km

Continues →

b. Explain why the muon is more likely to reach the scientist on the ground than classical physics predicts, from the frame of reference of the muon.

Breakdown	Answer
Explain that the effects of special relativity are responsible for the muon being more likely to reach the ground.	The effects of special relativity in the muon's frame of reference is responsible for the muon being more likely to reach the scientist on the ground than classical physics predicts.
Explain that the distance between the two scientists, as measured by the muon in its frame of reference, is contracted.	Due to the muon's velocity, the distance between the two scientists it measures, in its frame of reference, is contracted.
Relate the contraction of the distance between the scientists in the frame of reference of the muon, to a decrease in the likelihood the muon decays before reaching the scientist on the ground.	Because the distance between the scientists is contracted, it takes less time for the two scientists to travel past the muon, therefore the muon is less likely to decay before being detected by the scientist on the ground.

c. Explain why the muon is more likely to reach the ground than classical physics predicts, from the frame of reference of the scientists.

Breakdown	Answer
Explain that the effects of special relativity are responsible for the muon being more likely to reach the ground.	The effects of special relativity in the scientists' frame of reference is responsible for the muon being more likely to reach the ground than classical physics predicts.
Explain why the half-life of the muon is increased in the frame of reference of the scientists.	Due to the muon's relative velocity, the time measured for its half-life is dilated in the scientists' frame of reference.
Relate the increase in half-life of the muon, in the frame of reference of the scientists, to an increase in the likelihood the muon reaches the scientist on the ground.	Therefore the muon is less likely to decay by the time it reaches the scientist on the ground, as it has a longer half-life when measured from the scientists' frame of reference than classical physics predicts.

PROGRESS QUESTIONS

Question 1

The explanation as to why more muons reach the ground than classical physics predicts is that

A. classical physics accounts for the effects of general relativity.

B. classical physics is not able to describe the motion of the muons.

C. as the muons are travelling at relativistic speeds relative to Earth, the effects of special relativity allow more muons to reach the ground.

D. as the muons are travelling at the speed of light relative to Earth, the effects of special relativity allow more muons to reach the ground.

Question 2

12 km above the Earth an equal number of muons are created travelling at $0.97c$ and $0.98c$. Which of the following best describes the number of muons that will reach the Earth?

A. No muons will reach the Earth, as they will all decay before they are able to.

B. More muons travelling at $0.97c$ will reach the surface of the Earth than muons travelling at $0.98c$.

C. More muons travelling at $0.98c$ will reach the surface of the Earth than muons travelling at $0.97c$.

D. An equal number of muons travelling at $0.97c$ will reach the surface of the Earth as muons travelling at $0.98c$.

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The effects of special relativity in particle accelerators 4.1.27.2

Particle accelerators accelerate charged particles, like electrons or protons.

How do the effects of special relativity affect the design of particle accelerators?

We can look at the length of the Stanford linear accelerator (Figure 3) from the frame of reference of an observer on Earth, or the perspective of a particle travelling the length of the particle accelerator at a relative speed of 0.998c ($\gamma = 16$).

In the frame of reference on a stationary observer on Earth:

- The length of the particle accelerator is its proper length, $L_0 = 3.2$ km, as the particle accelerator is at rest relative to the observer.

In the frame of reference of the particle:

- The length of the particle accelerator is contracted, $L = 0.2$ km, as the particle accelerator is moving relative to the particle.

The straight sections of particle accelerators must be long enough for research purposes as the length of the accelerator is contracted in the particle's frame of reference. This can result in the design of extremely long particle accelerators.

Some particle accelerators include sections that are curved and sections that are straight. In the frame of reference of a particle travelling at constant relativistic speed, the length of the straight sections are contracted due to their velocity relative to the particle.

Figure 3 An aerial photo of the Stanford Linear Accelerator

USEFUL TIP

The discussion of particles undergoing circular motion at relativistic speeds is outside the scope of the VCE Physics study design.[2]

KEEN TO INVESTIGATE?

[2] **How does relativity affect the motion of a particle travelling in a circular path?**
Search: Particle accelerators that are circular

WORKED EXAMPLE 2

A particle accelerator is being designed to conduct research on electrons travelling at $0.995c$ ($\gamma = 10$) relative to it. Scientists require the length of the accelerator to be 350 m when measured from the electron's frame of reference. Determine how long the scientists need to build the accelerator.

Step 1

Identify known and unknown variables and write down the formula that relates these variables.

Note that the length of the particle accelerator is contracted from the electron's frame of reference.

$L = 350$ m, $\gamma = 10$, $L_0 = ?$

$$L = \frac{L_0}{\gamma}$$

Step 2

Substitute values into the formula and solve for the length of the particle accelerator, in the frame of reference of the scientist.

$$350 = \frac{L_0}{10}$$

$$L_0 = 3500 = 3.5 \times 10^3 \text{ m}$$

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PROGRESS QUESTIONS

Question 3

A linear accelerator must be designed to be longer than predicted by classical physics as

A. the length of the accelerator is shorter due to the rotation of the Earth.

B. the length of the accelerator is shorter when measured from the accelerator's frame of reference.

C. the length of the accelerator is shorter when measured from the frame of reference of a particle moving relative to it.

D. the length of the accelerator is longer when measured from the frame of reference of a particle moving relative to it.

Question 4

A linear accelerator is built 5675 m long. If a proton travels the length of the accelerator at 0.999c ($\gamma = 22$) relative to it, determine the length of the linear accelerator in the proton's frame of reference.

A. 1.8×10^2 m **B.** 2.6×10^2 m **C.** 5.7×10^3 m **D.** 1.2×10^5 m

GPS time signals 4.1.27.3

GPS satellites are a group of satellites which emit and receive signals to determine the location of objects on Earth.

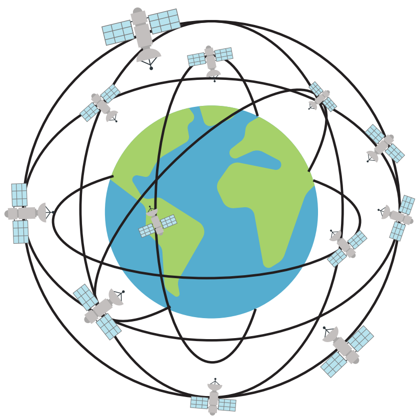

Figure 4 A network of GPS satellites orbiting the Earth

How must time signals from GPS satellites be corrected to account for special relativity?

There are many GPS satellites that orbit the Earth at approximately 3.9×10^{3} m s^{-1} (Figure 4). This gives them a Lorentz factor of just $\gamma = 1.00000000085 = 1 + 8.5 \times 10^{-11}$. In many applications, this Lorentz factor would be negligible, but GPS signals require a high degree of accuracy to locate objects reliably.

Three GPS satellites receive the same signal from someone on Earth. By comparing how long each signal takes to reach each satellite, the location of the person can be determined within an accuracy of 5 m (Figure 5).

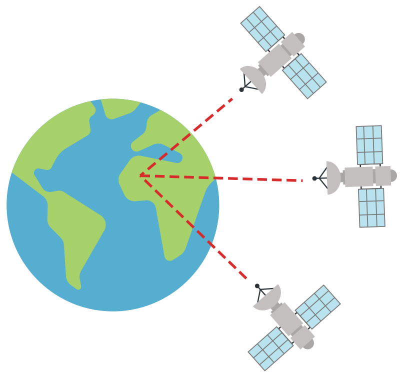

Figure 5 Three GPS satellites receiving a signal from Earth

Let's consider a GPS satellite and person on Earth both measuring the time it takes the satellite to travel from directly above Melbourne to directly above Geelong. Assume the satellite is travelling at 3.9×10^3 m s^{-1} in a straight line relative to the person on Earth. We can consider two events:

- The satellite leaving a point directly above Melbourne.
- The satellite arriving at a point directly above Geelong.

In the frame of reference of the person on Earth:

- The person measures a dilated time, t, as the two events occur at two different locations in space – above Melbourne and above Geelong (can be thought of as two clocks).

In the frame of reference of the GPS satellite:

- The satellite measures the proper time, t_0, as the two events occur at the same location in space – the satellite (can be thought of as one clock).

So from the frame of reference of the person on Earth, less time has passed on the satellite's clock. Table 2 shows an example of this difference in time over the course of a day. Assume that special relativity is the only factor causing a difference in measured time between the clocks.

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Table 2 An example of the difference in time passed between a clock on the Earth and onboard a GPS satellite.

the length of a day on the GPS satellite as measured by a clock on the GPS satellite.	$t_0 = 86400$ s
Lorentz factor of GPE satellite travelling at 3.9×10^3 m s^{-1} in a straight line relative to Earth.	$\gamma_{GPS} = 1.000000000085 = 1 + 8.5 \times 10^{-11}$
the length of a day on the GPS satellite as measured by a clock on Earth.	$t = t_0 \gamma_{GPS}$ $t = 86400 \times 1.000000000085$ $t = 86400.0000073$ s
Time difference	$diff = t - t_0$ $diff = 86400.0000073 - 86400$ $diff = 7.30 \times 10^{-6} = 7.30$ μs

This difference of 7.3 μs a day (or 2.7 ms a year) would significantly affect the ability of a GPS satellite to measure the location of a signal accurately. To correct for this difference, the clocks on board GPS satellites could be corrected to tick at a quicker rate than clocks on the Earth, so that the time signals received on Earth from GPS satellites are accurate in the reference frame of a stationary observer on the Earth. In reality GPS satellites orbiting Earth have other factors affecting their clocks, but these are outside the scope of the VCE Physics study design.[3]

KEEN TO INVESTIGATE?

[3] **How are the clocks on GPS satellites corrected for the effects of relativity**
Search: Real-World Relativity: The GPS navigation system

WORKED EXAMPLE 3

The International Space Station (ISS) orbits the Earth at 8.48×10^6 m s^{-1} ($\gamma = 1.0004$). After a full week has passed according to the clocks on the ISS ($t = 6.05 \times 10^5$ s), determine the difference in time between a stationary clock on Earth and the clock on the ISS due to the effects of special relativity. Assume the effects of special relativity apply to the ISS.

Step 1

Identify known and unknown variables and write down the formula that relates these variables.

Note that an observer on Earth will measure a dilated time as the two events occur at different locations in space.

$t_0 = 6.05 \times 10^5$ s, $\gamma = 1.0004$, $t = ?$

$t = t_0 \gamma$

Step 2

Substitute values into the formula and solve for the time measured by the observer on Earth.

$t = 6.05 \times 10^5 \times 1.0004$

$t = 6.05242 \times 10^5$ s

Step 3

Calculate the difference in time.

$t_{diff} = t - t_0$

$t_{diff} = 6.05242 \times 10^5 - 6.05 \times 10^5$

$t_{diff} = 242$ s

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PROGRESS QUESTIONS

Question 5

The best description of a GPS satellite is

A. a satellite orbiting the Earth at a high speed, that measures the distance a signal travels from the Earth to itself.

B. a satellite orbiting the Earth at a high speed, that measures the time it takes for signals to travel from Earth to itself.

C. a satellite orbiting the Earth at close to the speed of light, that measures the distance a signal travels from the Earth to itself.

D. a satellite orbiting the Earth at close to the speed of light, that measures the time it takes for signals to travel from Earth to itself.

Question 6

A clock onboard a GPS satellite must be corrected for the effects of special relativity because

A. regular clocks do not function onboard GPS satellites due to effects of special relativity.

B. clocks on GPS satellites run faster compared with clocks on Earth due to effects of special relativity.

C. clocks on GPS satellites run slower compared with clocks on Earth due to effects of special relativity.

D. the distance the GPS satellites travel is contracted in their own frame of reference due to effects of special relativity.

Theory summary

Example	Effects of special relativity	Observation
Muon decay	• The length between the muons' creation and their detection is contracted in the muons' frame of reference. • The half-life of the muons is increased due to time dilation, in the reference frame of an observer on Earth.	Muons are more likely to reach Earth than classical physics predicts.
Length of particle accelerators	The length of the particle accelerator is contracted in the particle's frame of reference.	The length of a particle accelerator must be designed with consideration that from a particle's frame of reference it will only travel a fraction of the designed length, depending on their Lorentz factor.
GPS satellites	A person on Earth measures a dilated time for the time that passes on a GPS satellite.	Clocks on GPS satellites would tick at a slower rate when observed by a stationary observer on Earth due to the effects of special relativity, and so can be designed to tick at a faster rate to correct the difference.

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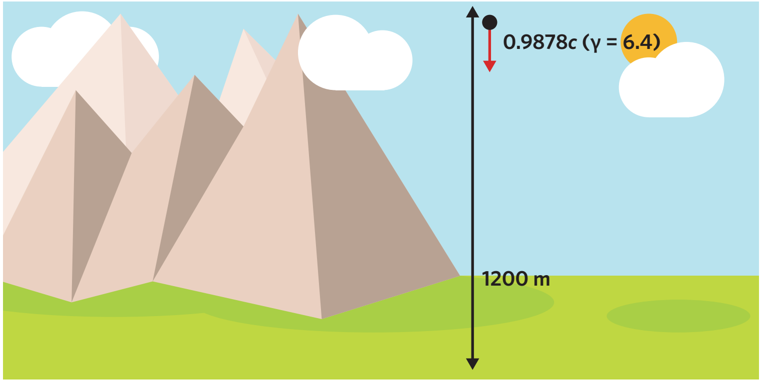
11C Questions

Mild 🌶 Medium 🌶🌶 Spicy 🌶🌶🌶

Deconstructed exam-style

Use the following information to answer questions 7–9.



A muon, with a lifetime of 2.4 s, is produced at the top of a mountain 1200 m high. It travels at $0.9878c$ ($\gamma = 6.4$) relative to Earth.

Question 7 🌶 (1 MARK)

What is the height of the mountain, as measured in the muon's frame of reference?

A. 1.9×10^2 m

B. 1.2×10^3 m

C. 1.9×10^3 m

D. 7.7×10^3 m

Question 8 🌶 (1 MARK)

In the muon's frame of reference, how long does it take to reach the bottom of the mountain?

Question 9 🌶🌶 (3 MARKS)

Determine whether the muon is able to reach the ground before decaying.

Exam-style

Question 10 🌶 (1 MARK)

The average lifetime of stationary muons is measured in a laboratory to be 2.2 μs. The lifetime of relativistic muons produced in Earth's upper atmosphere, as measured by ground-based scientists, is 16 μs. The resulting time dilation observed by the scientists gives a Lorentz factor, γ, of

A. 0.14

B. 1.4

C. 3.5

D. 7.3

Adapted from VCAA 2019 NHT exam Multiple choice Q17

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Question 11 (6 MARKS)

A particular GPS satellite orbits the Earth at an altitude of 20 000 km, with a speed 2.7×10^3 m s^{-1} ($\gamma = 1.00000000004 = 1 + 4 \times 10^{-11}$). An electromagnetic signal from a person on Earth is measured by the GPS satellite to take 6.67×10^{-2} s to reach it.

a. An observer on Earth measures in their own frame of reference how long it takes the satellite to receive the signal. Calculate the difference between the time measured by the observer on Earth and the time measured by the satellite. 🌶🌶 3 MARKS

b. Explain the effects of special relativity on the clocks on GPS satellites and how they need to be adjusted to match the clocks on Earth from Earth's frame of reference. 🌶🌶🌶 3 MARKS

Question 12 (5 MARKS)

Two identical particles with the same half-life are moving through a 2.8 km particle accelerator, as measured by a stationary observer on the Earth. Particle *Y* is travelling at 2.8×10^{8} m s^{-1} ($\gamma = 2.8$) and Particle *Z* is travelling at 2.9×10^8 m s^{-1} ($\gamma = 3.9$).

a. Which row correctly lists the measured length of the particle accelerator, in each different frame of reference? Use calculations to support your answer. 🌶🌶 2 MARKS

	Particle *Y*	Particle *Z*	Stationary scientists
Row 1	1.0 km	0.72 km	2.8 km
Row 2	0.72 km	1.0 km	2.8 km
Row 3	2.8 km	2.8 km	2.8 km
Row 4	7.8 km	11 km	2.8 km

b. *Key science skill*

With reference to the length of the accelerator in each particle's frame of reference, predict whether the scientists are more likely to observe Particle *Y* or Particle *Z* reaching the end of the particle accelerator. 🌶🌶 3 MARKS

FROM LESSON 12A

Question 13 (6 MARKS)

Scientists are studying a set of particles travelling at 0.9997*c* ($\gamma = 41$). For the scientists to analyse their decay, the particles must travel 15 m in their own frame of reference. A private investor has stated that they will provide $65 000 to fund the material required to build the 15 m long particle accelerator.

a. *Key science skill*

Determine whether the private investor has overestimated or underestimated the cost of the material required to create the particle accelerator. 🌶🌶 3 MARKS

FROM LESSON 12A

b. *Key science skill*

The Large Hadron Collider (LHC) took 10 years and cost $4.75 billion to construct. It is also estimated that discovering the Higgs Boson cost a further $13 billion in running costs. However, advancements in particle accelerator technology have resulted in benefits to radiotherapy, touchscreens, and aerospace engineering. Scientists also consider the discovery of the Higgs boson as a leap forward in particle physics that could open the door to new technologies not thought of yet. Evaluate whether the high costs of developing the Large Hadron Collider are worth the potential benefits to society. 🌶🌶🌶 3 MARKS

FROM LESSON 12A

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Use the following information to answer questions 14 and 15.

Pions are particles that are produced by cosmic rays above the surface of the Earth. Pions are unstable particles, with a half-life of 26 ns.

Question 14 (1 MARK)

In which frame of reference will an undilated value of the half-life be observed?

A. in Earth's frame

B. in any inertial frame

C. in each pion's own frame

D. in the frame of the high-energy source of each pion

Adapted from VCAA 2016 exam Detailed Study 1 Q5

Question 15 (3 MARKS)

Consider one pion approaching Earth at a speed of 0.98c. It decays after 26 ns have passed in its own frame of reference. How long did the pion exist as measured in Earth's frame of reference?

Adapted from VCAA 2016 exam Detailed Study 1 Q6

Question 16 (7 MARKS)

The clocks onboard a particular GPS satellite are sped up by 0.23 μs per hour to account for the effects of special relativity.

a. Show that $(\gamma - 1)$, where γ is the Lorentz factor of the GPS satellite relative to the Earth, is 6.4×10^{-11}. 2 MARKS

b. Calculate the speed of the satellite. 2 MARKS

c. Explain the consequences of not accounting for the effects of special relativity on the function of the GPS satellite. 3 MARKS

Question 17 (7 MARKS)

Tests of relativistic time dilation have been made by observing the decay of short-lived particles. A muon, travelling from the edge of the atmosphere to the surface of Earth, is an example of such a particle. To model this in the laboratory, another fundamental particle with a shorter half-life is produced in a particle accelerator. It is travelling at 0.99875c ($\gamma = 20$). Scientists observe that one of these particles travels at 9.14×10^{-5} m in a straight line from one end of the accelerator to the other. It is not accelerating.

a. Calculate the lifetime of the particle in the scientists' frame of reference. 2 MARKS

Adapted from VCAA 2017 exam Short answer Q11a

b. Calculate the length of the accelerator as measured from the particle's frame of reference. 2 MARKS

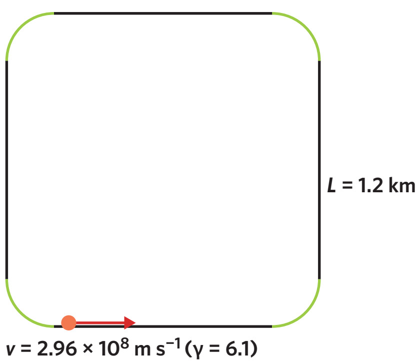
Adapted from VCAA 2017 exam Short answer Q11b

c. Explain why the scientists would observe more particles at the end of the accelerator than classical physics would expect, from the particles' frame of reference. 3 MARKS

Adapted from VCAA 2017 exam Short answer Q11c

Question 18 (4 MARKS)

Scientists are studying a group of identical particles travelling at 2.96×10^8 m s^{-1} ($\gamma = 6.1$) around a particle accelerator. The particle accelerator is made up of four straight sections each built 1.2 km long and four green curved sections shown in the diagram. The particles take 3.8 μs to complete one lap of the particle accelerator in their own frame of reference. Determine the total time taken for the particles to travel around the curved sections of the track, as calculated by the scientists. Assume that time is dilated by the same factor in the straight sections and the curved sections.



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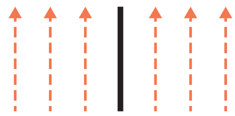
Previous lessons

Question 19 (2 MARKS)

A loop of wire is placed parallel to a magnetic field as shown, and is moved to the right. Describe how the flux through the loop changes. Justify your answer.



FROM LESSON 5A

Question 20 (1 MARK)

Students are recreating Young's double slit experiment, and observe an interference pattern on a screen. The beam is now replaced with light of a lower frequency. The second dark band from the centre of the interference pattern would

A. become narrower.

B. remain in the same position.

C. move closer to the centre of the pattern.

D. move further away from the centre of the pattern.

Adapted from VCAA 2013 exam Short answer Q22b

FROM LESSON 8B

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11D Mass-energy

STUDY DESIGN DOT POINTS

- interpret Einstein's prediction by showing that the total 'mass-energy' of an object is given by: $E_{tot} = E_k + E_0 = \gamma mc^2$ where $E_0 = mc^2$, and where kinetic energy can be calculated by: $E_k = (\gamma - 1)mc^2$
- apply the energy-mass relationship to mass conversion in the Sun, to positron-electron annihilation and to nuclear transformations in particle accelerators (details of the particular nuclear processes are not required)

11A 11B 11C 11D

4.1.28.1 Mass-energy equivalence

4.1.29.1 Conservation of mass-energy

ESSENTIAL PRIOR KNOWLEDGE

11B Lorentz factor

See question 101.

How do nuclear power plants harness energy from atoms?

Energy and mass are equivalent, and a small amount of matter can be exchanged for a tremendous amount of energy. For example, if one gram of mass was entirely converted to energy, it could provide the energy needed for a city for days. This lesson will explore this mass-energy equivalence and how it is responsible for the radiation emitted by stars like the Sun. This lesson will also investigate how the relativistic kinetic energy of an object is different from the predictions of classical physics.

KEY TERMS AND DEFINITIONS

mass-energy equivalence the principle that mass can be considered a form of energy; mass can be converted into energy and energy can be converted into mass

total mass-energy the sum of the kinetic and rest energies of a mass or system

rest energy the energy of an object at rest, equivalent to the energy of its mass

relativistic kinetic energy the kinetic energy of a mass as calculated using special relativity

FORMULAS

- **Lorentz factor**
  $\gamma = \frac{1}{\sqrt{1 - \frac{v^2}{c^2}}}$
- **total mass-energy**
  $E_{tot} = \gamma mc^2$
- **rest mass-energy**
  $E_0 = mc^2$
- **relativistic kinetic energy**
  $KE = (\gamma - 1)mc^2$
- **mass-energy conversion**
  $\Delta E = \Delta mc^2$

Mass-energy equivalence 4.1.28.1

Any mass has an equivalent amount of energy associated with it. This is known as **mass-energy equivalence**. The **total mass-energy** of a mass depends on its rest mass and the speed at which it is moving.

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How can we calculate the energy associated with mass?

The total energy associated with a mass can be found using:

FORMULA

$$E_{tot} = \gamma mc^2$$

E_{tot} = total mass-energy (J)
γ = Lorentz factor (no units)
m = mass of object (kg)
c = speed of light (3.0×10^8 m s^{-1})

USEFUL TIP

As no object can travel faster than the speed of light, it is referred to as the universal speed limit.

In Lesson 11B, we saw that the Lorentz factor approaches infinity as an object approaches the speed of light. We can see from the equation for total mass-energy that if the Lorentz factor approaches infinity, so too will the total mass-energy of the object. Since it is impossible to have infinite energy, no object with mass can reach the speed of light.

When an object is stationary, its Lorentz factor is 1. Substituting this into the formula for total-mass energy, we find that an object's **rest energy** can be found using:

USEFUL TIP

We will use E_0, but E_{rest} can also be used E_0 to represent the rest energy of an object.

FORMULA

$$E_0 = mc^2$$

E_0 = rest energy (J)
m = mass of object (kg)
c = speed of light (3.0×10^8 m s^{-1})

WORKED EXAMPLE 1

A proton, of mass 1.67×10^{-27} kg, is travelling at 2.72×10^8 m s^{-1}.

a. Calculate the rest-energy of the proton.

Step 1

Identify known and unknown variables and write down the formula that relates these variables.

$m = 1.67 \times 10^{-27}$ kg, $c = 3.0 \times 10^8$ m s^{-1}, $E_0 = ?$

$E_0 = mc^2$

Step 2

Substitute values into the formula and solve for the rest energy of the proton.

$E_0 = 1.67 \times 10^{-27} \times (3.0 \times 10^8)^2$

$E_0 = 1.50 \times 10^{-10} = 1.5 \times 10^{-10}$ J

b. Calculate the total mass-energy of the proton.

Step 1

Identify known and unknown variables and write down the formulas that relate these variables.

$m = 1.67 \times 10^{-27}$ kg, $c = 3.0 \times 10^8$ m s^{-1}, $v = 2.72 \times 10^8$ m s^{-1}, $\gamma = ?$, $E_{tot} = ?$

$$\gamma = \frac{1}{\sqrt{1 - \frac{v^2}{c^2}}}$$

$E_{tot} = \gamma mc^2$

Continues →

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Step 2

Substitute values into the formula and solve for the Lorentz factor of the proton.

$$\gamma = \frac{1}{\sqrt{1 - \frac{(2.72 \times 10^8)^2}{(3.0 \times 10^8)^2}}}$$

$$\gamma = 2.37$$

Step 3

Substitute values into the formula and solve for the total mass-energy of the proton.

$$E_{tot} = 2.37 \times 1.67 \times 10^{-27} \times (3.0 \times 10^8)^2$$

$$E_{tot} = 3.56 \times 10^{-10} = 3.6 \times 10^{-10}\ \text{J}$$

PROGRESS QUESTIONS

Question 1

Which of the following statements is correct?

A. Rest energy increases as speed increases.

B. Rest energy decreases as speed increases.

C. Rest energy is the equivalent energy of a mass at rest.

D. Rest energy is the equivalent energy of a mass moving in an inertial reference frame.

Question 2

The mass-energy of an electron with $m_e = 9.1 \times 10^{-31}$ kg, travelling at 2.3×10^8 m s^{-1} ($\gamma = 1.56$) is closest to

A. 4.3×10^{-22} J.

B. 5.7×10^{-22} J.

C. 1.3×10^{-13} J.

D. 1.7×10^{-13} J.

How can we calculate the kinetic energy of a mass travelling close to the speed of light?

The difference between the total energy and the rest energy of a mass is its **relativistic kinetic energy**.

$$KE = E_{tot} - E_0$$
$$KE = \gamma mc^2 - mc^2$$
$$KE = (\gamma - 1)mc^2$$

FORMULA

$$KE = (\gamma - 1)mc^2$$

KE = relativistic kinetic energy (J)
γ = Lorentz factor (no units)
m = mass of object (kg)
c = speed of light (3.0×10^8 m s^{-1})

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At low speeds the classical calculation of kinetic energy, $KE = \frac{1}{2}mv^2$, is a good approximation; but at extremely high speeds it gives inaccurate results. The formula for relativistic kinetic energy is true for all speeds. Figure 1 shows how the relativistic kinetic energy formula gives significantly different results compared to the classical formula when a mass approaches the speed of light.

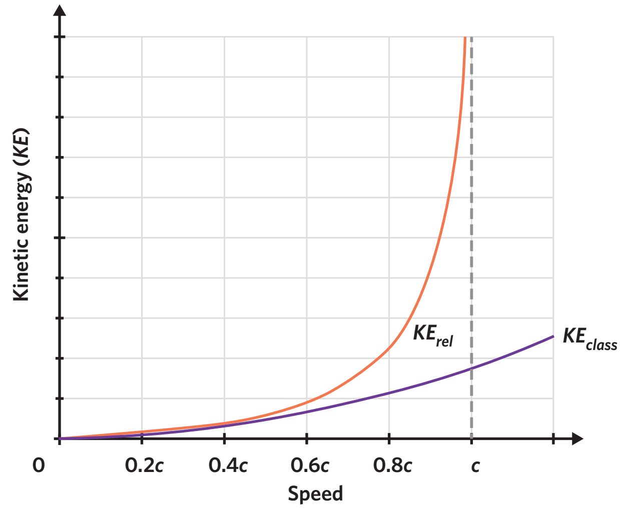

Figure 1 A comparison of classical and relativistic predictions of kinetic energy

As an object approaches the speed of light, its relativistic kinetic energy approaches infinity while its classical kinetic energy increases as a quadratic equation. According to classical kinetic energy, we should be able to accelerate objects past the speed of light – which we can't. The formula for relativistic kinetic energy shows us why an object with mass can never reach the speed of light as it would take an infinite amount of energy.

USEFUL TIP

Because the classical kinetic energy is accurate at non-relativistic speeds, we can use the classical formula to find kinetic energy in most everyday scenarios. However when dealing with high speed scenarios, we have to use the relativistic kinetic energy formula.

WORKED EXAMPLE 2

A neutron, of mass 1.67×10^{-27} kg, is travelling at 2.85×10^{8} m s^{-1} (with a Lorentz factor of $\gamma = 3.20$). Calculate the kinetic energy of the neutron.

Step 1

Identify known and unknown variables and write down the formulae that relate these variables.

Note that since the proton is moving close to the speed of light the relativistic kinetic energy formula is used to calculate its kinetic energy.

$m = 1.67 \times 10^{-27}$ kg, $c = 3.0 \times 10^{8}$ m s^{-1}, $\gamma = 3.20$, $KE = ?$

$KE = (\gamma - 1)mc^2$

Step 2

Substitute values into the formula and solve for the kinetic energy of the neutron.

$KE = (3.20 - 1) \times 1.67 \times 10^{-27} \times (3.0 \times 10^{8})^2$

$KE = 3.31 \times 10^{-10} = 3.3 \times 10^{-10}$ J

PROGRESS QUESTIONS

Question 3

The relativistic kinetic energy of an electron with a velocity close to c is

A. equal to its classical kinetic energy.

B. less than its classical kinetic energy.

C. greater than its classical kinetic energy.

D. not able to be determined, as not enough information is given.

Continues →

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Question 4

A proton of mass 1.67×10^{-27} kg, is travelling through space at a constant velocity of 2.50×10^{8} m s^{-1} ($\gamma = 1.81$). The kinetic energy of this proton is closest to

A. 1.2×10^{-10} J

B. 2.2×10^{-10} J

C. 2.7×10^{-10} J

D. 3.7×10^{-10} J

Adapted from VCAA 2020 exam Multiple choice Q12

Conservation of mass-energy 4.1.29.1

Mass can be converted into different forms of energy. Although we have learned that mass and energy are always conserved individually, it is really mass-energy that is always conserved in an isolated system.

How is mass-energy conserved?

When studying classical physics, we assume that for a given system, the total mass of the system is conserved. However, with the introduction of special relativity, we know that mass can be converted to energy and vice versa, so we can't always assume that the mass of a system remains constant. Instead, we must consider that the total mass-energy of a system is conserved.

$$\sum E_{total\ products} + E_{supplied} = \sum E_{total\ reactants} + E_{released}$$

This means that the mass of a system can be converted into different forms of energy, and different forms of energy can be converted to mass. Figure 2 shows the energy in a particular system at different points in time. Some rest energy at Time 1 is converted into light energy at Time 2, but the total mass-energy of the system is conserved.

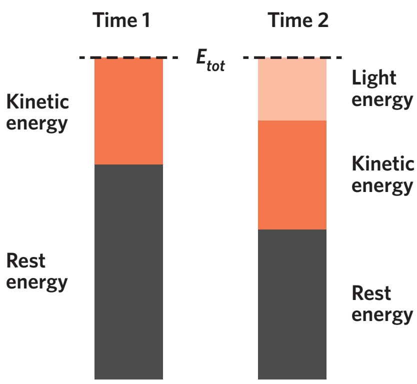

Figure 2 The total mass-energy of a system is the same at both Time 1 and Time 2.

We can relate the change in energy of a system to the change in mass of a system using:

FORMULA

$\Delta E = \Delta mc^2$

ΔE = change in energy (J)
Δm = change in mass (kg)
c = speed of light (3.0×10^8 m s^{-1})

How can we apply mass-energy conservation to different contexts?

We can apply mass-energy conservation to fusion reactions that take place in the Sun, positron-electron annihilation, and nuclear transformations that take place in particle accelerators.

STRATEGY

A chemical equation shows the reactants of the reaction on the left hand side and the products of the reaction on the right hand side of the arrow. When applying mass-energy equivalence, the total energy of the reactants must always equal the total energy of the products.

Fusion in the Sun

The Sun fuses small atoms together, such as hydrogen, to create larger atoms, such as helium atoms, and releases energy in the process.

- As energy is released, the total mass of the reactants does not add up to the total mass of the products (Figure 3).
- Some of the mass has been converted into different forms of energy, including heat and light.
- We can use the formula $\Delta E = \Delta mc^2$ to calculate the energy released in a fusion reaction.

USEFUL TIP

Because fusion reactions constantly occur in the Sun, its mass decreases over time. The Sun loses approximately 1.35×10^{17} kg of mass per year, which corresponds to a release of approximately 1.22×10^{34} J of energy in the form of light (electromagnetic radiation) per year.

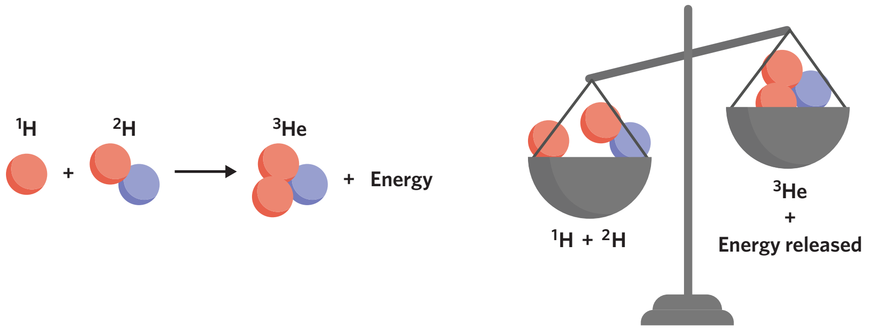

Figure 3 A fusion reaction that occurs in the Sun, where the initial mass of the system is greater than the final mass of the system

Positron-electron annihilation

There are two scenarios of positron-electron annihilation. The first is a low energy scenario in which:

- The kinetic energy of the reactants is negligible. Therefore, the total mass-energy of the particles can be approximated using their rest energies, $E_0 = mc^2$.
- The positron and electron annihilate each other, converting all of the mass of both particles into energy in the form of electromagnetic radiation (Figure 4).
- As the positron is the antiparticle of the electron, they have the same mass and the same rest energy $\left(E_{0\,e} = E_{0\,p}\right)$.

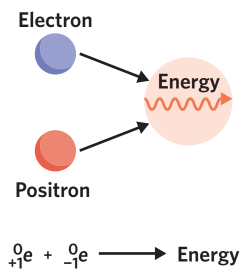

Figure 4 A representation of low-energy positron-electron annihilation

The mass-energy equation for low energy positron-electron annihilation can be written as:

$$E_{0\,p} + E_{0\,e} = E_{released}$$
$$2E_{0\,e} = E_{released}$$

USEFUL TIP

The mass of an electron is given on the VCAA data sheet as 9.1×10^{-31} kg. This is the same as the mass of a positron.

The second is the high energy scenario, in which:

- The kinetic energy of the reactants must be considered. Therefore, the energy of the positron and electron can be found using their total energy, $E_{tot} = \gamma mc^2$.
- Since the particles are moving at high speed, their total mass-energy can be converted into multiple products which have mass as well as energy (Figure 5).

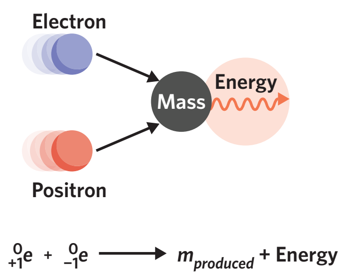

Figure 5 A representation of high-energy positron-electron annihilation

The mass-energy equation for high energy positron-electron annihilation can be written as:

$$E_{0\,p} + E_{0\,e} = m_{produced} + E_{released}$$
$$2E_{0\,e} = m_{produced} + E_{released}$$

Particle accelerators

Particle accelerators are machines that accelerate charged particles (like protons or electrons) to high speeds before colliding these high energy particles with one another.

- When high speed particles collide, their high kinetic energy means they are capable of producing various other heavier particles as well as emitting energy (Figure 6).
- Some of these particles have very short life-spans and can only be studied in particle colliders as they are difficult to detect elsewhere.

Image: vchal/Shutterstock.com

Figure 6 Representation of a high energy collision in a particle accelerator

The strategy for applying the mass-energy relationship to mass conversion in the Sun and positron-electron annihilation can also be applied to nuclear transformations in particle accelerators.

WORKED EXAMPLE 3

In a particle accelerator, a neutron, of mass 1.67×10^{-27} kg, is collided with a uranium-235 atom of mass 3.9029×10^{-25} kg. They produce a barium-144 particle ($m_{Ba} = 2.3899 \times 10^{-25}$ kg) and a krypton-92 particle ($m_{Kr} = 1.5265 \times 10^{-25}$ kg). Calculate the amount of mass converted to kinetic energy of the products. Assume the kinetic energy of the neutron and the uranium-235 atom are negligible, and that no light or heat is released in the reaction.

Step 1

Identify known and unknown variables and write down the formula that relates these variables.

Note that the difference between the mass of the reactants and products will be equivalent to the kinetic energy of the products.

$m_n = 1.67 \times 10^{-27}$ kg, $m_U = 3.9029 \times 10^{-25}$ kg,
$m_{Ba} = 2.3899 \times 10^{-25}$ kg, $m_{Kr} = 1.5265 \times 10^{-25}$ kg, $\Delta E = ?$

$\Delta E = \Delta mc^2 = (m_f - m_i)c^2$

Step 2

Calculate the initial and final mass of the system.

$m_i = m_n + m_U = 1.67 \times 10^{-27} + 3.9029 \times 10^{-25}$

$m_i = 3.9196 \times 10^{-25}$

$m_f = m_{Ba} + m_{Kr} = 2.3899 \times 10^{-25} + 1.5265 \times 10^{-25}$

$m_f = 3.9164 \times 10^{-25}$

Step 3

Substitute values into the formula and solve for the energy released.

$\Delta E = (3.9194 \times 10^{-25} - 3.9196 \times 10^{-25}) \times (3.0 \times 10^8)^2$

$\Delta E = -2.88 \times 10^{-11} = -2.9 \times 10^{-11}$ J

As the energy associated with the mass has decreased by 2.9×10^{-11} J due to the reaction, the products must have 2.9×10^{-11} J of kinetic energy.

PROGRESS QUESTIONS

Question 5

A nucleus in an excited state emits a gamma ray of 3.6×10^{-13} J as it decays to its ground state. The initial mass of the excited nucleus is M_i. The nucleus after decay

A. has the same mass as the nucleus before decay.

B. has 4.0×10^{-30} kg less mass than the nucleus before decay.

C. has 8.0×10^{-30} kg less mass than the nucleus before decay.

D. has 4.0×10^{-30} kg more mass than the nucleus before decay.

Adapted from VCAA 2021 NHT exam Multiple choice Q20

Question 6

A positron-electron annihilation creates two gamma rays with the same energy. Assume the kinetic energy of the positron and electron is negligible. The energy of each gamma ray released is closest to

A. 2.7×10^{-22} J.

B. 5.5×10^{-22} J.

C. 8.2×10^{-14} J.

D. 1.6×10^{-13} J.

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Theory summary

- All mass has energy associated with it.
- Rest energy is calculated by $E_0 = mc^2$.
- The relativistic kinetic energy of a mass is given by $KE = (\gamma - 1)mc^2$ and approaches infinity as its speed approaches the speed of light (c).
- Relativistic and classical kinetic energy produce almost identical results at low speeds, but at relativistic speeds classical kinetic energy becomes inaccurate.
- Total mass-energy is always conserved and can be calculated by $E_{tot} = \gamma mc^2$.
- Mass can be converted into energy and energy can be converted into mass using $\Delta E = \Delta mc^2$.
- Examples of mass-energy conversions include:
  - fusion in the Sun
  - positron-electron annihilation
  - nuclear transformations in particle accelerators.

11D Questions

Mild 🌶 Medium 🌶🌶 Spicy 🌶🌶🌶

Deconstructed exam-style

Use the following information to answer questions 7–10.

In a nuclear fusion reaction in the Sun's core, two deuterium nuclei, each with a mass of 3.3436×10^{-27} kg, fuse to produce one helium-4 nucleus with a mass of 6.6465×10^{-27} kg. Ignore the kinetic energy of the masses before and after the reaction.

Question 7 🌶 (1 MARK)

State the initial and final mass of the system.

Question 8 🌶 (1 MARK)

Calculate the change in mass of the system.

Question 9 🌶 (1 MARK)

Which of the following correctly identifies the relationship between the change in mass and energy released?

A. $\Delta E = \frac{\Delta m}{c^2}$

B. $\Delta E = \Delta mc$

C. $\Delta E = \Delta mc^2$

D. $\Delta E = \gamma \Delta mc^2$

Question 10 🌶🌶 (3 MARKS)

Calculate the energy released in the fusion reaction.

Adapted from VCAA 2019 NHT exam Short answer Q19

Exam-style

Question 11 (4 MARKS)

A proton of mass 1.67×10^{-27} kg is travelling at $0.80c$ ($\gamma = 1.67$).

a. Calculate the total energy of the proton. 🌶 2 MARKS

b. Calculate the relativistic kinetic energy of the proton. 🌶 2 MARKS

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Question 12 (1 MARK)

On average, the Sun emits 3.8×10^{26} J of energy each second in the form of electromagnetic radiation. This energy originates from the nuclear fusion reactions taking place in the Sun's core.

The corresponding loss in the Sun's mass each second would be closest to

A. 2.1×10^{9} kg.

B. 4.2×10^{9} kg.

C. 8.4×10^{9} kg.

D. 2.1×10^{12} kg.

Question 13 (6 MARKS)

A positron and electron, both travelling at 0.90c ($\gamma = 2.29$), annihilate each other.

a. Show the total energy of the system is 3.8×10^{-13} J. 2 MARKS

b. State how much energy is released in the annihilation. 1 MARK

c. *Key science skill*

Two scientists are trying to predict the amount of energy released due to the annihilation of a positron and electron. They calculate the kinetic energy of the positron and electron using $\frac{1}{2}mv^2$. Explain why the values calculated by the scientists are lower than the values they obtain experimentally, and how they could correctly calculate the kinetic energy of the particles. 3 MARKS

FROM LESSON 12A

Question 14 (3 MARKS)

Can a particle with mass be accelerated to the speed of light? Explain why or why not.

Question 15 (2 MARKS)

The star Alpha Centauri A emits an average of 4.20×10^{26} J of electromagnetic radiation every second. What is the corresponding rate at which mass inside this star is lost? Write your answer in kg s^{-1}.

Question 16 (3 MARKS)

A neutron has a mass of 1.67×10^{-27} kg and relativistic kinetic energy of 1.81×10^{-10} J. What is the speed of the neutron?

Question 17 (1 MARK)

Key science skill

A helium ion is accelerated from a speed of 9.00×10^{7} m s^{-1} to a speed of 1.50×10^{8} m s^{-1} in a lab. Scientists obtain the following data from the experiment:

Rest mass energy of a helium ion	5.98×10^{-10} J
The Lorentz factor at 9.00×10^{7} m s^{-1}	$\gamma = 1.05$
The Lorentz factor at 1.50×10^{8} m s^{-1}	$\gamma = 1.15$

Which of the options below is the amount of energy required to accelerate the helium ion?

A. 2.90×10^{-19} J

B. 5.98×10^{-11} J

C. 1.02×10^{-9} J

D. 5.98×10^{-9} J

Adapted from VCAA 2012 Exam 1 Detailed Study 1 Q12

Question 18 (2 MARKS)

A star is transforming energy at a rate of 2.90×10^{25} J s^{-1}.

Explain the type of transformation involved and what effect, if any, the transformation would have on the mass of the star. No calculations are required.

Adapted from VCAA 2022 exam Short answer Q9

Question 19 (3 MARKS)

A neutral pion is a type of particle. In a collider experiment, a neutral pion with $\gamma = 10.0$ decays into two photons. The total energy of both photons together is measured to be 2.17×10^{-10} J. Before the decay only the neutral pion exists and after the decay only the photons exist. What is the rest mass of the neutral pion?

Question 20 (6 MARKS)

A particle of mass 3.34×10^{-27} kg has kinetic energy that is 12 times its rest energy.

a. Show that the Lorentz factor of this particle is 13. 1 MARK

Adapted from VCAA 2019 NHT exam Multiple choice Q18

b. Calculate the difference between the classical and relativistic kinetic energy of the particle. 5 MARKS

Question 21 (1 MARK)

According to Einstein's relativity theory, the rest energy is mc^2 for a particle of rest mass m and the kinetic energy of the particle is γmc^2.

Which one of the curves best gives the relationship of kinetic energy to rest energy as a function of speed?

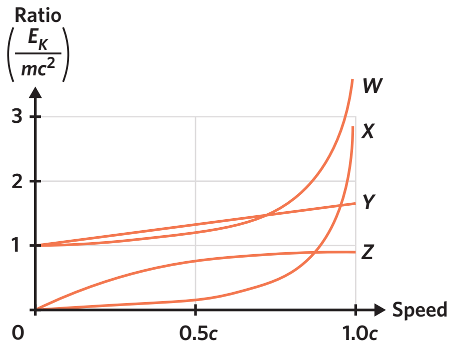
A. curve W

B. curve X

C. curve Y

D. curve Z

Adapted from VCAA 2015 exam Detailed Study 1 Q11



Question 22 (4 MARKS)

A positron and electron, both with a Lorentz factor $\gamma = 2.93$, annihilate each other in a collision that takes place in a particle accelerator. Two pions are created, each of mass 2.406×10^{-28} kg. Calculate the mass of the heaviest particle that they are able to produce as a result of the collision.

Question 23 (4 MARKS)

Scientists are studying a nuclear transformation in a particle accelerator that occurs in two stages.

$n + {}^{235}\text{U} \rightarrow {}^{236}\text{U} \rightarrow {}^{144}\text{Ba} + {}^{89}\text{Kr} + 3n$

- A stationary uranium nucleus is bombarded with a low speed neutron and absorbs its mass.
- The isotope of uranium produced is unstable and decays, producing:
  - a high speed barium nucleus
  - a high speed krypton nuclei
  - three high speed neutrons.

Assume the kinetic energy of the unstable uranium isotope is negligible. Describe how the total mass of the system changes in each stage. Explain your answer.

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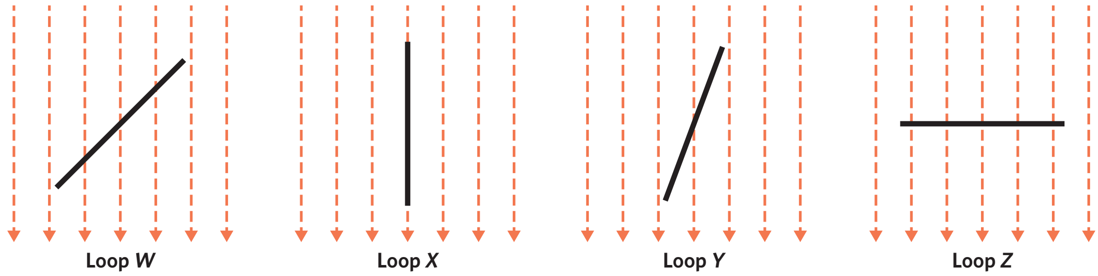
Previous lessons

Question 24 (1 MARK)

The diagram shows the side-view of a loop of wire at different angles within a magnetic field. Rank the diagrams in order of increasing magnetic flux (from least flux to most flux) passing through the loop.



FROM LESSON 5A

Question 25 (2 MARKS)

Describe how the stopping voltage is found experimentally.

FROM LESSON 9A

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Chapter 11 review

Mild 🌶 Medium 🌶🌶 Spicy 🌶🌶🌶

These questions are typical of one hour's worth of questions on the VCE Physics Exam.

Total marks: 50

Section A

All questions in this section are worth one mark.

Unless otherwise indicated, the diagrams in this book are not drawn to scale.

Question 1 🌶

Consider the motion of three spacecraft. Spacecraft 1 is accelerating, with an initial velocity of 500 km s^{-1}. Spacecraft 2 has a constant velocity of 500 km s^{-1}. Spacecraft 3 has a constant velocity of 900 km s^{-1}. There is a scientist in each rocket performing the same experiment which involves the motion of a ball. Which of the following statements correctly describes their results?

A. All of the experimental results will agree.

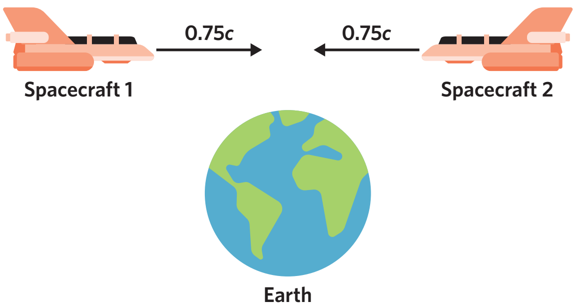
B. None of the experimental results will agree.

C. Spacecraft 1 and spacecraft 2 experimental results will agree.

D. Spacecraft 2 and spacecraft 3 experimental results will agree.

Use the following information to answer questions 2 and 3.

A scientist from Earth measures two spacecraft travelling at a constant velocity of 0.75c towards each other.



Question 2 🌶🌶

The proper time it takes for spacecraft 1 to pass the Earth's equator will be measured in the reference frame of

A. spacecraft 1.

B. spacecraft 2.

C. the scientist on Earth.

D. an absolute universal time.

Question 3 🌶

Spacecraft 2 turns on a laser. At what speed would a scientist on spacecraft 1 measure the light from the laser to be travelling?

A. 0.25c

B. c

C. 1.3c

D. 1.5c

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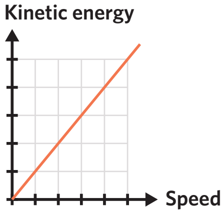
Question 4

Which of the following graphs best represents the kinetic energy vs. speed graph as an object approaches the speed of light?

A.


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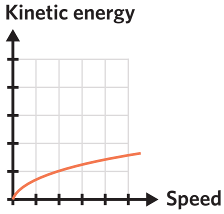
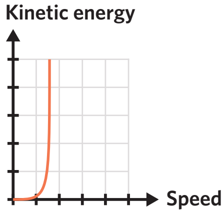
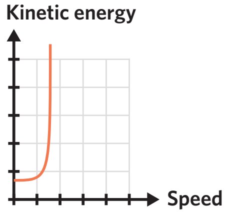


C.


D.


Adapted from VCAA 2018 NHT exam Multiple choice Q13

Question 5

A particle accelerator moves an electron with a total energy of 1.06×10^{-12} J at a constant speed. The length of the particle accelerator as measured from the electron's frame of reference is 24 m. Which of the following is the difference in the length of the particle accelerator from the electron's frame of reference and the particle accelerator's frame of reference.

A. 1.8×10^{2} m

B. 2.9×10^{2} m

C. 3.1×10^{2} m

D. 9.8×10^{3} m

Section B

In questions where more than one mark is available, appropriate working must be shown.

Unless otherwise indicated, the diagrams in this book are not drawn to scale.

Question 6 (9 MARKS)

The Blitztern is travelling from Earth to a star system 5.84×10^{16} m away, at a constant speed of $0.85c$ relative to Earth. Assume the star system is at rest relative to the Earth.

a. Calculate the time it takes the Blitztern to travel to the star system as measured by an observer on Earth. 2 MARKS

b. Is this time measured by an observer on Earth a proper or dilated time? Explain your answer. 2 MARKS

c. Calculate the time interval that would be measured onboard the Blitztern. 3 MARKS

d. Calculate the distance from Earth to the star system as measured by an observer on board the Blitztern. 2 MARKS

Question 7 (3 MARKS)

Shaniqua is in an inertial frame of reference and observes a rocket moving at a constant velocity. She notes that the clocks on the rocket measure events on Earth as taking five times longer than her clocks. All clocks are operating normally in their frame of reference. If the rocket has a mass of 8000 kg, calculate the kinetic energy of the spaceship in Shaniqua's frame of reference. Show your working.

Adapted from VCAA 2018 exam Short answer Q15

Question 8 (6 MARKS)

Protons in the Large Hadron Collider are accelerated to speeds of over 0.999*c* around a circular track with a circumference of 27 km.

a. Explain whether these protons are in an inertial frame of reference when they are: 3 MARKS

- speeding up around the circular track
- travelling at a constant speed around the circular track.

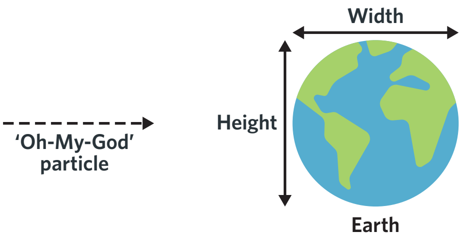
b. Explain why the straight section of the particle accelerator must be designed to be longer than the distance the protons travel in their own frame of reference. 3 MARKS

Question 9 (3 MARKS)

Scientists observe a large number of muons, produced in the upper atmosphere, reach the surface of the Earth even though their half-lives indicate that many more of them should decay before arriving. Explain why this is the case from the frame of reference of a stationary scientist on Earth.

Adapted from VCAA 2022 exam Short answer Q11

Question 10 (6 MARKS)



The highest-energy particle ever observed was the 'Oh-My-God' particle. The particle travelled parallel to the width of the Earth, as shown in the diagram. It had the same mass as a proton, $m_p = 1.67 \times 10^{-27}$ kg, and a Lorentz factor of $\gamma = 3.2 \times 10^{11}$. The width and height of the Earth are both 1.3×10^4 km in the Earth's reference frame.

a. Determine the height of Earth when measured from the particle's reference frame. 1 MARK

b. Determine the width of Earth when measured from the particle's reference frame. 2 MARKS

c. Calculate the relativistic kinetic energy of the 'Oh-My-God' particle in the Earth's frame of reference. 2 MARKS

d. Determine the 'Oh-My-God' particle's kinetic energy in its own frame of reference. 1 MARK

Question 11 (6 MARKS)

A rocket of mass 5.30×10^5 kg accelerates to a maximum speed 0.80*c* relative to the nearby planet Neptune.

a. Calculate the total energy of the rocket when at its maximum speed, in the reference frame of an observer on Neptune. 3 MARKS

b. Calculate the equivalent amount of mass which, when converted to energy, could propel the rocket to that speed. 3 MARKS

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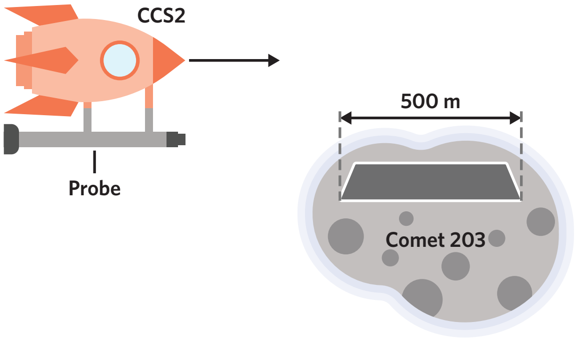
Question 12 (4 MARKS)

A comet-chasing spacecraft, CCS2, approaches Comet 203 at a speed for which $\gamma = 1.5$ relative to Comet 203. There is a landing probe attached to CCS2 that must land on a 500 m long landing strip previously built by engineers on the comet.



a. What is the length of this landing strip, as measured by instruments on CCS2? 2 MARKS

Adapted from VCAA 2015 exam Detailed Study 1 Q7

b. Spacecraft CCS2 releases the probe that will land on the comet. Near touchdown, the probe is at the same velocity as the comet. Describe a reference frame that would be able to measure the proper length for the landing area. 2 MARKS

Adapted from VCAA 2015 exam Detailed Study 1 Q8

Question 13 (6 MARKS)

Two students, Narek and Wilma, are discussing whether GPS satellites' clocks need to account for the effects of special relativity.

Narek says that if an observer on Earth were to measure a day passing on a GPS satellite's clock, they would measure the same time passing as on their clock on Earth and so the satellite clocks don't need to be adjusted. Wilma says that although the effects of special relativity are small, clocks aboard GPS satellites are adjusted to tick slower to account for the effects of special relativity.

Evaluate their statements.

Question 14 (2 MARKS)

A train passes a platform travelling at a constant speed relative to the platform. A stationary observer on the platform measures the length of the train to be 55 m long, while the driver of the train measures it to be 95 m long. Calculate the speed of the train.

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Unit 4 AOS 1 review

Mild 🌶 Medium 🌶🌶 Spicy 🌶🌶🌶

These questions are typical of one hour's worth of questions on the VCE Physics Exam.

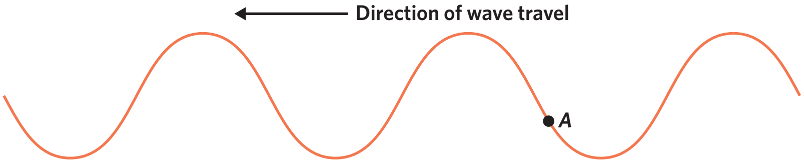
Total marks: 50

Section A

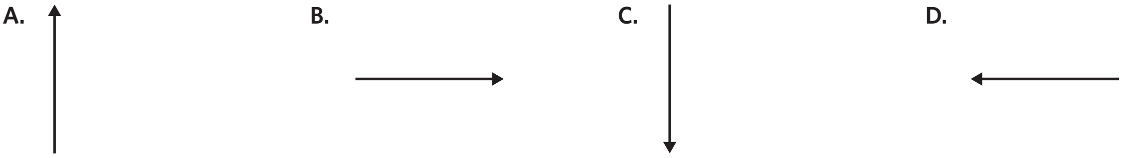
All questions in this section are worth one mark.

Unless otherwise indicated, the diagrams in this book are not drawn to scale.

Question 1 🌶

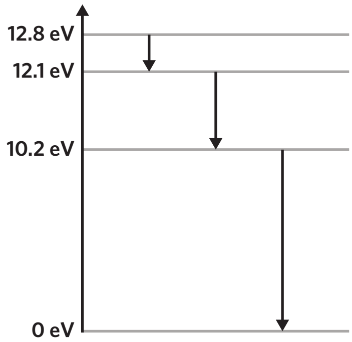


A string is vibrated to form a travelling wave. Which of the following best gives the direction that point *A* is moving at the instant shown?



Question 2 🌶

Some of the energy levels of the hydrogen atom are shown in the diagram below. A hydrogen atom has been excited to the 12.8 eV energy level. It returns to the ground state via the three transitions shown.



Which of the following indicates the energies of the emitted photons?

A. 0.7 eV, 1.9 eV, 10.2 eV

B. 0.7 eV, 2.6 eV, 10.2 eV

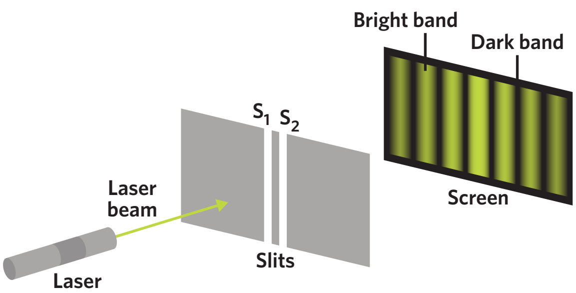
C. 1.9 eV, 2.6 eV, 10.2 eV

D. 10.2 eV, 12.1 eV, 12.8 eV

Adapted from VCAA 2022 NHT exam Multiple choice Q17

Question 3 🌶🌶

A red laser used in a double-slit experiment creates an interference pattern on a screen, as shown in the diagram. The red laser is replaced with a green laser. Which one of the following best explains what happens to the spacing between adjacent bright bands when the green laser is used?



A. The spacing increases.

B. The spacing decreases.

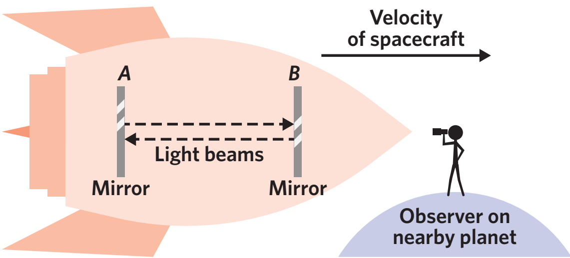
C. The spacing stays the same.

D. The spacing cannot be determined from the information given.

Adapted from VCAA 2021 NHT exam Multiple choice Q16

Question 4 🌶🌶🌶

A spacecraft carrying a light clock is moving at a constant velocity of 0.60*c* ($\gamma = 1.25$) relative to an observer on a nearby planet. One period of the clock is the time taken for light to travel from *A* to *B* and back to *A*. The proper length between the two mirrors is 5.00 m. According to the observer, the period of this clock is closest to



A. 13 ns

B. 21 ns

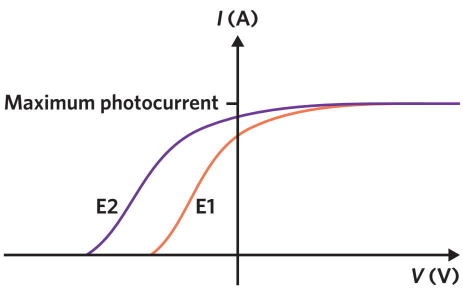
C. 27 ns

D. 42 ns

Adapted from VCAA 2014 exam Detailed Study 1 Q9

Question 5 🌶🌶

Two photoelectric effect experiments, E1 and E2, are conducted using incident light with the same frequency. The measured photocurrent is plotted against electrode potential for both experiments. Which of the following statements best explains the different results between E1 and E2?



A. The light used in E1 has a lower intensity than in E2.

B. The light used in E1 has a higher intensity than in E2.

C. The metal plate used in E1 has a lower work function than that used in E2.

D. The metal plate used in E1 has a higher work function than that used in E2.

Section B

In questions where more than one mark is available, appropriate working must be shown.

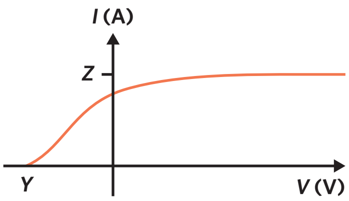
Unless otherwise indicated, the diagrams in this book are not drawn to scale.

Question 6 🌶 (2 MARKS)

Calculate the mass-energy of an electron with $m_e = 9.1 \times 10^{-31}$ kg, travelling at 2.85×10^8 m s^{-1} ($\gamma = 3.20$).

Question 7 (4 MARKS)

Bailey is investigating how changing the frequency of light affects the photocurrent in a photoelectric experiment. The graph shows the photocurrent produced versus electrode potential for the first frequency used.

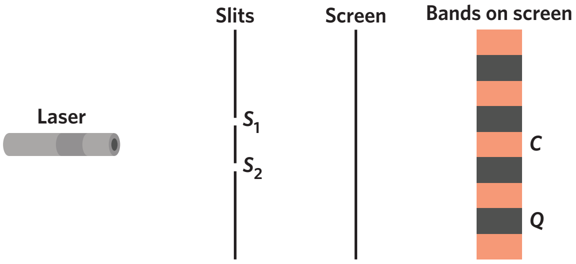


a. Identify what values are represented by the *Y* on the horizontal axis and the *Z* on the vertical axis. 🌶 2 MARKS

b. Bailey repeats the experiment using light with double the frequency of the first experiment. Copy the graph and draw the expected results using a dotted line. 🌶🌶 2 MARKS

Question 8 (4 MARKS)

Xi, Kim and Donald are carrying out a double-slit experiment with a laser of frequency 5.0×10^{14} Hz. The arrangement of their apparatus is shown. The point C is the central bright band of the interference pattern and point Q represents the second dark band from C.



a. Calculate how much longer the distance from S_1 to Q is than the distance from S_2 to Q. 🌶 2 MARKS

b. Xi, Kim and Donald repeat the experiment using a different laser and find that the point Q is now the second bright band from C. Calculate the wavelength of the new laser. 🌶🌶 2 MARKS

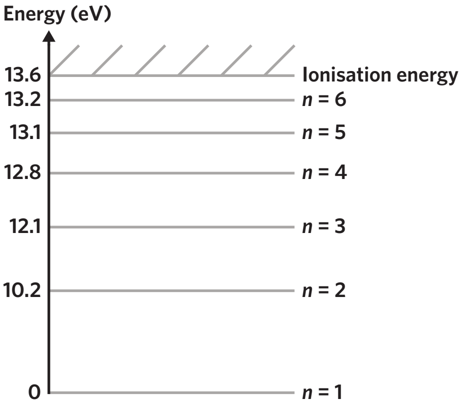
Adapted from VCAA 2014 exam Short answer Q19

Question 9 🌶🌶🌶 (4 MARKS)

Mollie and DeAndre are playing with a 0.50 m string with one fixed end and one free end. They produce a travelling wave in the string with a wavelength of 8.0 cm and a period of 0.020 s. After this, DeAndre attempts to create a standing wave with a frequency of 20 Hz on the same string. Use calculations to identify whether DeAndre will be able to produce this standing wave in the string.

Question 10 (9 MARKS)

The diagram shows the electron energy levels of a hydrogen atom. Consider the photon emitted when an electron transitions from $n = 6$ to $n = 2$.



a. Show that the energy of the photon is 4.8×10^{-19} J. 🌶 2 MARKS

b. Calculate the wavelength of the photon emitted. 🌶🌶 2 MARKS

c. Identify all the possible energies (in eV) of the photons that could be emitted due to transitions when an electron starts in the $n = 5$ state and ends in the $n = 3$ state. 🌶🌶 3 MARKS

d. Explain why electrons in atoms exist in discrete energy levels only. 🌶🌶🌶 2 MARKS

Adapted from VCAA 2018 exam Short answer Q19b

Question 11 🌶🌶 (3 MARKS)

A scientist in an inertial frame of reference observes a train of mass 4.9×10^5 kg moving past her at a constant velocity of 2.68×10^5 km s^{-1}. Calculate the kinetic energy of the train in the scientist's frame of reference.

Adapted from VCAA 2018 exam Short answer Q15

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Question 12 (3 MARKS)

Two speakers are set up directly facing each other. They output coherent sound waves with a frequency of 425 Hz. Leslie stands in the centre between the two speakers, then walks toward one speaker until she hears the third loud region from the centre. How far has Leslie walked? Take the speed of sound to be 340 m s^{-1}.

Adapted from VCAA 2018 exam Short answer Q11b

Question 13 (2 MARKS)

A biology teacher is covering a VCE Physics class and tells the class that 'Young's double-slit experiment provides evidence for the particle model of light rather than the wave model of light'. Evaluate their statement.

Adapted from VCAA 2013 exam Short answer Q22d

Question 14 (3 MARKS)

Dorothy conducts two photoelectric effect experiments. She uses a different frequency of light for each experiment. In both cases, she starts with light that has a very low intensity and she measures the photocurrent as she steadily increases the intensity.

In the first experiment, she uses light with a fixed frequency of 6.0×10^{14} Hz and she finds that increasing the intensity causes an increase in the photocurrent. In the second experiment, she uses light with a fixed frequency of 2.0×10^{13} Hz and she finds that there is no photocurrent when the light intensity is low. This is summarised in the table.

	$f = 6.0 \times 10^{14}$ Hz	$f = 2.0 \times 10^{13}$ Hz
Low intensity	Low photocurrent	No photocurrent
High intensity	High photocurrent	?

Dorothy predicts that when she increases the intensity of light in the second experiment she will measure a photocurrent. Explain why she may believe this is the case, and whether her prediction is correct.

Adapted from VCAA 2018 exam Short answer Q17aii

Question 15 (7 MARKS)

An experiment is set up to study muons created in the upper atmosphere. The muons are measured to have a speed of $0.950c$ ($\gamma = 3.20$) relative to the Earth.

a. In one observation, a $0.950c$ muon travels 1.5 km, as measured by a stationary observer on Earth. If measured in the muon's frame of reference, would this length be the same, shorter or longer? Explain your answer, and include a calculation. 3 MARKS

Adapted from VCAA 2022 NHT exam Short answer Q11a

b. In order to get a better vantage point of the muons, an astronaut on a satellite, travelling at 4.5×10^4 m s^{-1} relative to the Earth, observes the decay of a separate set of muons. They measure that the muon takes 2.3×10^{-6} s to reach the ground. Calculate the difference in the time measured by the astronaut's clock to that measured by a stationary clock on Earth. 4 MARKS

Question 16 (4 MARKS)

Explain two predictions that the wave model makes regarding the photoelectric effect and identify the results which disprove these predictions.

Adapted from VCAA 2017 exam Short answer Q17c

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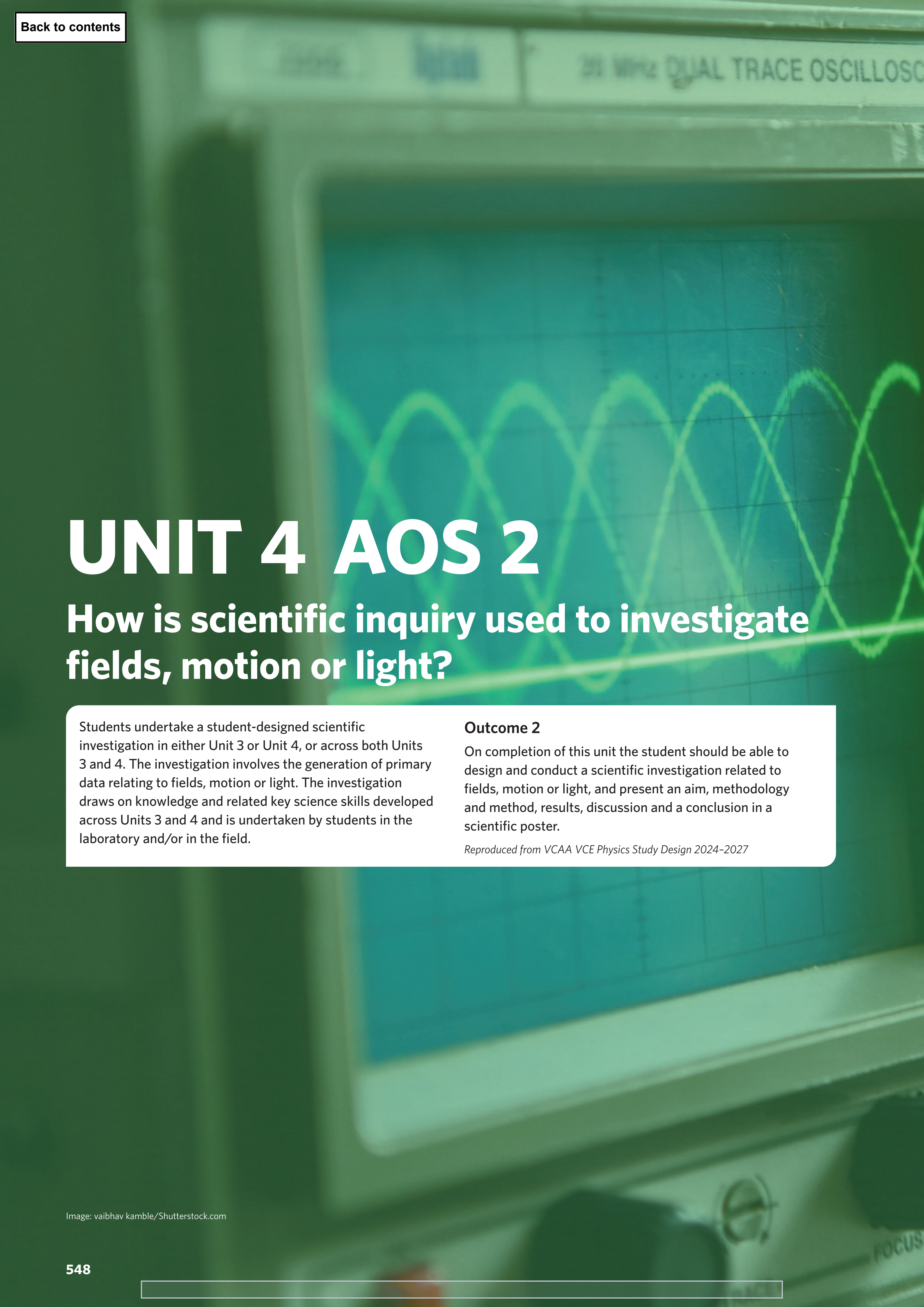

UNIT 4 AOS 2

How is scientific inquiry used to investigate fields, motion or light?

Students undertake a student-designed scientific investigation in either Unit 3 or Unit 4, or across both Units 3 and 4. The investigation involves the generation of primary data relating to fields, motion or light. The investigation draws on knowledge and related key science skills developed across Units 3 and 4 and is undertaken by students in the laboratory and/or in the field.

Outcome 2

On completion of this unit the student should be able to design and conduct a scientific investigation related to fields, motion or light, and present an aim, methodology and method, results, discussion and a conclusion in a scientific poster.

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Image: vaibhav kamble/Shutterstock.com

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12

CHAPTER 12

Scientific investigations

STUDY DESIGN DOT POINTS

- identify the physics concepts specific to the investigation and explain their significance, including definitions of key terms and physics representations
- explain the characteristics of the selected scientific methodology and method including: techniques of primary qualitative and quantitative data generation relevant to the selected investigation; and appropriateness of the use of independent, dependent and controlled variables in the selected scientific investigation
- identify and apply concepts of accuracy, precision, repeatability, reproducibility, resolution and validity of data; and the identification of, and distinction between, error and uncertainty
- identify and apply health, safety and ethical guidelines relevant to the selected investigation
- discuss the nature of evidence that supports or refutes a hypothesis, model or theory
- apply methods of organising, analysing and evaluating primary data to identify patterns and relationships including: the physical significance of the gradient of linearised data; causes of uncertainty; use of uncertainty bars; and assumptions and limitations of data, methodologies and methods
- model the scientific practice of using a logbook to authenticate generated primary data

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LESSONS

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12A Asking questions, identifying variables and making predictions

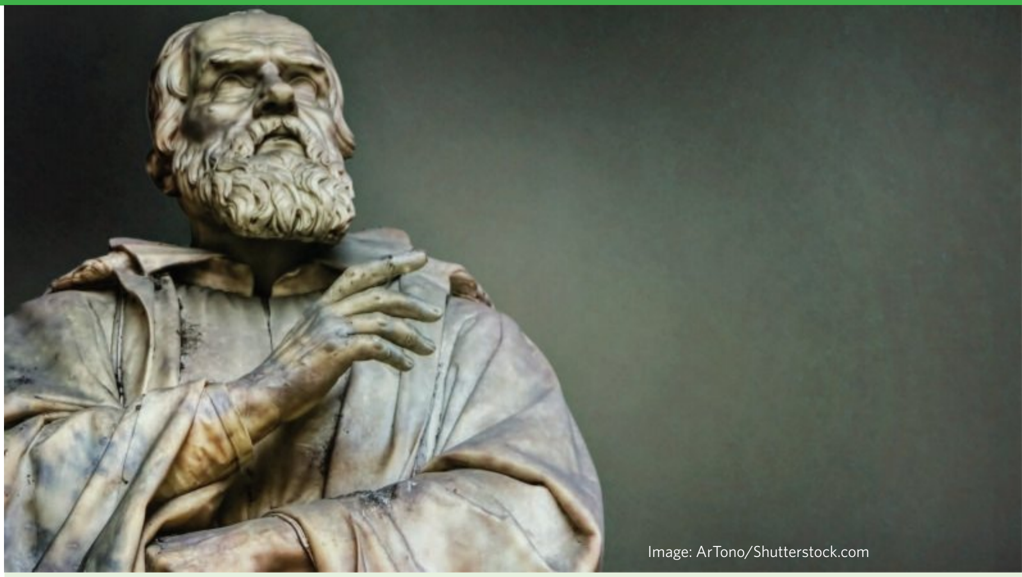
Image: ArTono/Shutterstock.com

STUDY DESIGN DOT POINTS

- explain the characteristics of the selected scientific methodology and method including: techniques of primary qualitative and quantitative data generation relevant to the selected investigation; and appropriateness of the use of independent, dependent and controlled variables in the selected scientific investigation
- discuss the nature of evidence that supports or refutes a hypothesis, model or theory

12A 12B 12C 12D 12E

4.2.2.1 Variables, types of data, and characteristics of data

4.2.5.1 The scientific method

4.2.5.2 Theories, models, and laws

How do we know if science is fact or fiction?

'Why' is a great question to ask. Why is the sky blue? Why do things fall? Or as Galileo Galilei asked, why does the Earth seem to revolve around the Sun and not the other way round? Science is the process of asking questions and seeking explanations for how the universe behaves so that we can make informed and accurate predictions. Physics is the part of science that focuses on the most fundamental features of the universe: matter and energy. This lesson will explain the scientific method as a process of seeking answers to questions by testing predictions involving different variables.

KEY TERMS AND DEFINITIONS

independent variable a variable that is deliberately manipulated by the experimenter

dependent variable a variable that is measured by the experimenter, expected to be impacted by the independent variable

controlled variable a variable that has been held constant in an experiment

primary data original data collected firsthand by researchers

secondary data data that has been previously collected that is accessible to different researchers

quantitative data data that can be described by numerical values

qualitative data data that cannot be described by numerical values

observation the acquisition of data using senses such as seeing and hearing or with scientific instruments

hypothesis a proposed explanation that predicts a relationship between variables and can be tested through experimentation

aim the purpose of an experiment

theory (scientific) an explanation of a physical phenomenon that has been repeatedly confirmed by experimental evidence and observation

model (scientific) a representation of a physical process that cannot be directly experienced

law (scientific) a statement, based on repeated experiments or observations, that describes or predicts a phenomenon.

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Variables, types of data, and characteristics of data 4.2.2.1

Different types of variables that can be measured when gathering data in an experiment. It is important to have an understanding of data types and their characteristics to communicate our results effectively.

Why do we have different types of variables?

When conducting an experiment, we investigate the relationship between variables. To try to find a relation between variables *X* and *Y*, we make one the independent variable and the other the dependent variable.

- The **independent variable** is directly and intentionally changed to determine what effect it has on the dependent variable.
- The **dependent variable** is measured to determine whether it is affected by (dependent on) the changes to the independent variable.
- A **controlled variable** is kept constant to avoid affecting the results for the dependent variable.

If we were conducting an experiment to see how changing the angle of inclination of an inclined plane affects the final speed of a ball rolling down the ramp, our variables would be as shown in Table 1.

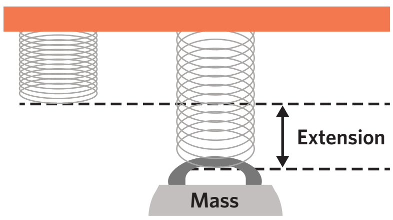
Table 1 Classification of the variables in inclined plane experiment

Variable classification	Example(s)
Independent variable	The angle of inclination of the plane
Dependent variable	Final speed of the ball
Controlled variables	Rolling length, size of ball, material of ramp, material of ball, air temperature/density, etc.

PROGRESS QUESTIONS

Use the following information to answer questions 1 and 2.

Elodie conducts an experiment in which she attaches different masses to a hanging spring and measures the extension of the spring for each mass. She uses the same spring for all measurements.



Question 1

Which variable in this experiment is the dependent variable?

A. mass attached
B. the density of the air
C. extension of the spring
D. spring constant of the spring used

Question 2

Which variable in this experiment is a possible controlled variable? **(Select all that apply)**

A. mass attached
B. the density of the air
C. extension of the spring
D. spring constant of the spring

USEFUL TIP

Primary data may also be referred to as 'first hand' data and secondary data as 'second hand' data

How can we classify different types of data?

To develop a scientific theory, we conduct experiments and obtain data used to develop conclusions about our area of study. Two types of data can be collected and analysed:

- **Primary data**
  - is gathered by a researcher directly from an experiment.
  - typically means we have performed the experiment ourselves.
- **Secondary data**
  - is collected indirectly from other experiments.
  - typically is found by researching the topic we are investigating.

Data can also be classified as quantitative or qualitative.

- **Quantitative data**
  - is represented by a numerical value.
  - For example, the length of a ruler can be recorded as 30 cm.
- **Qualitative data**
  - is represented by a non-numerical quantity.
  - For example, the material that a container is made from can be recorded as silicone.

Both quantitative and qualitative data are important to the scientific method.

PROGRESS QUESTIONS

Question 3

Which of the following is best classified as quantitative data?
(Select all that apply)

A. the diameter of a ball

B. the angle of inclination of a ramp

C. the material from which a ball is made

D. the type of ball (basketball, soccer ball, etc.)

Question 4

Secondary data

A. can only be quantitative.

B. can be either qualitative or quantitative.

C. is data obtained directly from an experiment.

D. can only be obtained by researching a topic on the internet.

The scientific method 4.2.5.1

The scientific method is a process that begins with the idea that all possible explanations for an **observation** could be true unless (and until) they are disproved. This process uses variables and data to provide great confidence in explanations about the world which have not yet been disproved.

How do we use the scientific method?

We use the scientific method to follow a sequence of logical steps to gather information to test an explanation, known as the **hypothesis**. That is, we try to disprove the hypothesis. If the hypothesis has not been disproved after multiple attempts to do so, then we have greater confidence that it is a correct explanation for our observations.

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We will use the scientific method to find a relationship between the angle of an inclined plane and the time it takes the ball to reach the bottom (Table 2).

Table 2 The scientific method breakdown

	Method	Example
Step 1: Observe and question	We observe a physical phenomenon and ask why this phenomenon occurs.	We roll a ball down a steep incline and a shallow incline, and observe that it takes the ball a shorter time to reach the bottom for a steeper incline. We ask what factors determine how long it takes a ball to roll down an inclined plane.
Step 2: Formulate an aim and hypothesis.	The aim of an experiment is a statement about the purpose of the research, and the hypothesis makes a testable prediction by describing the effect of changing one variable on another variable. To ensure the hypothesis meets this requirement, it can help to follow a structure such as: 'It is predicted that [increasing/decreasing] [independent variable] will [increase/decrease] [dependent variable] because [describe predicted relationship between independent variable and dependent variable].'	We consider which conditions were or could have been different between the two rolls down the plane. For example, the length of the roll, the angle of the plane, the time the ball was in contact with the plane. We formulate an aim: 'To investigate the relationship between the angle of inclination of a plane and the time it takes the ball to reach the bottom.' We formulate a hypothesis: 'It is predicted that increasing the angle of inclination of the plane will decrease the time it takes the ball to reach the bottom, because larger angles of inclination correspond to a larger component of the gravitational force acting parallel to the plane.'
Step 3: Experiment – test the hypothesis	When performing an experiment, only an independent variable should be deliberately changed. All other variables (controlled variables) should be kept constant. We should take several measurements of our dependent variable, at regular and frequent intervals of change in our independent variable. We record any relevant results, whether that is quantitative or qualitative, and record our method in detail (this will be explored further in Lesson 12C).	We measure the time it takes the ball to reach the bottom of the plane with a variety of angles of inclinations but we try to keep all other variables constant, such as the path of the ball, the material of the ball, size of ball, etc. We use eight different angles of inclinations of the plane. Using a greater number of angles will give us greater confidence in any trends we observe. We take five measurements of the time it takes the ball to reach the bottom of the plane for each value of the angle of inclination and then calculate the average time for each angle of inclination.
Step 4: Analyse and conclude	We should present information in a way that makes it clear what (if any) relationship exists between the variables in our experiment, such as plotting graphs of the dependent variable versus the independent variable. We try to make conclusions based on the analysis as to whether the data supports the hypothesis. We acknowledge any factors that may have affected our results that we could not control, or any uncertainty in our results. We can never have complete certainty that the conclusion is true because there may be variables that we did not correctly control or recognise.	We choose to represent the data on a graph, with the angle of inclination of the plane on the horizontal axis and the average time it takes the ball to reach the bottom of the plane on the vertical axis. We notice that the average time it takes the ball to reach the bottom of the plane seems to decrease as the angle of inclination of the plane increases. We conclude that our results support our hypothesis that 'increasing the angle of inclination of the plane will decrease the time it takes the ball to reach the bottom'. Even though we kept the path length constant, our measuring device could have an associated systematic error or we could have failed to control a variable.
Step 5: Share the results	We make our results, and the method we used, public for other people to view.	If other experimenters conduct their experiments rolling a ball down a plane and final similar results, then we become increasingly confident that increasing the angle of inclination of the plane will decrease the time it takes the ball to reach the bottom.

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PROGRESS QUESTIONS

Question 5

A hypothesis should always

A. state a scientific law.

B. predict the relationship between variables in an experiment.

C. include numerical calculations obtained from an experiment.

D. predict the specific values that will be measured in an experiment.

Question 6

Which of the following statements about the scientific method are true? **(Select all that apply)**

A. The scientific method guarantees that correct conclusions will be obtained.

B. The scientific method attempts to systematically eliminate incorrect explanations about the world.

C. The more data collected and the more independent experiments conducted, the greater confidence we can have in the conclusions of experiments that follow the scientific method.

D. We have confidence in a hypothesis that is supported by the scientific method because the experimenter has tried without success to disprove the hypothesis.

Theories, models, and laws 4.2.5.2

Theories, **models**, and **laws** help us communicate our understanding of the world around us. They may change as we develop better technology, but are accepted as true until disproved.

How do theories, models, and laws help our understanding of the physical world?

When the predictions made by a hypothesis have been tested many times, and the results consistently support the hypothesis, then the scientific community will consider the hypothesis to be true with a high degree of confidence. At this point, the explanation is now considered a scientific theory.

A law is a summary of that observation. When looking at the law on its own, we don't gain an understanding of why it happens, only what happens. For example, Newton's first law of motion tells us that an object will stay in motion unless acted upon by an external force.

We can use models to simplify concepts and phenomena that cannot be easily experienced or observed. For example, we model matter as being continuous, rather than made up of discrete atoms. Figure 1(a) shows the solid model of a cube, and Figure 1(b) shows a representation of where matter is concentrated in the nuclei of atoms, and the cube is mostly empty space.

USEFUL TIP

We can never say something is correct with complete certainty and any explanation must be considered possible until it has been disproved.

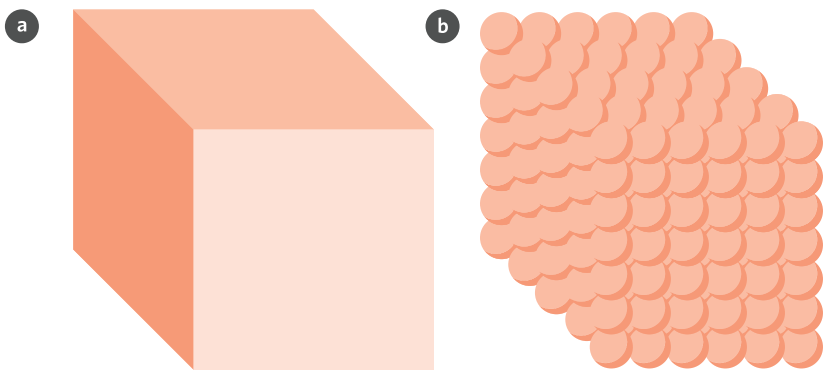

Figure 1 **(a)** Matter modelled as a solid, continuous entity and **(b)** attempting to model matter as a discrete entity made of atoms. Note that this diagram is not to scale.

USEFUL TIP

Examples of models we use in VCE Physics are the particle model of atomic nuclei, the electromagnetic wave model for light, and a vector model for forces.

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PROGRESS QUESTIONS

Question 7

A conclusion that is formed with high confidence due to withstanding rigorous testing and which can explain observations and predict the results of future experiments is best described as

A. a hypothesis.

B. a scientific model.

C. a scientific theory.

D. an observation or measurement.

Question 8

A simple representation that helps to describe and predict scientific results but which is known to be incomplete or partly incorrect is best described as

A. a hypothesis.

B. a scientific model.

C. a scientific theory.

D. an observation or measurement.

Theory summary

- An independent variable is directly changed by the experimenter.
- A dependent variable is observed or measured by the experimenter and is expected to be impacted by the independent variable.
- A controlled variable is kept constant to avoid affecting the observations or measurements of the dependent variable.
- Primary data is collected first-hand and secondary data is obtained from someone else, usually through research.
- Information collected in an experiment can be classified as quantitative (numerical) or qualitative (non-numerical) data.
- The scientific method is a way of reasoning to create theories about how the world works, by testing whether or not a hypothesis is supported by observations.
- A hypothesis is a proposed explanation which makes testable predictions about the relationship between variables.
- A scientific law is a statement of what happens in a phenomenon. A scientific theory is the how or why such an event occurs.
- Scientific models are representations which help explain physical theories.

12A Questions

Mild 🌶 Medium 🌶🌶 Spicy 🌶🌶🌶

Exam-style

Question 9 (2 MARKS)

Nathan wants to experiment on centripetal force but does not have the equipment he needs at home. Instead, he researches online for data to use.

a. What type of data has Nathan collected? 🌶 1 MARK

b. If Nathan is then able to complete the experiment himself with school equipment, what type of data does he collect? 🌶 1 MARK

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Question 10 (2 MARKS)

Explain the difference between a scientific law and a theory.

Question 11 (3 MARKS)

For each of the following statements **a**, **b** and **c**, identify whether they are best described as a:

- Scientific law
- Scientific model
- Scientific hypothesis.

a. The shape of the Earth is treated as a perfect sphere for the purpose of calculations. 1 MARK

b. Ice melts into water when provided with sufficient heat. 1 MARK

c. If larger-mass objects roll downhill at a greater rate than smaller-mass objects, then the time taken for the cart to reach the bottom should decrease when the mass on the cart is increased. 1 MARK

Question 12 (5 MARKS)

Meg conducts an experiment in which she measures how loud the alert tone from her phone is at various distances. She measures the sound as 'quiet', 'medium', 'loud', and 'very loud'. She uses the same volume setting on her phone for each trial and conducts the experiment in a large quiet outdoor space.

a. Identify the independent variable and whether it is measured with quantitative data or qualitative data. 2 MARKS

b. Identify the dependent variable and whether it is measured with quantitative data or qualitative data. 2 MARKS

c. State a possible controlled variable in this experiment. 1 MARK

Adapted from 2017 VCAA Exam Short answer Q9b

Question 13 (3 MARKS)

Ava and Julian notice that when they drop a rubber ball from a low height onto concrete, the ball doesn't bounce back as high as when it is dropped from a greater height. They want to conduct an experiment to find the relationship between the height a ball is dropped and the peak of its initial bounce.
Write a hypothesis for this experiment.

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12B Scientific conventions

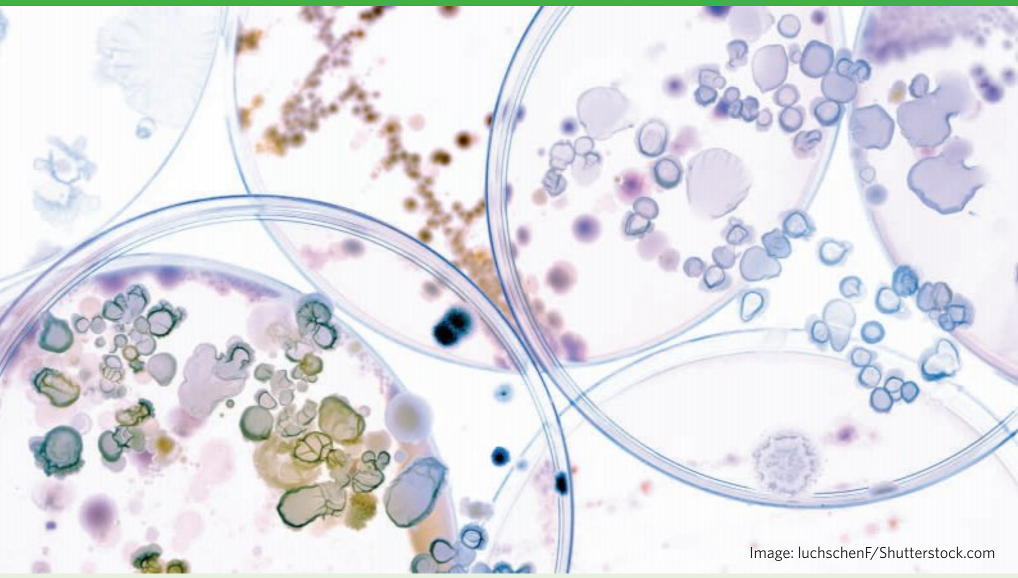

Image: luchschenF/Shutterstock.com

How small is a cell?

Scientists need to communicate information about objects as small as a bacterium or subatomic particle, as large as black holes, or far as the distance between the Earth and the Sun. All these distances or lengths can be measured in metres, however scientists have developed language and conventions in order to communicate about their relative sizes in different ways. By using scientific notation and conventions of measurement, everyone can understand the size and confidence of these values.

STUDY DESIGN DOT POINT

- apply the conventions of science communication: scientific terminology and representations; symbols, equations and formulas; standard abbreviations; significant figures; and units of measurement

12A 12B 12C 12D 12E

4.2.8.1 Units of measurement

4.2.8.2 Significant figures

KEY TERMS AND DEFINITIONS

magnitude the size or numerical value of a quantity without sign (positive or negative) or direction

SI unit an accepted standard unit used for measuring a quantity

significant figures all digits quoted, starting with the first non-zero digit, giving an indication of the confidence in a measurement

Units of measurement 4.2.8.1

We use units of measurement as a standard reference for the **magnitude** of different quantities, so that different physical objects and processes can be compared. There are many different systems of measurement used in different countries and contexts.

How can we describe quantities using SI units?

The seven base units are, found in Table 1, defined in terms of physical constants or processes. For example:

- The metre is defined with reference to the speed of light.
- The second is defined by the frequency of energy transitions in caesium-133.

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USEFUL TIP

When an answer is asked for in SI units, this includes both base units and derived units.

USEFUL TIP

The astronomical unit is a unit of length used in astronomy, the study of objects beyond Earth's atmosphere. It is the mean distance from the Earth to the Sun, approximately 150 million kilometres.

Table 1 The base **SI units** and their symbols

Quantity	Unit name	Symbol
Time	second	s
Length	metre	m
Mass	kilogram	kg
Electric current	ampere	A
Temperature	kelvin	K
Amount of substance	mole	mol
Luminous intensity	candela	cd

All other SI units are derived from the base SI units (formed by multiplying or dividing the SI units). A few examples of derived SI units can be found in Table 2, but are not required knowledge for VCE Physics.

Table 2 Some derived SI units and their symbols

Quantity	Unit name	Symbol	Equivalent base SI units
Frequency	hertz	Hz	s^{-1}
Force	newton	N	$kg\ m\ s^{-2}$
Energy	joule	J	$kg\ m^2\ s^{-2}$
Resistance	ohm	Ω	$kg\ m^2\ s^{-3}\ A^{-2}$

Certain quantities like velocity and acceleration, shown in Table 3, do not have their own dedicated SI units. Instead they each use equivalent base and/or derived SI units. These units are required knowledge for VCE Physics.

USEFUL TIP

We can gain a lot of clues about physics problems from unit analysis. For example, if we see the unit for velocity is $m\ s^{-1}$ (metres divided by seconds), that indicates that the formula for velocity will contain some length variable divided by some time variable.

Table 3 The equivalent base/derived SI units for other select quantities

Quantity	Equivalent base/derived SI units
Velocity	$m\ s^{-1}$
Acceleration	$m\ s^{-2}$
Area	m^2
Volume	m^3
Specific heat capacity	$J\ kg^{-1}\ K^{-1}$
Specific latent heat	$J\ kg^{-1}$

Prefixes, shown in Table 4, are used to change the magnitude and indicate the factor by which the value should be multiplied. For example, nine picometers = 9.0 pm = 9.0×10^{-12} m.

USEFUL TIP

The SI unit for mass (the kilogram) is a special case since it has a prefix already within its name ('kilo'). Prefixes are put in front of 'grams' instead. For example, one milligram expressed in SI units would be 10^{-6} kilograms.

Table 4 Some SI prefixes

Symbol	p	n	μ	m	k	M	G
Prefix	pico	nano	micro	milli	kilo	mega	giga
Order of magnitude	10^{-12}	10^{-9}	10^{-6}	10^{-3}	10^3	10^6	10^9

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PROGRESS QUESTIONS

Question 1

Which of the following are base or derived SI units? **(Select all that apply)**

A. volts **B.** ohms **C.** seconds **D.** fahrenheit

Question 2

What is 6.4 kJ, expressed in J?

A. 6.4×10^{-3} J **B.** 6.4 J **C.** 6.4×10^{3} J **D.** 6.4 kV

Significant figures 4.2.8.2

When representing numerical information, it is important to communicate how confident we are in the measurement.

How do we use significant figures?

Significant figures indicate to what degree we are confident in a value. This ties heavily into the concept of uncertainty which will be explored in Lesson 12C.

There are certain conventions used when representing numbers in VCE Physics, so that the reader can understand how confident we are in our values. Table 5 shows how conventions are used to determine the number of significant figures in a value.

Table 5 Significant figure conventions

Convention	Example	Number of significant figures
Leading zeros are never significant	0.32	Two
All non-zero digits are always significant	53.2	Three
Trailing zeros are always significant.	53.00 **OR** 5300	Four
Zeros between digits are always significant.	302	Three

Table 6 shows the rules that we follow so the results of our calculations are expressed to the correct level of confidence given the level of certainty in the numbers with which we started.

Table 6 Conventions for calculations

Operation	Convention for answer	Example
Addition and subtraction	Least number of decimal places	$34.477 + 2.31 = 36.78$ Final answer has 2 decimal places as 2.31 has 2 decimal places
Multiplication and division	Least number of significant figures	$34.477 \times 2.31 = 79.6$ Final answer has 3 significant figures as 2.31 has 3 significant figures

USEFUL TIP

The significant figures given for constants in a formula sheet limits the number of significant figures in exam-style questions. For example, any question involving $c = 3.0 \times 10^{8}$ m s^{-1} will be limited to 2 significant figures.

STRATEGY

In worked solutions in this book, we will provide additional significant figures in each line of working to avoid rounding errors in the final answer.

Calculations should be rounded to the correct number of significant figures only in the last step of working. Otherwise, rounding during working can result in an incorrect answer.

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PROGRESS QUESTIONS

Question 3

The number 180 030 contains

A. one significant figure.

B. five significant figures.

C. six significant figures.

D. seven significant figures.

Question 4

The answer to $7.113 + 0.64$, expressed to the correct number of decimal places, is

A. 7.7. **B.** 7.75. **C.** 7.753. **D.** 7.7530.

Question 5

The answer to 0.51×1.996, expressed to the correct number of significant figures, is

A. 1.0. **B.** 1.02. **C.** 1.018. **D.** 1.0180.

How do we use scientific notation?

We can use scientific notation to express the value to the correct number of significant figures. We write numbers in scientific notation in the following form:

$$m \times 10^n$$

m must be a number where the absolute value is greater than or equal to 1 and less than 10 (such as 5 or 4.56) and n is an integer. All the digits in m are significant.

We use scientific notation for two reasons:

- to write large and small numbers with only a few digits.
  - For example, 6.67×10^{-11} without using scientific notation is written as 0.0000000000667.
- to correctly represent the degree of certainty we have in numerical values.
  - For example, if we say a building is 20 m tall then we are saying that we measured it to the nearest m.
  - However, if we write that the building is 2.00×10^1 m tall, we are saying that we measured it to be 20.0 m tall, or 20 m tall to the nearest 10 cm.

Table 7 shows how to write numbers using scientific notation.

Table 7 Examples of how to write numbers using scientific notation

Number	Scientific notation	Significant figures
230	2.30×10^2	3
−0.00067	-6.7×10^{-4}	2
0450.2	4.502×10^2	4
0.3700	3.700×10^{-1}	4

USEFUL TIP

The absolute value of a number is the non-negative value of that number. It is often expressed as $|x|$ such that

- $|5| = 5$.
- $|-5| = 5$.

USEFUL TIP

When converting from standard notation to scientific notation, the magnitude of n is the number of digits between the first significant digit and the decimal place.

- If the first significant digit is before the decimal place, move the decimal place n digits to the left, Figure 1(a).
- If the first significant digit is after the decimal place, move the decimal place n digits to the right (the n value is negative), Figure 1(b).

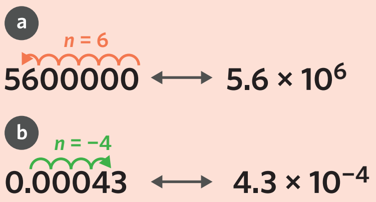

Figure 1 Converting between standard and scientific notation when n is **(a)** positive and **(b)** negative

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WORKED EXAMPLE 1

Convert 467.1 km to the SI unit for length, with two significant figures.

Step 1

Identify known and unknown variables and write down the formula that relates these variables.

$L = 467.1$ km, $L = ?$ m

L (km) $\times 10^3 = L$ (m)

Step 2

Substitute values into the formula and solve for the length in metres.

$467.1 \times 10^3 = 4.671 \times 10^5$ m

Step 3

Convert the value to the required number of significant figures.

$4.671 \times 10^5 = 4.7 \times 10^5$ m

PROGRESS QUESTIONS

Question 6

How can we express 0.030 L in scientific notation?

A. 3.0×10^{-2} L

B. 3.0×10^{-1} L

C. 3.0 L

D. 3.0×10^{2} L

Question 7

How do we express 8.7×10^3 g in standard notation?

A. 0.0087 g **B.** 8.7 g **C.** 8700 g **D.** 87000 g

Theory summary

- SI units are used in scientific contexts, and most physical formulas require SI units to be used to attain correct values.
  - Prefixes can be added to SI units to indicate different orders of magnitude.
- The following rules apply to significant figures:
  - All digits are significant except leading zeros in VCE Physics.
  - When adding or subtracting, the final answer should have the same number of decimal places as the lowest provided quantity.
  - When multiplying or dividing, the final answer should have the same number of significant figures as the lowest provided quantity.
- Numbers can be written in scientific notation by writing them in the form $m \times 10^n$.

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12B Questions

Mild 🌶 Medium 🌶🌶 Spicy 🌶🌶🌶

Exam-style

Question 8 (5 MARKS)

Write the following numbers in scientific notation, to two significant figures.

a. 6000 🌶 1 MARK

b. 8 900 000 🌶 1 MARK

c. 63 700 🌶 1 MARK

d. 0.00034 🌶 1 MARK

e. 0.0125 🌶 1 MARK

Question 9 (5 MARKS)

Express the following quantities in terms of SI units and in scientific notation.

a. 600 ms 🌶 1 MARK

b. 0.400 μg 🌶 1 MARK

c. 23 MΩ 🌶 1 MARK

d. 360 nm 🌶 1 MARK

e. 7.0 pA 🌶 1 MARK

Question 10 🌶🌶 (2 MARKS)

Yusif and Nina are adding together a set of numerical data as listed below.

12.1, 14.25, 8.0, 10.984, 15.0982

Nina claims that the final answer should have two significant figures as the final answer should only have as many significant figures as the least in the addition. Yusif disagrees, and claims that the final answer should have only one number after the decimal place.

Evaluate whether Nina or Yusif is correct and provide a reason why.

Question 11 (2 MARKS)

Oliver wants to know how many times 200 goes into 7.4. He wants his calculation to follow scientific conventions.

a. How many significant figures should Oliver's solution have? 🌶🌶 1 MARK

b. Solve Oliver's problem. Give the answer in scientific notation and to the correct number of significant figures. 🌶🌶 1 MARK

Question 12 🌶🌶 (2 MARKS)

Calculate the electric potential energy (E) of a 4.00 C charge (Q) after passing through a 6.00 V (V) laptop charger to the correct number of significant figures. The formula for electric potential energy is $E = VQ$. For this question we do not need to change the units, as multiplying charge by voltage gives the SI unit for energy, J.

Question 13 🌶🌶🌶 (3 MARKS)

Calculate the average speed for the journey of a runner who takes 67.0 seconds to run 0.135 kilometres up a hill and a further 63 metres along a footpath to the correct number of significant figures. Average speed is calculated using $speed = \frac{total\ distance}{time}$.

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12C Collecting data

What are the consequences of invalid data?

Gathering data well and being able to assess its quality is a key part of science and has many applications in the modern world. Using bad data can have catastrophic and expensive consequences as it did for Amazon in 2014 when numerous items in its store were accidentally repriced at one penny causing the retailer to lose mountains of money. To avoid catastrophic conclusions and make valid ones, when collecting data in an experiment, there are many things to keep in mind. Errors can occur when care is not given to the scientific method. This can impact the precision and accuracy of our data, as well as create uncertainties.

STUDY DESIGN DOT POINTS

- identify and apply concepts of accuracy, precision, repeatability, reproducibility, resolution and validity of data; and the identification of, and distinction between, error and uncertainty
- model the scientific practice of using a logbook to authenticate generated primary data

12A 12B **12C** 12D 12E

- **4.2.3.1** Precision, accuracy and resolution
- **4.2.3.2** Error and uncertainty
- **4.2.3.3 & 4.2.10.1** Validity, repeatability, reproducibility and logbooks

KEY TERMS AND DEFINITIONS

precision a relative indicator of how closely different measurements of the same quantity agree with each other

accuracy a relative indicator of how well a measurement agrees with the 'true' value of a measurement

resolution the smallest change in a quantity that is measurable

error a mistake, issue, or limitation with some aspect of the experiment causing results to deviate from the 'true' value

uncertainty the quantitative judgement of how well a measurement measures what it intends to

systematic error a consistent, repeatable deviation in the measured results from the true values, often due to a problem with the experimental design or calibration of equipment

personal error mistakes in the execution of an experiment or the analysis, caused by a lack of care that negatively impact or invalidate the conclusions of an experiment

random error the unpredictable variations in the measurement of quantities

validity the degree to which an experiment measures what it intends to measure

logbook a complete chronological record of the experimental procedure and results

repeatability the closeness of agreement of results when an experiment is repeated by the same experimenter under the same conditions (using the same equipment and in the same laboratory)

reproducibility the closeness of agreement of results when an experiment is replicated by a different experimenter under slightly different conditions (using their own equipment and laboratory)

Precision, accuracy, and resolution 4.2.3.1

Precision is an indicator of how well a set of measurements agree with each other. It can be thought of as a measure of the spread or range of data – a larger range is less precise.

Accuracy is an indicator of how well a measurement agrees with the 'true' value of a measurement. This 'true' value is the value that would be measured if it were possible to take measurements with no errors.

How are precision and accuracy different?

Both precision and accuracy are relative indicators, and therefore, measurements cannot be objectively 'precise' or 'accurate'. Instead, they can only be more or less precise or accurate compared to another set of measurements.

We can use targets to help us visualise the difference between precision and accuracy, shown in Figure 1. The bullseye of the target is the desired, 'true' value.

- Figure 1a shows our arrows consistently hitting a similar area of the target, but not the bullseye. This demonstrates precise yet inaccurate data.
  - If we translate this to data, our data would have a small range, and hence be more precise.
- Figure 1b shows our arrows hitting near the bullseye, but they are not closely spaced. This demonstrates accurate yet imprecise data.
  - If we translate this to data, the average of our data would be close to the 'true' value but may have a wide range of values.

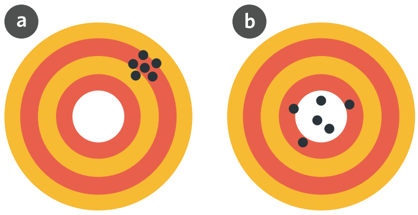

Figure 1 Targets depicting **(a)** high precision and **(b)** high accuracy

Precise measurements aren't necessarily accurate, and measurements that differ from the true value can still be considered precise. We can therefore categorise data based on both accuracy and precision, shown in Figure 2.

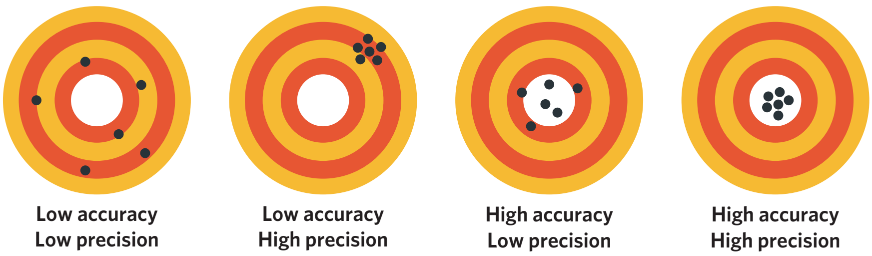

Figure 2 Targets Illustrating different levels of precision and accuracy

Resolution is the smallest change in the quantity being measured that causes a detectable change in the value indicated on the measuring instrument. The smaller the resolution, the less uncertainty the recorded value will have. The digital stopwatch, shown in Figure 3a, with a resolution of 0.01 s will be able to make a reading with a higher certainty compared to an analogue stopwatch, shown in Figure 3b, with a resolution of 0.5 s.

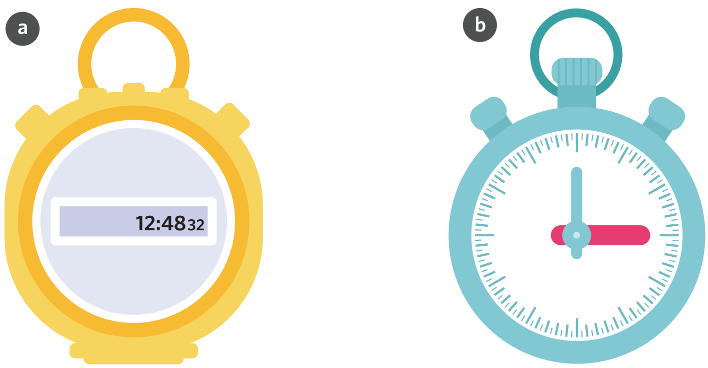

Figure 3 **(a)** The digital stopwatch has a higher resolution compared to the **(b)** analogue stopwatch.

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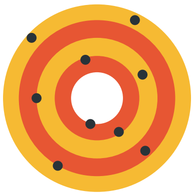
PROGRESS QUESTIONS

Use the following diagram for questions 1 and 2.



Question 1

The diagram shows data that is

A. not precise. **B.** very precise. **C.** very inaccurate. **D.** accurate and precise.

Question 2

The data shown is accurate because

A. it is not precise.
B. all the data points are on the target.
C. the data points are spread out across the target.
D. the average of the data points are close to the centre of the target.

Question 3

What is the resolution of a 10 cm ruler with millimetre marking?

A. 10 cm **B.** 1 cm **C.** 1 mm **D.** 0.5 mm

Error and uncertainty 4.2.3.2

The data we obtain in an experiment will never be perfectly accurate, as many types of **errors** can occur. Errors lead to an increase in **uncertainty** in the data collected in the experiment.

USEFUL TIP

Since all measurements are impacted the same by a systematic error, averaging them out will not improve the accuracy of the data.

What are the different types of errors?

Systematic errors are errors that uniformly affect the accuracy of data in an experiment. Examples include:

- An uncalibrated weighing scale. Each measurement would differ from the true value by a consistent amount.
- Parallax error, which occurs when an analogue scale is read at an angle to the display, shown in Figure 4.

To reduce the effect of systematic errors, we should calibrate all equipment before conducting the experiment, and analyse the method to identify steps that could introduce errors.

Personal errors are mistakes in an experiment's execution or analysis caused by a lack of care that negatively impact or invalidate the conclusions of an experiment. An example of personal error could be misreading the scale on a thermometer. Data points with these types of errors should not be included in the report or analysis of data.

Random error is the unpredictable variation in the measurement of quantities. In general, random errors can be reduced but not entirely avoided. Examples of where random error is introduced include:

- reading between the intervals of a measuring device.
- taking values from a device where the value is fluctuating.

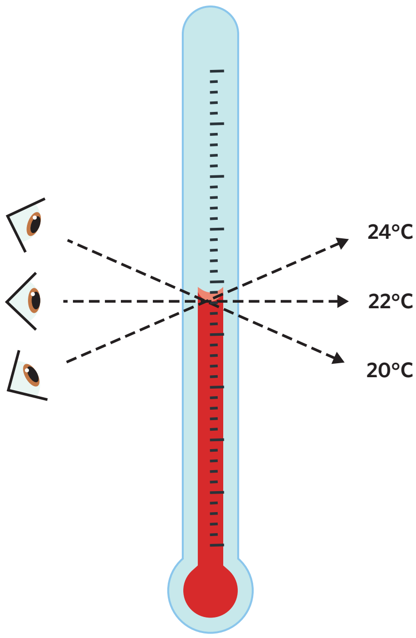


Figure 4 Examples of parallax error when reading a thermometer

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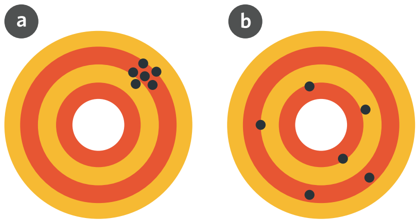

Figure 5 Targets depicting **(a)** systematic error and **(b)** random error

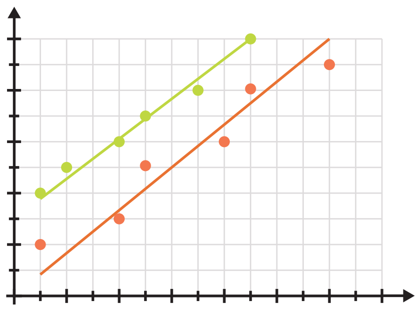

Figure 6 Plots of two experiments measuring a relationship between the same two variables

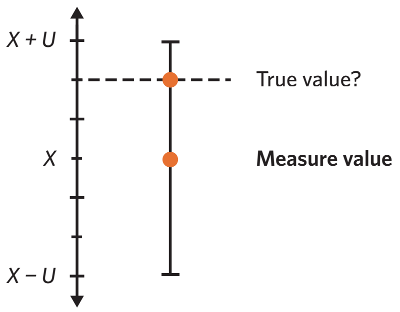

Figure 7 The 'true' value of X can be anywhere within the uncertainty bounds. U represents the uncertainty in this experiment.

Any physical measurement will have an associated random error which is caused by uncontrolled variations in the conditions of an experiment between each trial. We can reduce random error by:

- choosing equipment that will result in less variation.
- averaging the results from repeated measurement, improving accuracy.

We can use our target analogy to help us understand the difference between systematic and random error.

- In Figure 5a, the arrows, our data, are all impacted by the same systematic error and become less accurate.
- In Figure 5b, the arrows, our data, are impacted by random errors and become less precise.

We can see systematic and random errors when we plot our data. Plotting data is discussed in more detail in Lesson 12D. In Figure 6, the 'true' data is the dots that lie on the orange line.

- The green line has a non-zero *y*-intercept when it is supposed to. This is usually an indicator of systematic error since all points are impacted similarly.
- The orange data points that do not sit on the trendline indicate that random error has occurred, since not all points are impacted the same.

Any sources of error that cannot be removed, or were not identified during the experiment, should be discussed in the experimental report.

Uncertainty

Uncertainty is an indicator of a range that the 'true' value of a measurement should lie within, as shown in Figure 7. Although errors may increase uncertainty, having uncertainty in measurements is unavoidable as there will always be inaccuracies with any measuring instrument.

Uncertainty is usually expressed as the *average* $\pm$ *uncertainty*, or as uncertainty bars on a graph – which we will look at in Lesson 12D. For example, if the average of three measurements is 35 mm and the measuring device we use has an uncertainty of 1 mm, then we can express this as 35 $\pm$ 1 mm. This means that the range in which the true value should lie in is 34–36 mm.

USEFUL TIP

Uncertainty can be reduced by by increasing the resolution of a measuring device, so by using measurements with smaller intervals, such as using a ruler with millimetre markings rather than centimetre markings. This is because uncertainty of a measuring device is calculated as half of the smallest measuring increment.

For VCE Physics, we only need to be able recognise uncertainty in the form X $\pm$ U or as uncertainty bars, draw uncertainty bars, or state the uncertainty given as uncertainty bars.

PROGRESS QUESTIONS

Question 4

A measurement is given in the form 14 $\pm$ 1 cm. What is the uncertainty in the measuring device?

A. 1 cm **B.** 14 cm **C.** 0.1 cm **D.** 13 cm to 15 cm

Question 5

When a measurement is taken from the average of multiple readings, taking more readings

A. increases the effect of random error.
B. reduces the effect of systematic error.
C. does not change the effect of random error.
D. does not change the effect of systematic error.

Continues →

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Question 6

Which of the following statements about error is correct?

A. Random errors are unavoidable.

B. Personal errors are unavoidable.

C. Systematic errors do not affect all data points.

D. Random errors cause the measured value to be uniformly different from the true value.

Validity, repeatability, reproducibility, and logbooks 4.2.3.3 & 4.2.10.1

An experiment is regarded as valid if it successfully measures what it aims to measure. If there are any errors during any part of the experiment, it may impact the **validity** of the experiment. A **logbook** is a way of improving the validity of your own experiment and future attempts at the same experiment.

How do we know an experiment is valid?

The validity of an experiment can be impacted before, during, and after performing an experiment. Table 1 shows some of the requirements in order for an experiment to be considered valid.

Table 1 Some requirements for an experiment to be valid before, during and after an experiment. This list is not exhaustive.

Time period	Elements necessary to be valid
Before the experiment	• The experiment is designed to change only one independent variable at a time and measure one dependent variable. • No variables, other than the independent variable, are changed. • The experiment is designed to minimise errors and uncertainties. • All necessary assumptions for analysis (such as simplifications) are addressed in the design of the experiment.
During the experiment	• No controlled variables are allowed to change. • All steps of the scientific method are followed. • The experiment measures the correct dependent variable. • Appropriate equipment is used in order to minimise errors and uncertainties. • Observer bias is minimised. • An accurate and chronological logbook documenting the experimental process and results is kept.
After the experiment (data analysis)	• All data is included and explained. Data cannot be arbitrarily selected to produce the desired trend. • Any outliers are addressed in the discussion and are included in the initial data. • Results are examined. Correlation between two variables is not automatically assumed to mean causation.

There are two main ideas that are affected by the presence of errors:

- **Repeatability** refers to the closeness of results to an original experiment (the precision) when an experiment is repeated by the same experimenter under the same conditions (using the same equipment and in the same laboratory).
- **Reproducibility** refers to the closeness of results to an original experiment (the precision) when an experiment is repeated by a different experimenter under slightly different conditions (using their own equipment and laboratory).

PROGRESS QUESTIONS

Question 7

Experiments with reproducible results

A. can be replicated by other experimenters under the same conditions to yield similar results.

B. can be replicated by the same experimenter under the same conditions to yield similar results.

C. can be replicated by other experimenters under different conditions to yield similar results.

D. can be replicated by the same experimenter under different conditions to yield similar results.

Question 8

Experiments with repeatable results

A. can be replicated by other experimenters under the same conditions to yield similar results.

B. can be replicated by the same experimenter under the same conditions to yield similar results.

C. can be replicated by other experimenters under different conditions to yield similar results.

D. can be replicated by the same experimenter under different conditions to yield similar results.

Why do we need a logbook?

Logbooks are an experimenter's note-keeping device and a place to store all the information about the experiment they are performing. A logbook should:

- contain a table of contents.
- be kept in chronological order with records of date and time of entry.
- contain as much information as possible about the experimental method and any mistakes or errors that occurred during the experiment.
- contain any sketches or diagrams for the apparatus used in the experiment.
- contain all experimental data and some information about how it was taken.
- contain all working for any transformations or mathematical manipulations of the data used.
- contain any discussion or conclusions made about the experiment.
- contain anything else that might be useful for a future experimenter to look at to perform the experiment.

Logbooks are key to assessing the validity of our own experiments and for future experimenters to reproduce our work.

- Experimenters can compare their results to ours to assess the reproducibility of the experiment.
- Similarly, we can compare our own repetitions of the experiment to determine the repeatability.

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PROGRESS QUESTIONS

Question 9

Which of the following would not appear in a logbook?

A. a record of the room's temperature

B. a discussion of the experimental method

C. any graphs produced by the experimental data

D. a description of your experimental partner's breakfast

Theory summary

- Precision and accuracy are relative measures describing the spread of a set of measured values and how well the set of measurements relates to the 'true' value.
  - A more precise set of measurements will have a smaller range of data.
  - A more accurate set of measurements will have an average closer to the true value.
- Resolution is the smallest increment of change that can be detected by a measuring device.
- Experimental errors impact the data collected and results. Minimising these reduces uncertainty in our measurements.
  - Systematic error is a consistent, repeatable deviation in the measured results from the true values.
  - Random error is the unpredictable variations in the measurement of quantities.
- An experiment is valid if it is able to measure what it intends to measure.
- Repeatability and reproducibility refer to the ability of the results to be obtained by replicating the experiment under the same or different conditions.

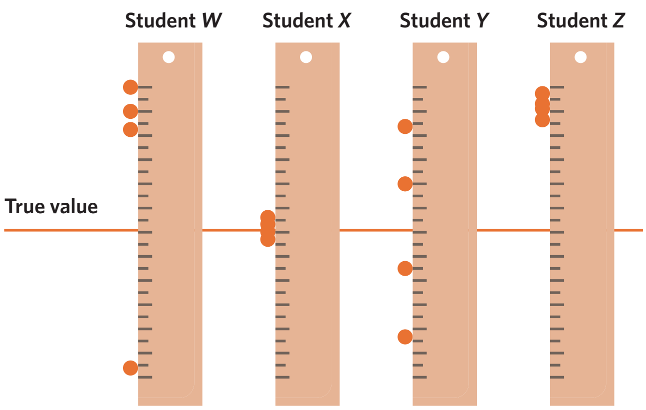
12C Questions

Mild 🌶 Medium 🌶🌶 Spicy 🌶🌶🌶

Exam-style

Use the following information to answer questions 10 and 11.

Four students take multiple measurements of the length of a piece of wire. The measurements are indicated as dots on a ruler (as shown on the diagram). The true value of the length of the wire is also indicated on the diagram.



Question 10 (1 MARK)

Which student's results are the most precise and accurate?

A. Student *W*

B. Student *X*

C. Student *Y*

D. Student *Z*

Adapted from 2019 VCAA NHT Exam Multiple choice Q20

Question 11 (1 MARK)

Which student's results are the least accurate?

A. Student *W*

B. Student *X*

C. Student *Y*

D. Student *Z*

Adapted from 2019 VCAA NHT Exam Multiple choice Q20

Question 12 (1 MARK)

Which one of the following statements about systematic and random errors is correct?

A. Effect of random errors can be reduced by averaging readings.

B. Effect of systematic errors can be reduced by averaging readings.

C. Effect of both random and systematic errors can be reduced by repeated readings.

D. Effect of neither systematic nor random errors can be reduced by repeated readings.

Adapted from 2017 VCAA exam Multiple choice Q20

Question 13 (10 MARKS)

Gen and Jana perform an experiment and measure the voltage across a resistor. The true value of the voltage is 4.2 V.

	Trial 1	Trial 2	Trial 3	Trial 4
Gen	4.0 V	4.5 V	3.6 V	4.3 V
Jana	3.8 V	4.1 V	4.2 V	3.9 V

a. Calculate the average of Gen's and Jana's results. 2 MARKS

b. Calculate the range of Gen's and Jana's results. 2 MARKS

c. Comment on the relative accuracy of Gen and Jana's results. 2 MARKS

d. Comment on the relative precision of Gen and Jana's results. 2 MARKS

e. Gen and Jana did not keep a logbook for this experiment. Comment on the reproducibility and repeatability of this experiment. 2 MARKS

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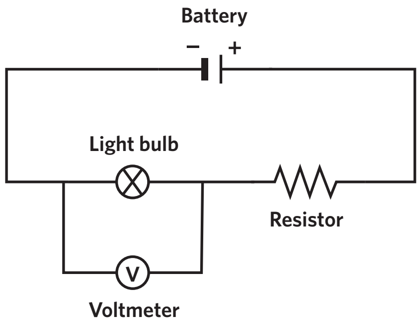
Question 14 (1 MARK)

Gwen designs an experiment to determine how the voltage drop across a lightbulb in a series circuit varies with the resistance of the lightbulb. The circuit also contains a resistor.



Consider the options below and indicate which options (when added individually to this experimental design) would result in the experiment (including experimental method, analysis, and conclusions) being invalid. **(Select all that apply)**

Note: knowledge of electricity and circuits is not required to answer this question

A. The resistance of the light bulb being tested is varied between 5 Ω and 20 Ω in 5 Ω intervals.

B. An 8 V battery is used for all trials.

C. The voltage of the battery is changed for the 20 Ω lightbulb test to a 6 V battery from an 8 V battery. This impacts the voltage drop across the light bulb.

D. Measurements of the voltage are taken three times for each light bulb and then averaged.

E. The resistance of the resistor is changed during trials of the 10 Ω light bulb. This impacts the voltage drop across the light bulb.

F. Gwen notices the display on the voltmeter flicks between a few values before settling down when she turns the circuit on, so she chooses the value that seems closest to her experimental prediction.

G. The voltmeter used dies halfway through the experiment and is switched out for a different model of voltmeter.

H. Data is analysed to plot resistance on the horizontal axis and voltage drop on the vertical axis.

I. An obvious outlier result is excluded from the data in Gwen's report and left unmentioned.

J. Another student is able to repeat Gwen's experiment and produce the same results.

Question 15 (3 MARKS)

Explain why ensuring measuring devices are properly calibrated can increase the accuracy of measurements.

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12D Representing and analysing data

STUDY DESIGN DOT POINT

- apply methods of organising, analysing and evaluating primary data to identify patterns and relationships including: the physical significance of the gradient of linearised data; causes of uncertainty; use of uncertainty bars; and assumptions and limitations of data, methodologies and methods

12A 12B 12C **12D** 12E

4.2.6.1 Plotting data

4.2.6.2 Drawing straight lines and curved lines of best fit

4.2.6.3 Calculating the gradient

ESSENTIAL PRIOR KNOWLEDGE

12A Independent and dependent variables

12C Uncertainty

See questions 102–103.

Image: Alex Cimbal/Shutterstock.com

How can data predict the future?

Analysing and using data effectively is one of the most important skills required for modern science. It allows us to predict weather patterns, determine the risk of particular illnesses, and discover new particles. This lesson explores key data skills such as graphing, drawing straight lines and curved lines of best fit, and analysing gradients. Understanding these conventions is important for clearly and correctly communicating data from a scientific investigation.

KEY TERMS AND DEFINITIONS

linearise the process of transforming data so that, when graphed, a straight line of best fit can be drawn through the data

gradient the graphical representation of the rate of change of one variable with respect to another

straight line of best fit a straight line that indicates the relationship between the independent and dependent variables on a graph

curved line of best fit a curved line that indicates the relationship between the independent and dependent variables on a graph

trendline see straight line of best fit or curved line of best fit

FORMULAS

- **gradient of a straight line**

$$gradient = \frac{rise}{run} = \frac{y_2 - y_1}{x_2 - x_1}$$

Plotting data 4.2.6.1

Graphs help provide a visualisation of data. There are conventions that should be followed for labelling the graph, choosing a scale for each axis, and plotting uncertainty bars. Data can also be **linearised** to help understand the relationship between variables.

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How do we represent our data visually?

Data collected in an experiment can be represented in a table. To help us understand the concepts and conventions of plotting graphs, we will use the example of an experiment that investigates the relationship between the time it takes for a block to slide down a one metre ramp and the angle of the ramp. We may include the uncertainties along with the average from our multiple trials, see Table 1.

Table 1 Data collected and analysed in an experiment

Angle (± 5°)	Time for block to slide down ramp (± 0.1 s)			Average time for block to slide down ramp (s)
	Trial 1	Trial 2	Trial 3	
10	3.2	3.5	3.4	3.4 ± 0.2
20	2.4	2.5	2.4	2.4 ± 0.1
30	1.8	2.1	2.0	2.0 ± 0.2
40	1.8	1.8	1.7	1.8 ± 0.1
50	1.5	1.7	1.6	1.6 ± 0.1
60	1.4	1.5	1.5	1.5 ± 0.1

USEFUL TIP

Averages can be calculated by taking the sum of a group of values and dividing by the number of values. For example the average of 3.2, 3.5 and 3.4 is

$$avg = \frac{3.2 + 3.5 + 3.4}{3} = 3.367 = 3.4$$

We can use the table to create a list of coordinate points that should be graphed to analyse the relationship between the independent variable and dependent variable.

- The first value in the coordinate pair corresponds to the independent variable and the second corresponds to the dependent variable.
- In our example, the independent variable is the angle of the ramp and the dependent variable is the average time for the block to slide down the ramp.
  - As such, the points to be plotted are: (10, 3.4), (20, 2.4), (30, 2.0), (40, 1.8), (50, 1.6), (60, 1.5).

There are several conventions that must be followed to correctly represent scientific data on a graph. We label the axes and title the graph to communicate what was recorded from the experiment.

- The independent variable should be plotted on the horizontal axis.
- The dependent variable should be plotted on the vertical axis.
- The variables should be labelled on the relevant axis with their respective units.
- The graph title should generally be of the form '[dependent variable] vs. [independent variable]'.

Each axis should have a consistent scale so that the intervals between grid lines on an axis represent a constant value. Note that this is not the case for logarithmic graphs; where the intervals instead represent a constant ratio.

- The scale on each axis should be chosen so that the data points take up the majority of the available graph space (the spread of the data points should cover more than 50% of each axis).
- An axis can (but does not have to) indicate a power of ten on the scale by which all values on that axis should be multiplied.

USEFUL TIP

In an exam, marked axes and a grid will be provided but sometimes an appropriate scale will need to be chosen. When answering graphing questions from this book, it is suggested to sketch answers on graph paper to practise choosing an appropriate scale to fit a given grid and data set.

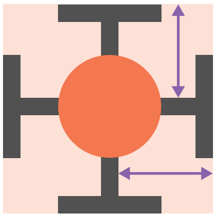

Figure 1 A point with horizontal and vertical uncertainty bars

If measurement uncertainties are stated, uncertainty bars can be plotted on the graph using lines with an end cap. The length of the lines indicate the magnitude of the uncertainty.

- Horizontal uncertainty bars represent the uncertainty in the independent variable.
- Vertical uncertainty bars represent the uncertainty in the dependent variable.
- The combination of the horizontal and vertical uncertainty bars indicates a rectangular area where the 'true' value may be, as indicated by the shaded box in Figure 1.

Using these principles, an appropriate graph for the data from Table 1 is shown in Figure 2.

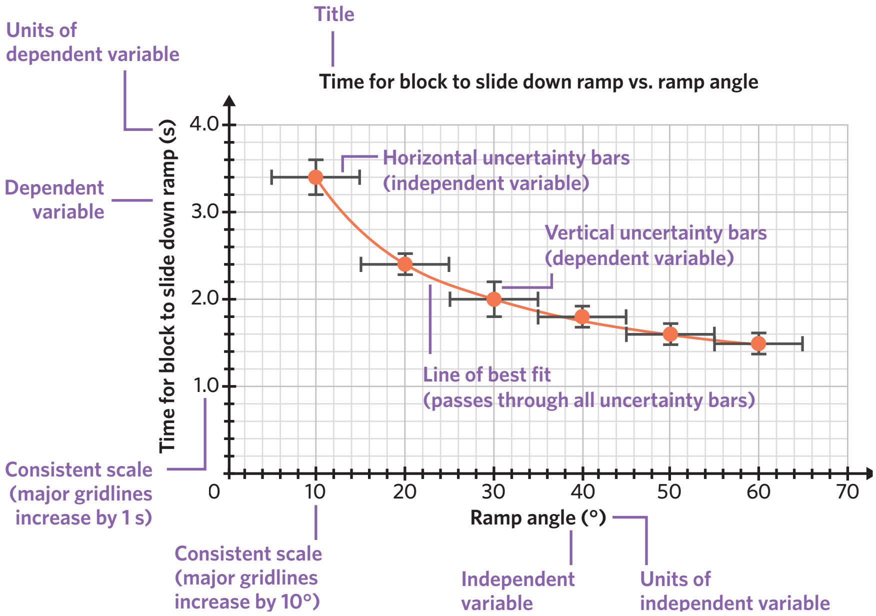

Figure 2 An annotated graph of the data from Table 1

PROGRESS QUESTIONS

Question 1

When creating a graph of data, which of the following is incorrect?

A. The axes should have consistent scales.

B. The independent variable should be plotted on the vertical axis.

C. The variables should be labelled on their respective axis with units.

D. The scale on the axes should be chosen such that the data points take up the majority of the available graph space.

Question 2

Which of the following statements is true regarding uncertainty bars?

A. Uncertainty bars indicate how easy the experiment was to complete.

B. Vertical error bars indicate the uncertainty in the independent variable.

C. The 'true' value of a data point should lie in the area indicated by the uncertainty bars.

D. The distance between the two end caps of an uncertainty bar is the magnitude of the uncertainty.

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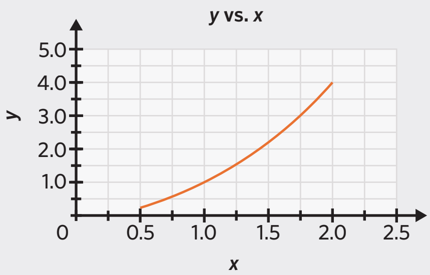
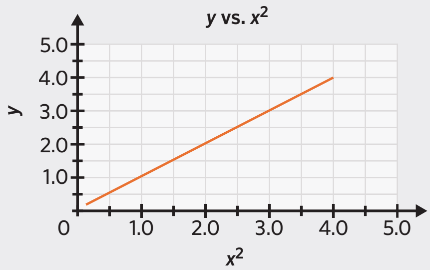
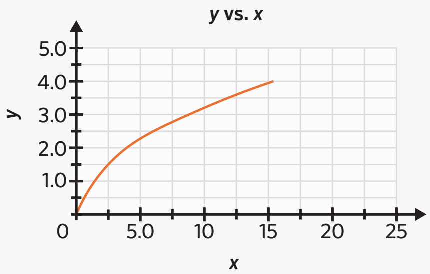
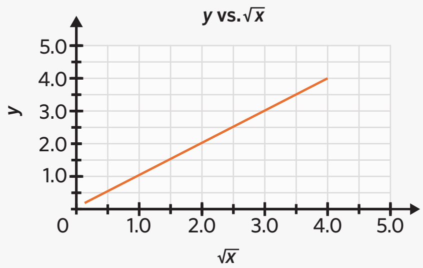
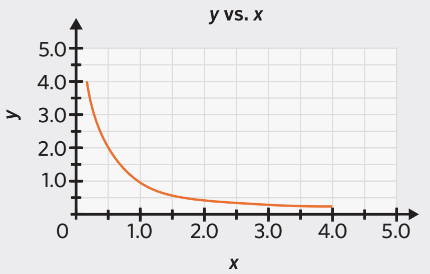
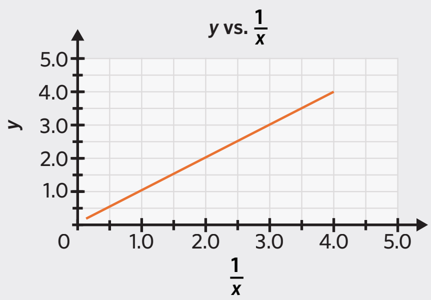
How can we make our data easier to analyse?

To help us determine a mathematical form for the relationship between two variables, we can linearise the data. Linearising data is the process of transforming one or both of the independent and dependent values, so that the graph demonstrates a linear (straight line) relationship.

- Linearised graphs do not need to trend towards the origin.
- If a variable is transformed appropriately and the result is a linear line that passes through the origin, this indicates a proportional relationship between the variables plotted. We can use k as a constant in the mathematical form to represent the **gradient** (slope) of the graph. Gradients will be discussed in more detail later in this lesson.

Table 3 Examples of how different graphs can be linearised by transforming variables

Type of graph	Visual	Transformation	Linearised graph, with x transformation
Parabolic, $y \propto x^2$ **or** $y = kx^2$		x values: square **OR** y values: take the square root	
Square root, $y \propto \sqrt{x}$ **or** $y = k\sqrt{x}$		x values: take the square root **OR** y values: square	
Hyperbolic, $y \propto \frac{1}{x}$ **or** $y = \frac{k}{x}$		x values: take the reciprocal **OR** y values: take the reciprocal	

USEFUL TIP

Similar transformations can be made to the dependent variable in order to linearise data and establish a relationship such as $\sqrt{y} \propto x$.

STRATEGY

Proportional relationships can also be used in calculations. For example, suppose $A \propto B$ and $A_1 = x$ when $B_1 = y$. Then if $A_2 = \frac{x}{3}$, we have that $B_2 = \frac{y}{3}$.

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WORKED EXAMPLE 1

A student collected data on the distance travelled (d) by a ball that starts from rest and rolls down a ramp for different durations of time (t). The angle of the ramp is fixed.

Time, t (s)	Distance, d (m)
1.00	0.50
2.00	2.00
3.00	4.50
4.00	8.00
5.00	12.5

a. Plot a time vs. distance graph for the data provided in the table. Draw a line of best fit for the data.

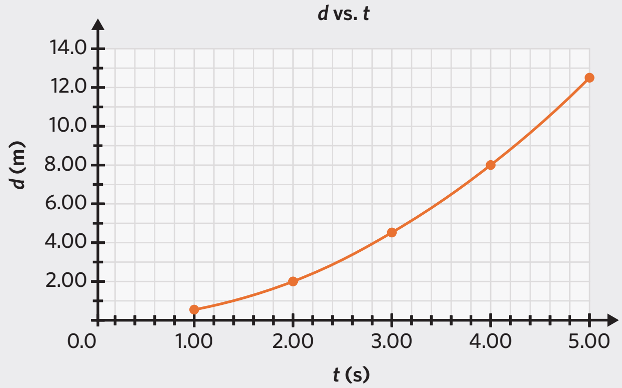
Breakdown

Plot the data from the table with time on the horizontal axis and distance on the vertical axis.

Label the axes and title the graph.

Draw a curved line of best fit.

Answer



b. Linearise the data and plot a graph to show that $d \propto t^2$.

Breakdown

Identify the transformation required to linearise the data.

Calculate the values of t^2. Note that the units undergo the same transformation.

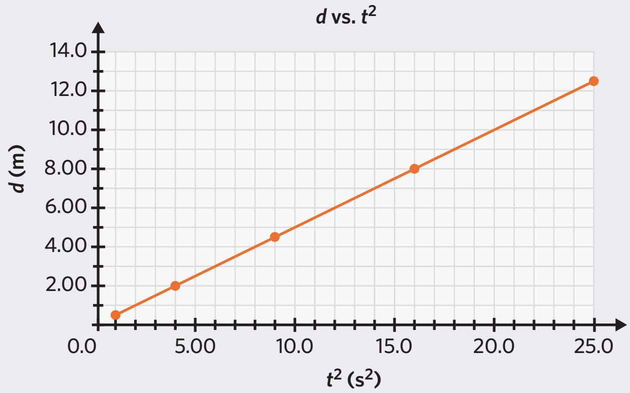
Plot the data from the table with the transformed independent variable on the horizontal axis and the dependent variable on the vertical.

Note that since the graph of d vs. t^2 is linear relationship, $d \propto t^2$.

Answer

As our original graph has a quadratic relationship, we can transform our time values by raising them to the power of two.

Time, t^2 (s)	Distance, d (m)
1.00	0.50
4.00	2.00
9.00	4.50
16.0	8.00
25.0	12.5



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PROGRESS QUESTIONS

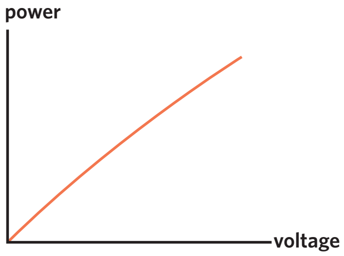
Use the following information to answer questions 3 and 4.

Physicists have determined that the power (P) dissipated in a resistor of fixed resistance (R), as the voltage (V) across the resistor is varied, can be calculated using the formula $P = \frac{V^2}{R}$.

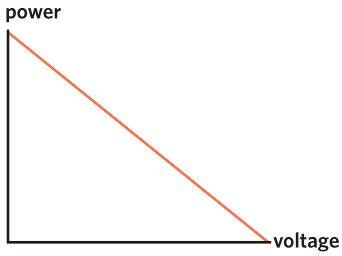
Question 3

Which of the following is a possible graph of P vs. V?

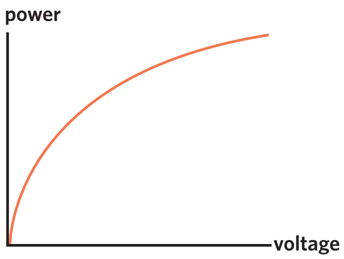
A.



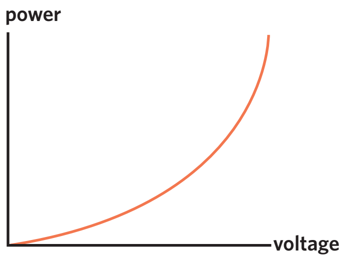
B.



C.



D.



Question 4

A student is testing this theory and wants to linearise their data. Which of the following would describe the linear relationship between the variables?

A. P vs. V **B.** P^2 vs. V^2 **C.** P vs. V^2 **D.** $\sqrt{P}$ vs. V^2

Drawing straight lines and curved lines of best fit 4.2.6.2

Straight lines of best fit and **curved lines of best fit** are straight and curved lines respectively that indicate the relationship between the independent and dependent variables on a graph.

USEFUL TIP

If we expect our graph to pass through the origin and our **trendline** does not, this is an indication of systematic error.

How do we draw straight lines and curved lines of best fit?

We can draw straight lines and curved lines of best fit to visualise a correlation between our variables. They can later be used to solve for unknown variables in physics equations.

Straight lines and curved lines of best fit must:

- pass through the uncertainty bars of all points (though it does not need to pass through the specific data point).
- not be forced to change direction in order to pass through all points.
- not be forced to pass through the origin.
- not be forced to pass through any point on the graph.
- not extend beyond the region of the points.

This ensures that all data points are treated as equally important.

USEFUL TIP

If a point or points in the data have experienced significant random error, they can become outliers and should be disregarded when plotting data and drawing trendlines.

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If a straight line cannot be drawn so that it passes through all the uncertainty bars, there cannot be a straight line of best fit, so the trend may be better represented by a curved line of best fit (Figure 3). It is also possible that the uncertainty is too great or the spread of data is too small to establish the true relationship.

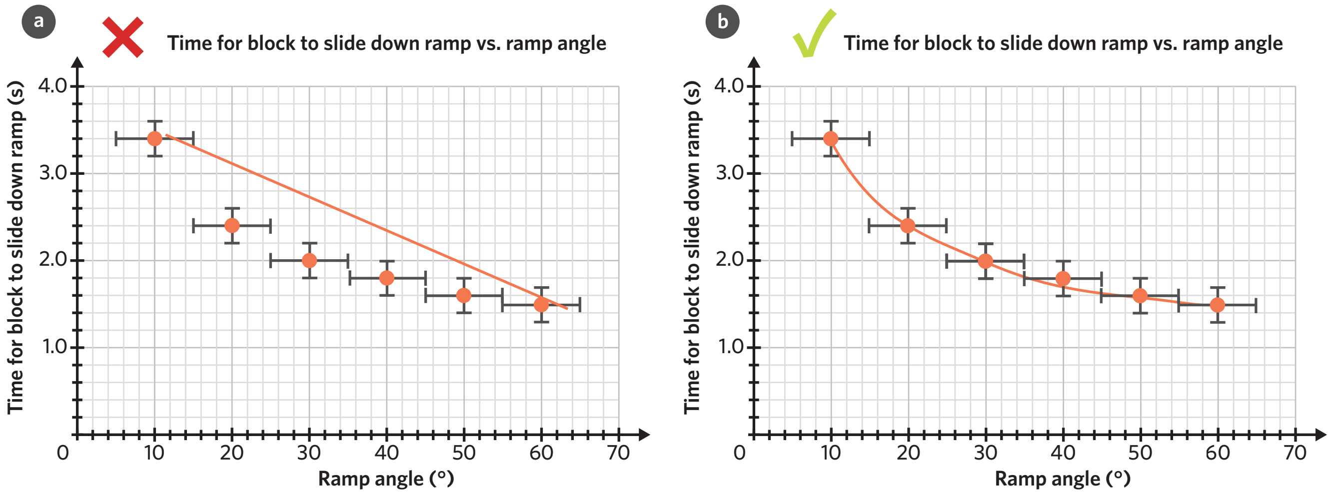


Figure 3 **(a)** An invalid straight line of best fit and **(b)** valid curved line of best fit drawn on the same set of data

PROGRESS QUESTIONS

Question 5

Which of the following statements regarding lines of best fit is correct? **(Select all that apply)**

A. Lines of best fit can always be drawn on a graph.

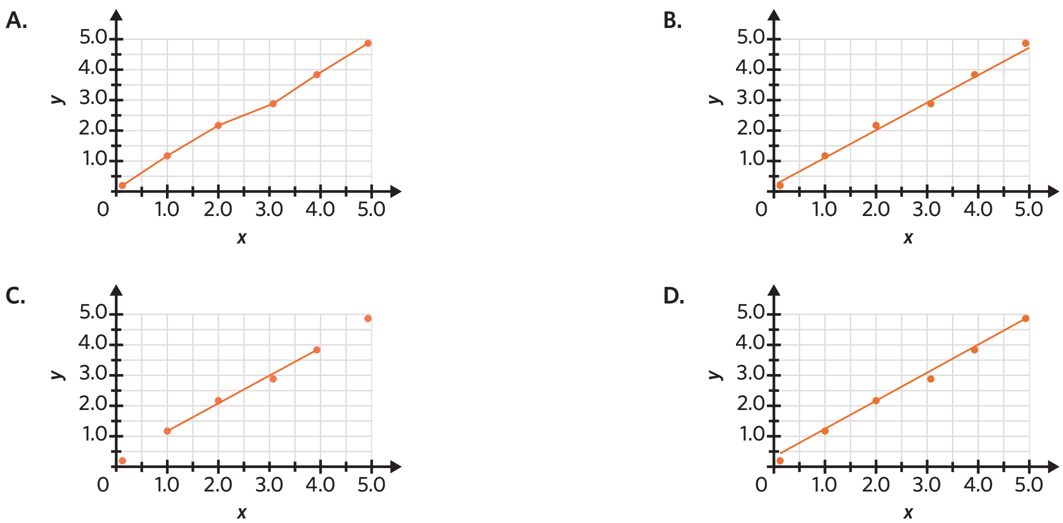
B. Lines of best fit do not have to pass through the origin.

C. Lines of best fit must pass through each point on the graph.

D. Lines of best fit must pass through the error bars of each point on the graph.

Question 6

Which of the following graphs has a straight line of best fit drawn correctly?



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Calculating the gradient 4.2.6.3

On a graph, the gradient (or slope) is the ratio of the change in the variable on the vertical axis to the change in the variable on the horizontal axis.

How do we calculate the gradient of a line of best fit?

A gradient is a rate of change.

- A positive gradient indicates that the dependent variable increases with an increase in the independent variable.
- A negative gradient indicates that the dependent variable decreases with an increase in the independent variable.
- The greater the magnitude of the gradient (the slope of the line of best fit), the more the dependent variable will increase (or decrease) per unit increase in the independent variable.

We can calculate the gradient of a straight line from two points on the line.

FORMULA

$$gradient = \frac{rise}{run} = \frac{y_2 - y_1}{x_2 - x_1}$$

(x_1, y_1) = a point on the line of best fit
(x_2, y_2) = another point on the line of best fit

USEFUL TIP

If it is known that the line passes through the origin, then the gradient formula can be simplified to: gradient $= \frac{y_2 - y_1}{x_2 - x_1} = \frac{y_2 - 0}{x_2 - 0} = \frac{y_2}{x_2}$. Not all lines will pass through the origin so it is important to check before taking this approach.

When calculating the gradient of a line of best fit:

- Use two coordinates that are on the straight line of best fit.
- Choose two coordinates that are relatively far apart. This reduces the effect of any random errors that we make when reading the points from the graph, which improves the accuracy of the gradient calculation.
  - Consider Figure 4, the orange and purple data points have the same error when compared to the 'true' values, but the gradient that would be calculated using the purple data points is more accurate than the gradient that would be calculated using the orangered data points.
- Check the scale on each axis and apply a scale factor if applicable.
- The units of the gradient are given by $\frac{units\ on\ vertical\ axis}{units\ on\ horizontal\ axis}$.

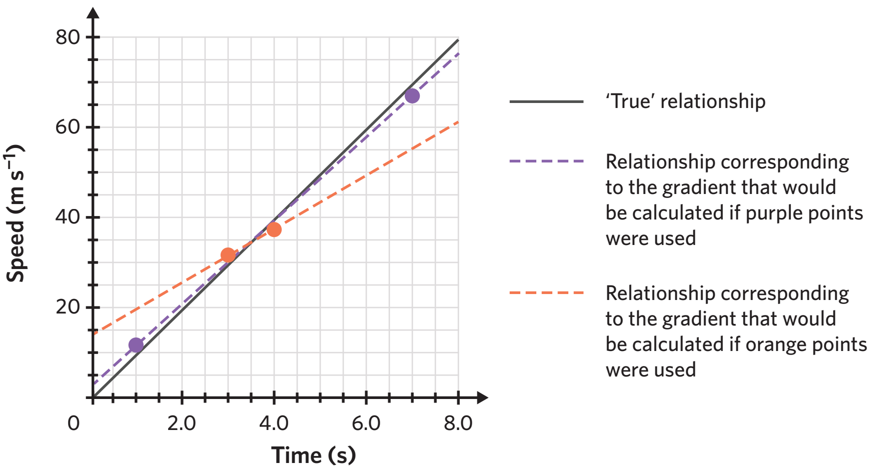

Figure 4 Using two points close together can lead to errors in calculation of gradient.

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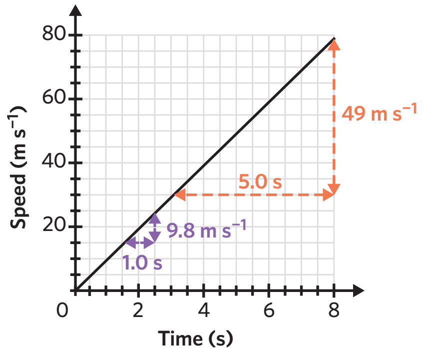


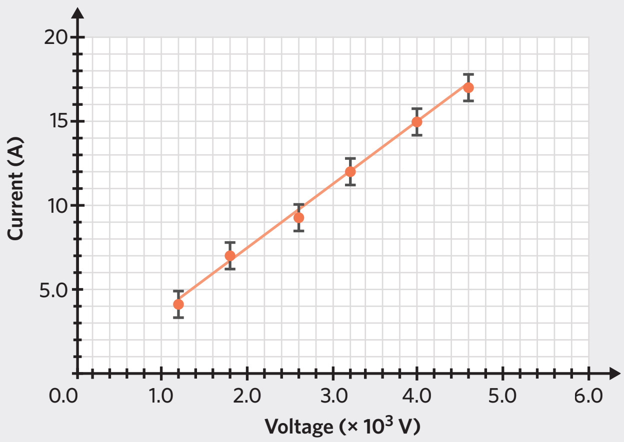
Figure 5 Speed vs time graph for an object in free fall without air resistance

Straight line graphs have a constant gradient, which means that the dependent variable (on the vertical axis) will increase or decrease by a fixed amount for every unit increase in the independent variable (on the horizontal axis). Consider Figure 5, which shows the speed of an object that has been released from rest.

- The object's speed increases by a fixed amount, 9.8 m s^{-1}, for each second that passes.
- This means the gradient is 9.8 m s^{-2} $\left(\frac{9.8 \text{ m s}^{-1}}{1 \text{ s}}\right)$.
- For example, when the time increases by 5.0 seconds, the speed increases by $5.0 \times 9.8 = 49$ m s^{-1}.

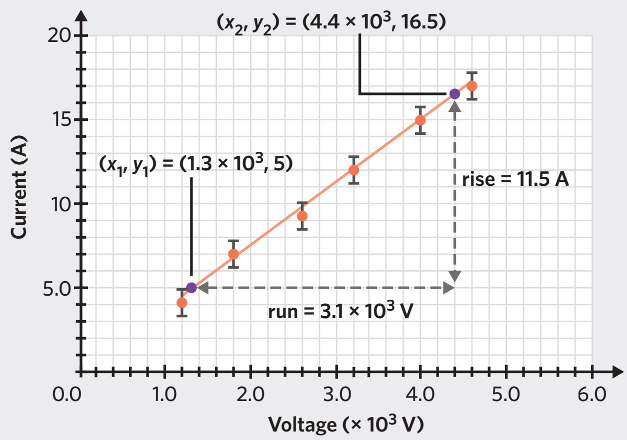
WORKED EXAMPLE 2

Find the gradient of this current vs. voltage graph.



Step 1

Identify known and unknown variables and write down the formula that relates these variables.



$(x_1, y_1) = (1.3 \times 10^3, 5)$, $(x_2, y_2) = (4.4 \times 10^3, 16.5)$, $gradient = ?$

$$gradient = \frac{y_2 - y_1}{x_2 - x_1}$$

Step 2

Substitute values into the formula and solve for the gradient.

$$gradient = \frac{16.5 - 5.0}{(4.4 - 1.3) \times 10^3}$$

$$gradient = 3.71 \times 10^{-3} = 3.7 \times 10^{-3} \text{ A V}^{-1}$$

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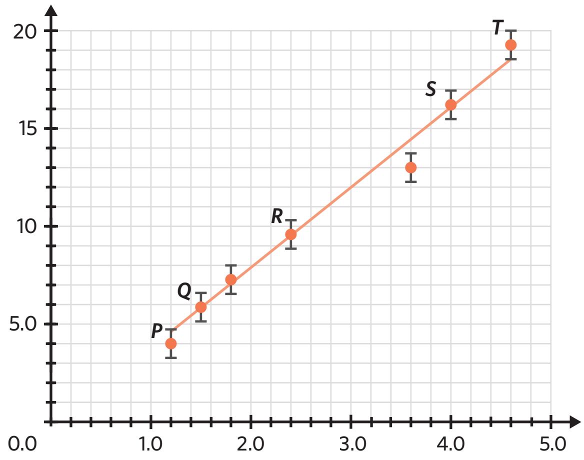
PROGRESS QUESTIONS

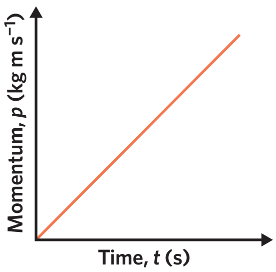
Question 7

Which two data points from those identified on the graph (P, Q, R, S, and T) would be the best choice to calculate the gradient of the line of best fit?



A. Q and S **B.** P and T **C.** R and S **D.** Q and R

Use the following graph to answer questions 8 and 9.



Question 8

Which of the following expressions does the gradient of this graph represent?

A. $\frac{t}{p}$ **B.** $\frac{\Delta p}{\Delta t}$ **C.** $p + t$ **D.** $\Delta p \times \Delta t$

Question 9

Which of the following units should be used for the gradient of this graph?

A. kg **B.** kg s **C.** kg m **D.** kg m s^{-2}

How do we interpret the gradient of a line of best fit?

We can determine the physical meaning of a gradient from an equation relating the dependent and independent variable and the context of the physical situation. Equations for straight lines of best fit follow the form $y = mx + c$, where m is the gradient and c is a constant.

- From Figure 5, $gradient = \frac{change\ in\ speed}{change\ in\ time} = \frac{\Delta v}{\Delta t}$.
- In Lesson 1A, we see how the magnitude of acceleration is given by $a = \frac{\Delta v}{\Delta t}$.
- Therefore, we can conclude that the gradient in Figure 5 is equal to the magnitude of acceleration.

USEFUL TIP

It is common for an exam question to ask us to use the gradient from a line of best fit to determine the experimental value of a known constant. It is important that we use the gradient of the line of best fit for the experimental data in these cases, rather than the known value.

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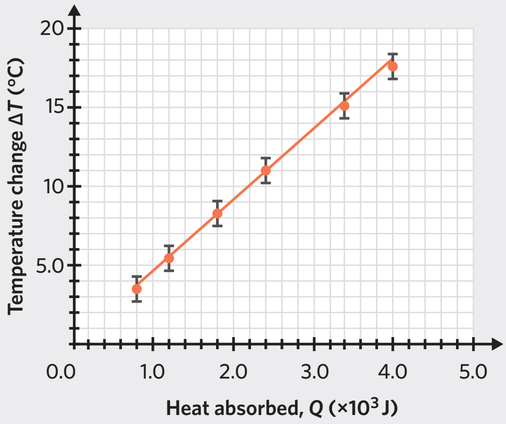
WORKED EXAMPLE 3

The change in temperature, ΔT (measured in °C), of an object that absorbs some heat, Q (measured in J), can be calculated from the equation $\Delta T = \frac{Q}{mc}$, where m is the mass of the object (measured in kg) and c is the specific heat capacity of the object (measured in J kg^{-1} °C^{-1}).

Scientists undertake an experiment where they measure the temperature change of an object, with a mass of 2.0 kg, as it is heated. They plot the data for ΔT vs. Q and draw a line of best fit as shown. The line of best fit has a gradient of 4.5×10^{-3} °C J^{-1}.



Use the gradient to calculate the value of the specific heat capacity of this object, c.

Step 1

Identify known and unknown variables and write down the formula that relates these variables.

Note that $gradient = \frac{rise}{run} = \frac{\Delta T}{Q}$.

$gradient = 4.5 \times 10^{-3}$ °C J^{-1}, $m = 2.0$ kg, $c = ?$

$\Delta T = \frac{Q}{mc} \Rightarrow \frac{\Delta t}{Q} = \frac{1}{mc}$

$\Rightarrow gradient = \frac{1}{mc}$

Step 2

Substitute values into the formula and solve for specific heat capacity of the object.

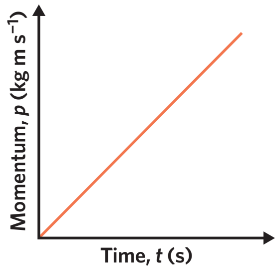
$4.5 \times 10^{-3} = \frac{1}{2.0 \times c}$

$c = 1.11 \times 10^{2} = 1.1 \times 10^{2}$ J kg^{-1} °C^{-1}

PROGRESS QUESTIONS

Question 10

It is known that $\Delta p = F\Delta t$, where F is the force acting on the object being measured. The gradient of the line of best fit is equivalent to



A. F.

B. $\frac{1}{F}$.

C. $\frac{F}{\Delta t}$.

D. $\frac{F}{\Delta p}$.

Question 11

It is known that $F = -k\Delta x$, where k is the spring constant. In an experiment, Leo extends a spring by different distances, x, and measures the force, F, the spring applies back. Force is the dependent variable and plotted on the vertical axis. What does the gradient of the line of best fit represent?

A. $-k$

B. $-F$

C. $-\frac{1}{k}$

D. $-\frac{F}{\Delta x}$

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Theory summary

- Independent variables are plotted on the horizontal axis and dependent variables on the vertical axis.
- Graphs should have a title and labelled axes, with units.
- The scale of the graph should be consistent and chosen so that the data points take up the majority of the graph space.
- Straight lines and curved lines of best fit should be smooth and pass through the uncertainty bars of all points.
  - They should not be forced to go through any point, including the origin.
- A gradient is the rate of change of one variable with respect to another.
- Gradients can be calculated by finding two points on the line of best fit and substituting them into the formula: $gradient = \frac{y_2 - y_1}{x_2 - y_1}$.
- Points should be chosen that are far apart on the line.
- By dividing the variables of the vertical axis by those of the horizontal axis, we can determine what the gradient represents.

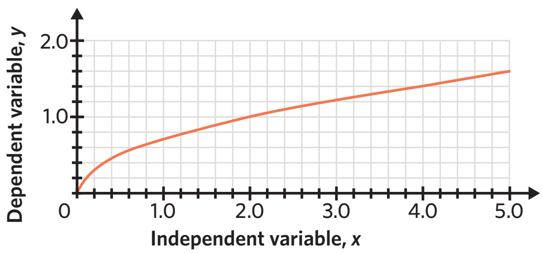
12D Questions

Mild 🌶 Medium 🌶🌶 Spicy 🌶🌶🌶

Exam-style

Question 12 🌶 (1 MARK)

Nat collects data in an experiment. When she plots it, the data has a curved line of best fit that looks like the square root graph pictured.



If Nat wants to linearise her data, what transformation should she do to the independent variable?

Question 13 🌶 (2 MARKS)

A straight line of best fit passes through the point (2.9, 7.6). If the line also passes through the origin, what is the gradient of the line?

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Question 14 (5 MARKS)

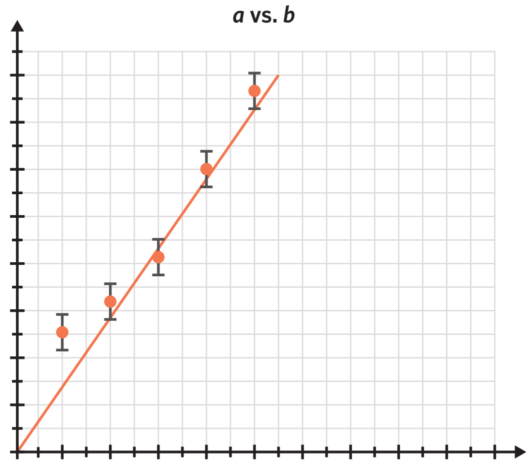
Fatima is running on a track that has a marking every 10 m. Her friend records the time in seconds that it takes her to run 100 metres, noting roughly the time it takes for her to pass each 10 m mark on the track.

Distance, d (m)	Time, t (± 1 s)
10	2
20	4
30	7
40	11
50	14
60	18
70	23
80	28
90	34
100	41

Draw a graph of this data with uncertainty bars. Include a straight line or curved line of best fit as appropriate.

Question 15 (4 MARKS)

The following graph of variable *a* and variable *b* is plotted with a line of best fit. Identify two errors made in drawing the graph, and explain how the graph could be improved.

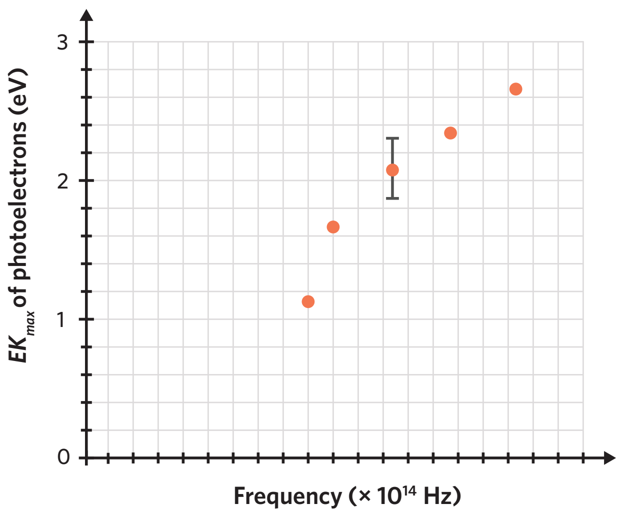


Question 16 (3 MARKS)

Students performing the photoelectric experiment on a metal have carefully determined the uncertainty in their measured values for the maximum kinetic energy of the emitted photoelectrons.
This is represented by an uncertainty bar (or error bar) drawn on one of the data points in the graph below. The uncertainty in the values for frequencies may be neglected.

Explain the conditions in which a straight line of best fit may be drawn for a set of data. Identify the steps needed to determine whether the data points in the graph above may be fitted by a straight line.

Adapted from VCAA Sample 2017 Exam Short answer Q17f



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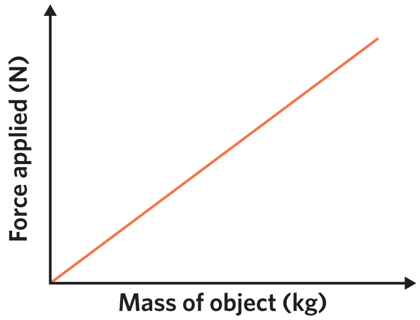
Question 17 (3 MARKS)

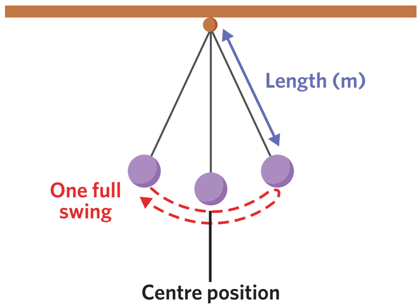
It is known that $F = mg$, where F is the force applied, m is the mass of an object, and g is the acceleration due to gravity. A student plots the following graph of the data they collected in an experiment.



The student says that the acceleration due to gravity is changing because the gradient of the graph is not a horizontal line. Is this student correct? Explain your answer.

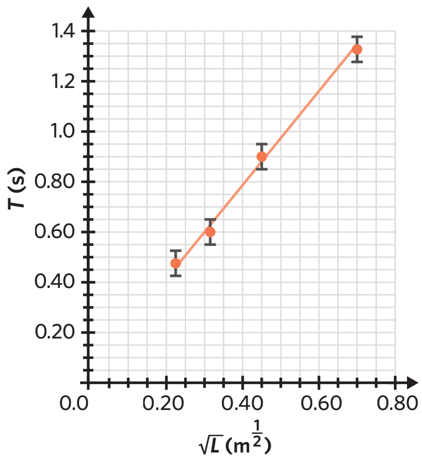
Question 18 (3 MARKS)

Students conduct an experiment in which they measure the period (the time taken to complete one full swing and return to the same position) of a pendulum of varying lengths.



It is known that the relationship between the length of a pendulum, L (m), and its period, T (s), is approximated by $T = 2\pi\sqrt{\frac{L}{g}}$, where g is the magnitude of the acceleration due to gravity (m s^{-2}).

The students plot T against $\sqrt{L}$ to obtain a line of best fit. The uncertainty in the period measurements is ±0.5 seconds. Note that the lengths are measured to a high level of confidence.



Use the line of best fit to calculate the magnitude of the acceleration due to gravity.

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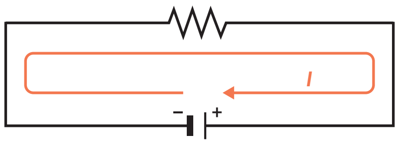
Question 19 (16 MARKS)

Wataru studies the current, I, passing through a resistor of resistance, R, in a circuit connected to a 1.5 V battery. Wataru believes that $I \propto \frac{1}{R}$.



Resistance, R (Ω)	**Uncertainty in resistance, R (Ω)**	**Current, I (A)**	**Uncertainty in current, I (A)**
0.50	±0.05	3.0	±0.1
1.00	±0.05	1.5	±0.1
1.50	±0.05	1.0	±0.1
2.00	±0.05	0.8	±0.1
2.50	±0.05	0.6	±0.1
3.00	±0.05	0.5	±0.1

a. Plot a graph of the data recorded in the table above. Include uncertainty bars and a curved line of best fit as appropriate. 🌶🌶 5 MARKS

b. Calculate the values of $\frac{1}{R}$ and hence plot the graph of I versus $\frac{1}{R}$. Include vertical uncertainty bars (horizontal uncertainty bars are not required), and include a line of best fit as appropriate. 🌶🌶 6 MARKS

c. Is Wataru's hypothesis that $I \propto \frac{1}{R}$ supported by her experimental data? Justify your answer. 🌶🌶🌶 2 MARKS

d. Ohm's law states that $V = IR$, which is consistent with Wataru's hypothesis. Using Ohm's law and the gradient of the line of best fit produced in part **b**, the calculate a value for the voltage of the circuit and compare it to the known supply voltage of the circuit of 1.5 V. 🌶🌶🌶 3 MARKS

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12E Communicating findings

STUDY DESIGN DOT POINTS

- explain the key findings and implications of the selected investigation
- apply the conventions of scientific poster presentation, including succinct communication of the selected scientific investigation, and acknowledgement of references
- identify the physics concepts specific to the investigation and explain their significance, including definitions of key terms and physics representations

12A 12B 12C 12D 12E

4.2.1.1 & 4.2.9.1 & 4.2.10.1 Creating a scientific poster

ESSENTIAL PRIOR KNOWLEDGE

12A Aim and hypothesis

12D Presenting graphs

See questions 104–105.

How can we communicate our findings from a scientific investigation?

A key element of the scientific method, introduced in Lesson 12A, is to share the results of investigations. One way to share results from an investigation is by creating a scientific poster. Scientific posters should contain the information required for others to recreate our investigation, as well as the results and conclusions we made from it. This lesson will outline some important considerations when creating a scientific poster.

Creating a scientific poster 4.2.1.1 & 4.2.9.1 & 4.2.10.1

This lesson will expand upon and explain the requirements VCAA outline for the creation and presentation of a scientific poster.

What should we include in a scientific poster?

Figure 1 shows a general outline of a template that may be followed to organise a scientific poster.[1]

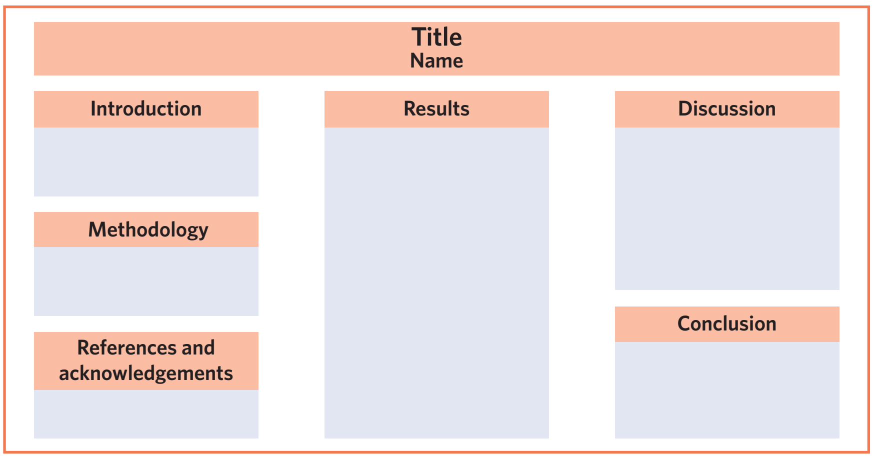

Figure 1 Visual template of a scientific poster

The relative size allocated to each section of the scientific poster indicates approximately how much information should be included in each section.

KEEN TO INVESTIGATE?

[1] **What templates can be used for creating a scientific poster?**
Search: Scientific poster templates

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Table 1 gives a guide as to what should be included in each section of the scientific poster. An example of how changing the angle of inclination of a plane affects the time it takes for a ball to travel down it is provided for further context.

Table 1 Different sections of a scientific poster

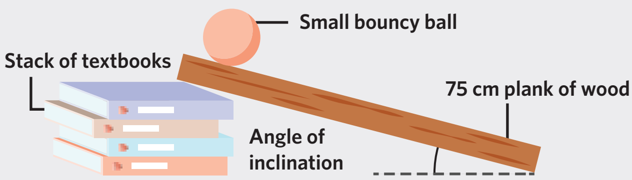
Section	Explanation	Example
Title	• A research question that conveys the purpose of investigation.	**Title:** How does changing the angle of inclination of a plane affect the time it takes for a ball to travel down it?
Introduction	• Provide reliable background information to the investigation. • Include key definitions and relevant formulas to the investigation. • State the experiment's aim and hypothesis. Lesson 12A explains how to write an experimental aim and hypothesis.	**Background information:** As the angle of inclination of the plane increases, the component of the force due to gravity acting on the ball down the plane, $F_{\|\|} = mg\sin(\theta)$, increases. This will increase the net force acting on the ball, due to Newton's second law of motion $F_{net} = ma$, and so it will accelerate at a greater rate. An increased acceleration down the plane will mean the ball will travel down in it a shorter time, according to $s = ut + \frac{1}{2}at^2$. **Key definitions:** angle of inclination: the angle a ramp makes to the horizontal surface **Relevant formula:** $F_{\|\|} = mg\sin(\theta)$ $s = ut + \frac{1}{2}at^2$ **Aim and hypothesis:** See Lesson 12A for a sample aim and hypothesis for this investigation.
Methodology	• State specific materials used and provide a labelled diagram or photograph of the experimental setup. • Provide a step-by-step procedure that can be followed to recreate the investigation. Note that all tables, graphs and diagrams included in the scientific poster should be sequentially numbered and a short caption may be included. This includes all sections of the scientific poster.	**Materials:** • 1 × 75 cm plank of wood • 1 × small bouncy ball • 1 × stack of books • 1 × protractor • 1 × stopwatch **Setup:**  **Figure 2** Experimental setup of investigating the effect changing the angle of inclination has on the time it takes the ball to travel down it **Procedure:** The step-by-step procedure used will vary depending on specific equipment available. The procedure should avoid using first person words such as "I titled the plane to a 30° angle from the horizontal", but instead opt for directions such as: **1.** Lean the ramp on a stack of books. **2.** Adjust the number of books until the ramp makes an angle of 30° to the horizontal... Continues →

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Table 1 Continued

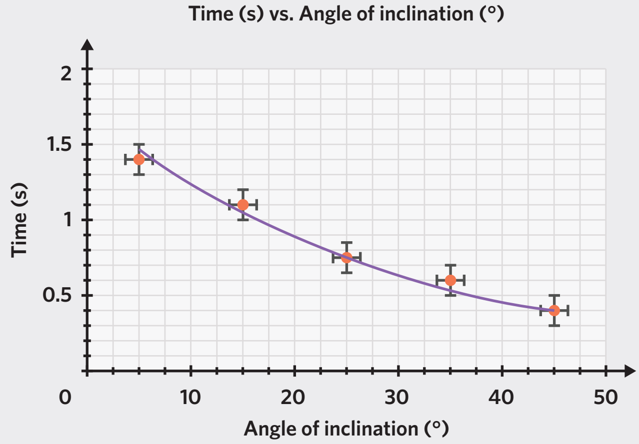
Section	Explanation	Example
Results	• Present the raw data in a relevant format. This may be in the form of a table, graph or diagram. • A brief explanation of the key information in the results • A sample calculation, if relevant • A statement as to the usefulness of results and whether they support the hypothesis Note that including both a table and a graph of the same results may be an inefficient use of poster space. Conventions for how to create graphs are explained in Lesson 12D.	**Data:**  **Figure 3** Time it takes for the ball to roll down an inclined plane vs. angle of inclination of the plane **Key features:** • The graph shows that increasing the angle of inclination of the plane reduces the time it takes the ball to reach the end of the plank. • The results from this experiment appear to be useful, as the graph shows a clear relationship between the angle of inclination of the plane and the time it takes for the ball to roll down it. • This observation supports the hypothesis of the investigation, that increasing the angle of inclination of the plane will decrease the time it takes for the ball to reach the bottom of it.
Discussion	• Show to what extent the results support the hypothesis. • Compare obtained results to those that were expected. • Analyse the experimental design and potential errors, why these errors may have occurred, and options for removing or minimising them. • Acknowledge and discuss any outliers. • Link overall findings to the experiment's aim. Note that VCAA suggests using the discussion section to move from the specifics of the investigation, to talk about the general understanding of the concept. Words such as "proved" and "disproved" should be avoided, and instead "supports" "partially supports" or "did not support" can be used to explain how the results link to the hypothesis.	• The data from the investigation supports the hypothesis that increasing the angle of inclination of the plane will decrease the time it takes for the ball to reach the bottom of it. Each increase in the angle of inclination of the plane led to a decrease in the time it took for the ball to roll down it. • Using the formula stated in the background theory $s = ut + \frac{1}{2}at^2$ and $F_{net} = mg\sin(\theta)$, the theoretical value of how long it takes a ball to roll down the inclined plane can be found using: $t = \sqrt{\frac{2s}{g\sin(\theta)}}$. Note that this relationship could be plotted on a graph with the experimental data to show the difference between the theoretical and experimental data. • The experimental data appears to have longer times for the ball to roll down the ramp than theoretical predictions. This is likely due to the effects of friction, which decrease the acceleration of the ball down the plane. • Potential errors could have been introduced into the experimental data through recording the time for the ball to roll down the ramp or measuring the angle of inclination of ramp incorrectly. Continues →

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Table 1 Continued

Section	Explanation	Example
Conclusion	• State the main experimental findings, whether it supported the hypothesis, and explain these using specific details or trends in your results. • State limitations, potential improvement, and future research that could be undertaken.	• The experiment's results show that increasing the angle of inclination of the plane will decrease the time it takes for the ball to reach the bottom of it. This supports the experiment's hypothesis, that increasing the angle of inclination of the plane will decrease the time it takes for the ball to reach the bottom of it. • The data is limited in the number of different angles of inclination used to test the hypothesis. The experiment could be improved by taking more data points for different angles of inclination. • Future research could be undertaken to investigate how increasing the angle of inclination of the plane will decrease the time it takes for the ball to reach the bottom of it, with different balls used or different materials used to create the inclined plane.
References and acknowledgements	• Reference/acknowledge any information used in assisting the creation of the scientific poster. • Any standard referencing style can be used to reference information used in the work.[2]	**KEEN TO INVESTIGATE?** [2] **How can a source be referenced in a scientific poster?** Search: Reference a source

PROGRESS QUESTIONS

Question 1

Which of the following should be included in the methodology? **(Select all that apply)**

A. A diagram showing the setup of the experiment.

B. A clear list of all materials required to complete the investigation.

C. An explanation of background theory relating to the investigation.

D. An explanation of any possible sources of error occurred in the investigation.

Question 2

The purpose of the results is to

A. explain how the investigation was undertaken.

B. decide whether the intended aim was successfully investigated.

C. draw conclusions by interpreting the data obtained in the experiment.

D. present the data obtained in the experiment, and a brief explanation as to its quality and agreement with the hypothesis.

Question 3

Which of the following correctly shows a possible conclusion to an investigation into how changing the angle of inclination affects the time taken for a ball to reach the bottom? **(Select all that apply)**

A. Our investigation proves the hypothesis that increasing the angle of inclination reduces the time it takes the ball to reach the bottom of the ramp.

B. Our investigation supports the hypothesis that increasing the angle of inclination reduces the time it takes the ball to reach the bottom of the ramp.

C. Our investigation disproves the hypothesis that increasing the angle of inclination reduces the time it takes the ball to reach the bottom of the ramp.

D. Our investigation does not support the hypothesis that increasing the angle of inclination reduces the time it takes the ball to reach the bottom of the ramp.

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Theory summary

- A scientific poster can be used to communicate findings from an investigation. It should include:
  - A title, posed as a research question.
  - An introduction, outlining relevant theory, an aim, and a hypothesis for the investigation.
  - A methodology, outlining relevant apparatus, experimental setup, and a step-by-step procedure.
  - Results, displaying raw data, the usefulness of the data, and how it relates to the hypothesis.
  - A discussion, focused around how the specifics of an investigation relate to the underlying physics concepts.
  - A conclusion, stating the main research finding, possible improvements and limitations of the investigation, and future research that could take place.
  - References and acknowledgements for any information that assisted in the creation of the poster.

12E Questions

Mild 🌶 Medium 🌶🌶 Spicy 🌶🌶🌶

Exam-style

Question 4 (2 MARKS)

A group of students are investigating how the height a ball is dropped from affects the maximum height of its bounce.

a. Write a title for this investigation. 🌶 1 MARK

b. The following method is written for the investigation, with step 2 excluded:

1. Drop a ball from a height of 50 cm.
2.
3. Repeat steps 1–2 four times, increasing the height the ball is dropped from by 10 cm each time.

Write a possible second step for the experiment. 🌶 1 MARK

Question 5 🌶 (3 MARKS)

Sadio is investigating the relationship between the angle of incidence of a light beam travelling through the air and the angle at which it refracts when it enters a tank of water. Identify the three general requirements that Sadio should include in their introduction. Specific information is not required.

Question 6 (4 MARKS)

Kathie is investigating the effects increasing the mass of a cart has on the time it takes for the cart to stop. Each cart initially is travelling at 10 m s^{-1}. They hypothesise that "increasing the mass of the cart will decrease the time it takes for the cart to come to rest."

She notes the following results in her logbook:

- When the mass of the cart is 500 g, it took 4.6 s for the cart to come to rest.
- When the mass of the cart is 750 g, it took 5.8 s for the cart to come to rest.
- When the mass of the cart is 1000 g, it took 7.9 s for the cart to come to rest.
- When the mass of the cart is 1500 g, it took 15.4 s for the cart to come to rest.

a. Display Kathie's results using a format suitable for a scientific poster. 🌶🌶 2 MARKS

b. Do the results support Kathie's hypothesis? Explain your answer. 🌶🌶 2 MARKS

Question 7 (3 MARKS)

A teacher demonstrates to their class an experiment that investigates the period of a small mass attached to the 60 cm string being swung around in a circle. The teacher swings a small mass above their head, and measures how long it takes to complete five revolutions. They then hold the string at a different point, to change the radius of the mass' circular path. State three pieces of equipment required to complete the experiment and measure its data.

Question 8 (3 MARKS)

A student is recreating Young's double slit experiment. They come to the conclusion that "the results from the investigation prove that light is a wave".

a. Evaluate the language used in the students' conclusions. 2 MARKS

b. State an alternative conclusion to the investigation. 1 MARK

Question 9 (5 MARKS)

A student provides the following discussion, relating to the extension of a spring when different masses are attached to it:

> *The results from the experiment support the hypothesis of the experiment that "increasing the mass attached to the spring will increase the extension of the spring". This relationship is clearly shown by the graph of mass attached vs. displacement of the spring. The experimental results do not support theoretical results, as the graph of mass attached vs. displacement of the spring is not linear, but appears parabolic. The aim of the experiment was successfully investigated, as a relationship between the mass attached to the spring and the extension of the spring was successfully obtained.*

Using the sample rubric provided, give the student a mark for their discussion. Explain your answer.

Information provided	Marks
The student shows the extent to which the results support the hypothesis.	/1
The student compares obtained results to theoretical results.	/1
The student analyses experimental design and possible sources of error.	/1
The student links the overall findings to the aim.	/1

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Chapter 12 review

Mild 🌶 Medium 🌶🌶 Spicy 🌶🌶🌶

These questions are typical of one hour's worth of questions on the VCE Physics Exam.

Total marks: 50

Section A

All questions in this section are worth one mark.

Unless otherwise indicated, the diagrams in this book are not drawn to scale.

Question 1 🌶

Which of the following best describes a hypothesis?

A. a testable scientific explanation

B. a well-tested scientific explanation

C. a scientific explanation by a famous scientist

D. a widely believed and highly plausible explanation

Adapted from VCAA 2020 exam Multiple choice Q19

Question 2 🌶

A scientific poster should not include

A. a table of the raw data obtained in the experiment.

B. a diagram or photograph of the experimental setup.

C. an explanation of possible sources of error in the experiment.

D. a conclusion stating that the investigation "proves" or "disproves" the hypothesis.

Question 3 🌶🌶

Which of the following statements about reproducibility and repeatability is false?

A. An experiment may not be repeatable or reproducible if it used small sample sizes or too few trials.

B. Reproducing experiments is a method of checking for undisclosed systematic errors in the method of the first experiment.

C. Reproducibility refers to the ability of a different experimenter to perform the same experimental method again using the same equipment to produce different results.

D. Repeatability refers to the ability of an experiment to be performed again a short while later by the same experimenter with the same equipment and produce the same results.

Question 4 🌶🌶

Gwen and Arthur are taking measurements of the velocity of a ball. Gwen obtains the following readings: 2.1 m s^{-1}, 2.5 m s^{-1}, 2.3 m s^{-1}, 2.4 m s^{-1}, 1.7 m s^{-1} (average 2.2 m s^{-1}). Arthur obtains the following readings: 2.2 m s^{-1}, 3.5 m s^{-1}, 1.2 m s^{-1}, 2.6 m s^{-1}, 2.5 m s^{-1} (average 2.4 m s^{-1}).

The true value of the ball's velocity is 2.4 m s^{-1}. Which one of the following statements is most correct?

A. Both sets of results are equally precise.

B. Both sets of results are equally accurate.

C. Gwen's results are more precise than Arthur's results.

D. Gwen's results are more accurate than Arthur's results.

Adapted from VCAA 2017 exam Multiple choice Q18

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Question 5

Anne is designing an experiment to calculate the impact of light intensity on photocurrent in the photoelectric effect. She changes the intensity of light relative to a maximum value (20%, 40%, 60%, 80%) in each trial. She repeats the experiment three times at each intensity level and averages the photocurrent readings taken by the ammeter. She uses a red laser for the 20% and 40% light intensity and a green laser for the 60% and 80% light intensity. She ensures that the ammeter is zeroed and calibrated before the experiment.

This experiment is invalid. Which of the following is the best description of its invalidity?

A. Calibrating the ammeter will be a source of systematic error in the experiment.

B. Anne does not have the correct measuring device to measure the photocurrent in the circuit.

C. Averaging the readings of each trial introduces the possibility of human error in the calculations.

D. Changing light intensity and the colour of the light at the same time means changing more than one independent variable at the same time.

Section B

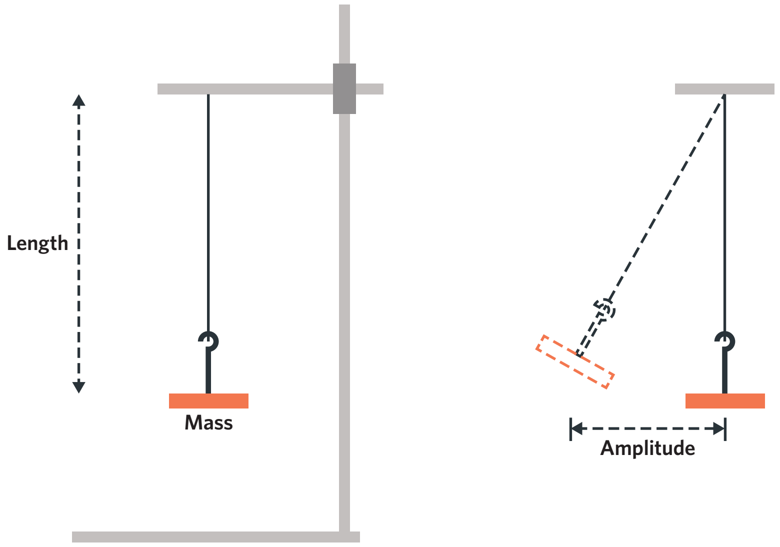
In questions where more than one mark is available, appropriate working must be shown.

Unless otherwise indicated, the diagrams in this book are not drawn to scale.

Question 6 (7 MARKS)

As part of an experimental investigation, Physics students use a pendulum, as shown below, to indirectly measure the magnitude of Earth's gravitational field at their location. The students use a constant mass and a constant amplitude of swing, changing only the length of the pendulum and then measuring the time for five oscillations using a stopwatch. They obtain four different time readings for four different lengths of the pendulum, measured using a ruler with 5 cm gradations.

By using the relationship $T = 2\pi\sqrt{\frac{L}{g}}$, where T is the period and L is the length of the pendulum, the students obtain four values for the magnitude of Earth's gravitational field.



a. Identify the independent, dependent and a possible controlled experiment in the students' experimental investigation. 3 MARKS

Adapted from VCAA 2019 exam Multiple choice Q18

b. Explains why the students measured the time for five oscillations rather than the time for one oscillation. Which type of error is this likely to reduce? 2 MARKS

Adapted from VCAA 2019 exam Multiple choice Q19

c. The students want to present their data in a scientific poster. State two potential improvements to the experimental investigation the students could state in their conclusion. 2 MARKS

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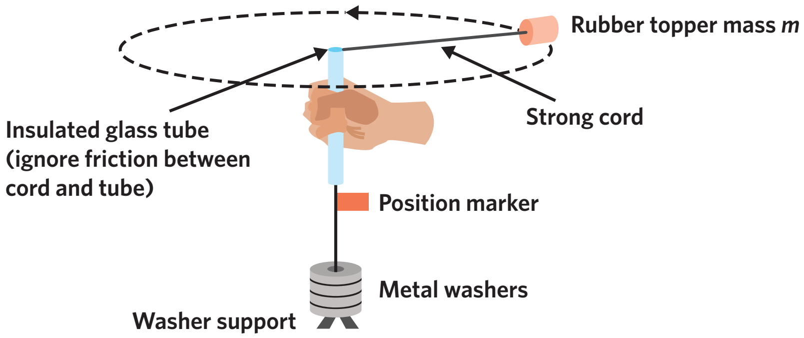
Question 7 (14 MARKS)

Two Physics students, Jerome and Priya, set out to investigate centripetal force. The diagram shows the experimental set-up and the apparatus that the students use. In reality, the students find that the cord is not quite horizontal but dips downward slightly due to the gravitational force acting on the rubber stopper. Their teacher explains that they can safely ignore this effect when collecting their experimental results.



Jerome and Priya note the following data in their logbook.

Radius of circle	0.76 m
Mass of each metal washer	30 g
Initial number of washers	10

Priya holds the glass tube and sets the rubber stopper rotating in a horizontal circle. She maintains a constant radius of the circle by keeping the position marker at a fixed position just below the bottom of the glass tube. Jerome uses a stopwatch to measure the time for 20 rotations of the rubber stopper, repeating this measurement three times. He notes all the data collected in their logbook. The experiment is then repeated four more times with two metal washers added each time.

a. What effect did the students taking repeated time measurements during the experiment have on their data? 1 MARK

b. Jerome and Priya record some of their results in a table. The students are told by their teacher that they can use $g = 10\ \text{N kg}^{-1}$ for their calculations.
Fill in the blank columns in the table below. 3 MARKS

Line number	Total mass of washers, M (kg)	Gravitational force acting on washers, $F_g = Mg$ (N)	Average time for 20 rotations (s)	Period, T (s)	$\frac{1}{T^2}$ (s^{-2})
1	0.30		14.0		
2	0.36		12.8		
3	0.42		11.8		
4	0.48		11.0		
5	0.54		10.4		

c. Using your values in the table, plot a graph of Mg on the y-axis against $\frac{1}{T^2}$ on the x-axis. 5 MARKS

On your graph:

- label each axis and include units
- use an appropriate scale.
- draw a straight line of best fit through the plotted points
- include uncertainty bars (in the x-direction only) of $\pm\ 0.1\ s^{-2}$.

d. Calculate the gradient of the graph plotted in part **c**. 2 MARKS

e. The relationship between the variables described in the experiment is known to be $Mg = \frac{4\pi^2 Rm}{T^2}$, where m is the mass of the rubber stopper. Using the gradient calculated in part **e**, show that the mass of the rubber stopper is approximately 50 g. 3 MARKS

Adapted from VCAA 2021 exam Short answer Q20

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Question 8 (14 MARKS)

An electrical engineer is testing Coulomb's law, which is an electromagnetic law that describes the force between two charged bodies. The electrical engineer changes the separation between two charged spheres and measures the electrostatic force. The amounts of charge on the two spheres are kept constant. It is known that the relationship between the separation of the two charged spheres, r, and the electrostatic force, F, is $F = k\frac{q_1 q_2}{r^2}$.

a. As a 'pilot study' of this experiment, the engineer measures the force between two charged metal spheres that are held 6.54 mm apart. Write this distance in SI units and scientific notation. 1 MARK

b. State a possible controlled variable for this investigation. Explain why this variable must be controlled, with reference to the validity of the experiment. 2 MARKS

c. Explain why, to linearise the data, the values of $\frac{1}{r^2}$ must be calculated. 1 MARK

d. The data recorded by the engineer is recorded in the table below. Calculate the values of $\frac{1}{r^2}$ in units of m^{-2}. Represent these values to the correct number of significant figures. 2 MARKS

Seperation r (mm)	**Force (N)**	$\frac{1}{r^2}$ **(m^{-2})**
10.0	6.90×10^{-27}	
20.0	1.73×10^{-27}	
30.0	7.67×10^{-28}	
40.0	4.31×10^{-28}	

e. Plot a graph of F vs. $\frac{1}{r^2}$. 4 MARKS

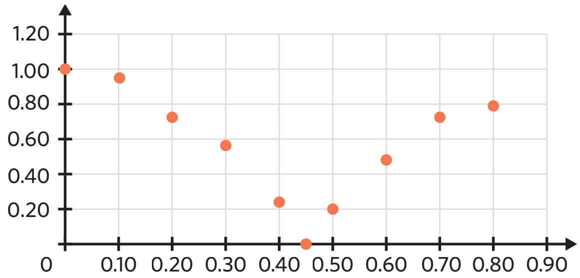
On your graph:

- label each axis and include units
- use an appropriate scale.
- draw a line of best for the data.

f. It is known that the value of q_1 is 5.00×10^{-20} C and the value of q_2 is 1.50×10^{-21} C. Use the line of best fit of the graph in part d to determine the value of Coulomb's constant, k, that would be obtained in this experiment. Give your answer in N m^2 C^{-2}. 4 MARKS

Question 9 (9 MARKS)

During their practical investigation, some Physics students investigate the movement of a small rubber ball. The ball falls from a height of 1.00 m and rebounds to a height of 0.78 m. The students record the ball's vertical position vs. time by using a smartphone's video feature and a metre rule scale. The uncertainty in the ball's vertical position is ±0.03 m. The results from the students' recorded data are plotted on the graph shown.



a. On the graph above: 4 MARKS

- label each axis and include units on each axis.
- insert appropriate uncertainty bars for the height values on the graph, for the readings for the first four data points after the ball is released.
- draw non-linear curves of best fit.

Adapted from VCAA 2021 NHT exam Short answer Q18d

b. Estimate the speed of the ball, $speed = \frac{distance}{time}$, at the instant of impact using an appropriate gradient of the graph. Use calculations to support your answer. 3 MARKS

Adapted from VCAA 2021 NHT exam Short answer Q18e

c. The students are presenting their findings in a scientific poster. Using the graph provided, provide a short explanation as to whether the ball is travelling quickest at a time before or after it bounces. 2 MARKS

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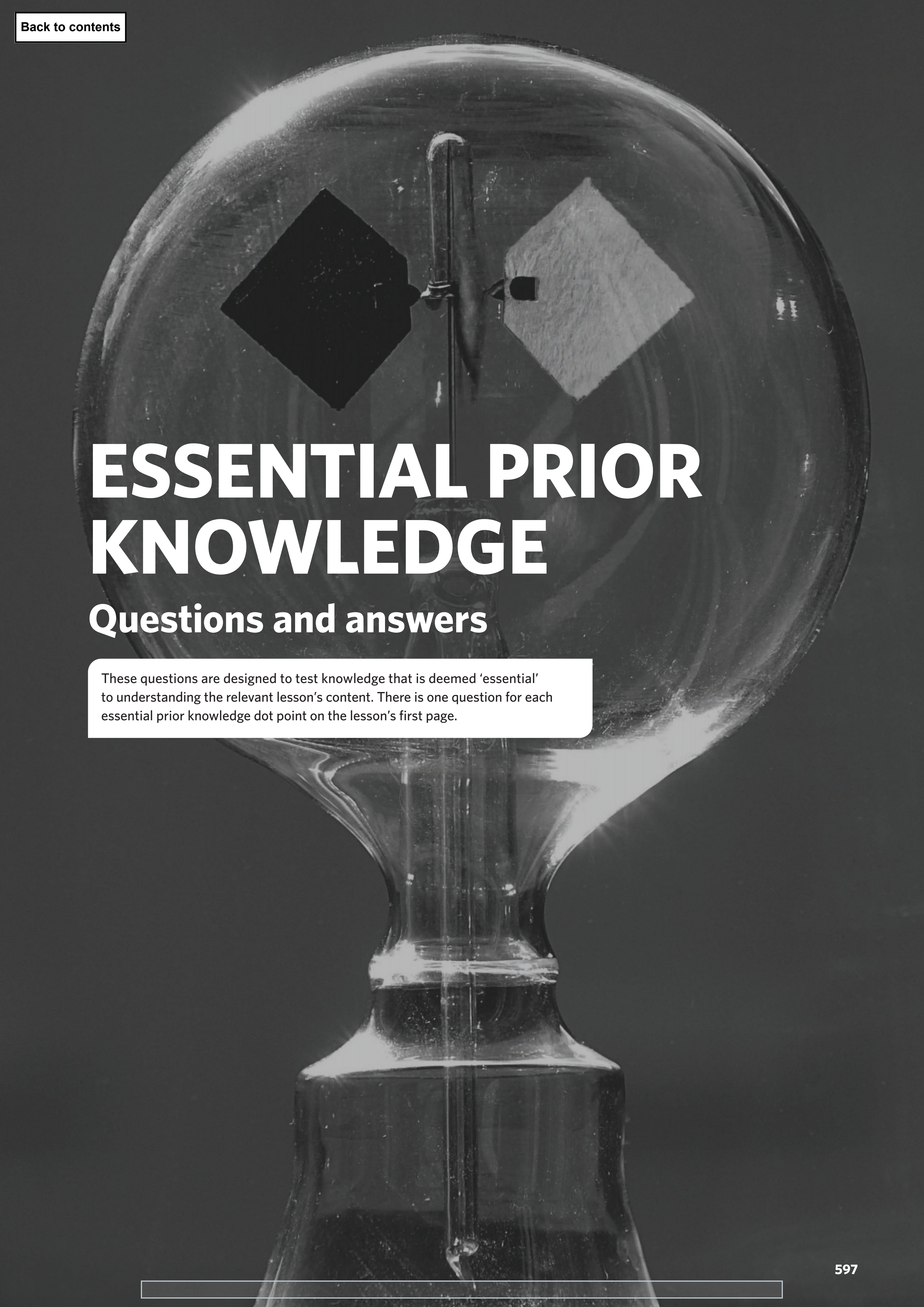

ESSENTIAL PRIOR KNOWLEDGE

Questions and answers

These questions are designed to test knowledge that is deemed 'essential' to understanding the relevant lesson's content. There is one question for each essential prior knowledge dot point on the lesson's first page.

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Essential prior knowledge questions

1A Kinematics recap

Question 1

A rearranged form of the equation $10 = \left(\frac{3+4}{2}\right)t$ in terms of t is given by

A. $t = \frac{2 \times 10}{3+4}$.

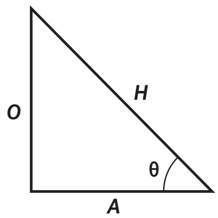
B. $t = \frac{2(3+4)}{10}$.

C. $t = \left(\frac{3+4}{2}\right) \times 10$.

D. $10 = \left(\frac{2}{3+4}\right)t$.

1B Forces recap

Question 2



The angle in the triangle, θ, can be found using

A. $\tan\left(\frac{O}{A}\right)$.

B. $\sin^{-1}\left(\frac{A}{H}\right)$.

C. $\cos\left(\frac{A}{H}\right)$.

D. $\tan^{-1}\left(\frac{O}{A}\right)$.

Question 3

Which of the following is not a vector quantity?

A. 4.0 m s^{-1}

B. 9.0 m s^{-2}, to the right

C. 14.0 m s^{-1}, to the left

D. 15 km h^{-1}, north

1C Inclined planes

Question 4

Which of the following is not a correct constant acceleration equation?

A. $s = \frac{1}{2}(u+v)t$

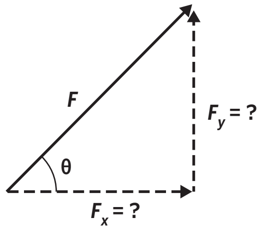
B. $v = u + at$

C. $s = u + v + \frac{1}{2}at^2$

D. $v^2 = u^2 + 2as$

Question 5

Which of the following options is correct?



A. $F_x = F_y = F$

B. $F_x = F_y = \frac{1}{2}F$

C. $F_x = F\sin(\theta)$, $F_y = F\cos(\theta)$

D. $F_x = F\cos(\theta)$, $F_y = F\sin(\theta)$

Question 6

Which of the following is not one of Newton's three laws of motion?

A. The net force on an object is given by $F_{net} = ma$.

B. The reaction force to the gravitational force is the normal force.

C. For every action force there is an equal and opposite reaction force, $F_{on\ A\ by\ B} = -F_{on\ B\ by\ A}$.

D. An object moving at a constant velocity will keep moving at that constant velocity unless acted on by an external net force.

1D Connected bodies

Question 7

A force of 10 N accelerates an object at 2.0 m s^{-2}. What is the object's mass?

A. 12 kg

B. 5.0 kg

C. 4.0 kg

D. 0.20 kg

Question 8

A ball is hit with a bat with a force of 20 N to the right. What is the magnitude and direction of the force on the bat by the ball?

A. $F_{ball\ on\ bat}$ = 10 N to the left

B. $F_{ball\ on\ bat}$ = 20 N to the left

C. $F_{ball\ on\ bat}$ = 20 N to the right

D. Not enough information to answer the question.

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Question 9

Which of the following statements is true about Earth's gravitational force?

A. Earth's gravity only acts on objects when they're falling.

B. Earth's gravity applies the same amount of force to all objects.

C. In the absence of air resistance, Earth's gravity accelerates all objects at the same rate.

D. Earth's gravitational force is the same strength no matter the distance from the surface.

1E Basic circular motion

Question 10

An object, travelling to the left, accelerates from 1.0 m s^{-1} to 3.0 m s^{-1} in 1.0 s. Which of the following correctly states the final instantaneous velocity of the object after the acceleration?

A. 1.0 m s^{-1}

B. 2.0 m s^{-1} left

C. 3.0 m s^{-1}

D. 3.0 m s^{-1} left

Question 11

A 2.0 kg mass is subject to a net force of 15 N, what is the magnitude of its acceleration?

A. 0.0 m s^{-2}

B. 7.5 m s^{-2}

C. 15 m s^{-2}

D. 30 m s^{-2}

1F Banked circular motion

Question 12

A normal force on an object acts

A. perpendicular to the object.

B. opposite to its gravitational force.

C. perpendicular to the surface it is on.

D. perpendicular to the force of gravity.

Question 13

The direction of the net force acting on an object undergoing uniform circular motion is

A. tangential to its circular path.

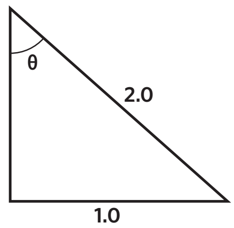
B. parallel to the object's motion.

C. towards the centre of its circular path.

D. away from the centre of its circular path.

Question 14

Calculate the angle θ in the triangle shown.



A. $\theta = 30°$

B. $\theta = 45°$

C. $\theta = 60°$

D. $\theta = 75°$

1G Vertical circular motion

Question 15

Evan is hanging off a ledge and each of his hands is pulling down with 500 N. What is the normal force acting on each hand?

A. 51 N

B. 250 N

C. 500 N

D. 1000 N

Question 16

A car is turning around a circular corner.
Which of the following provides the centripetal force?

A. normal force

B. centrifugal force

C. force due to gravity

D. force due to friction

1H Projectile motion

Question 17

Which of the following is not a constant acceleration equation?

A. $p = mv$

B. $v = u + at$

C. $s = \frac{1}{2}(u + v)t$

D. $s = vt - \frac{1}{2}at^2$

Question 18

Which equation can be used to calculate the angle in a right-hand triangle when given the opposite and adjacent sides?

A. $\sin(\theta) = \frac{opposite}{adjacent}$

B. $\cos(\theta) = \frac{opposite}{adjacent}$

C. $\tan(\theta) = \frac{opposite}{adjacent}$

D. $\tan(\theta) = \frac{adjacent}{opposite}$

1I Momentum and impulse

Question 19

Which of the following could not correctly describe the velocity of an object?

A. 3.2 m s^{-1}, 20° from the horizon

B. 10 km h^{-1} south

C. 60 km h^{-1}

D. 82 m s^{-1} up

Question 20

Which of the following is not one of Newton's laws of motion?

A. $F_{net} = ma$

B. $F_{on\ A\ by\ B} = -F_{on\ B\ by\ A}$

C. the equations of constant acceleration

D. An object will stay in motion unless acted upon by an unbalanced force.

2A Kinetic energy, work and power

Question 21

Speed is a

A. unit.

B. direction.

C. vector quantity.

D. scalar quantity.

Question 22

Which of the following could correctly describe the displacement of an object?

A. 1.0 mm

B. 1.0 cm

C. 1.0 m

D. 10 m down

Question 23

What is the magnitude of the net force acting on a 2.0 kg ball accelerating 5.0 m s^{-2} to the right?

A. 2.0 N

B. 2.5 N

C. 5.0 N

D. 10 N

2B Elastic and inelastic collisions

Question 24

A man, with a mass of 80.0 kg, walks into a bar at a speed of 2.00 m s^{-1}. What is the magnitude of his momentum?

A. 40.0 kg m s^{-1}

B. 80.0 kg m s^{-1}

C. 160 kg m s^{-1}

D. 320 kg m s^{-1}

Question 25

A man, with a mass of 82.0 kg, walks out of a bar at a speed of 1.50 m s^{-1}. What is his kinetic energy?

A. 61.5 J

B. 92.3 J

C. 123 J

D. 185 J

2C Gravitational potential energy

Question 26

A shopping trolley is pushed with a force of 5.0 N over a distance of 5.0 m. What is the work done on the shopping trolley?

A. 1.0 J

B. 5.0 J

C. 10 J

D. 25 J

Question 27

A 2.00 kg bird is flying at 40.0 m s^{-1}. What is its kinetic energy?

A. 40 J

B. 80 J

C. 1.6×10^3 J

D. 3.2×10^3 J

2D Strain potential energy

Question 28

A person is running in a straight 100 m race, to the right. When they are 60 m from the finish, their displacement from their original position is

A. 40 m.

B. 40 m, to the right.

C. 60 m.

D. 60 m, to the right.

Question 29

A force of 5.00 N is applied to a block across 2.50 m. The work done on the block is

A. 5.00 J.

B. 12.5 J.

C. 25.0 J.

D. 100 J.

Question 30

On the freeway, a 500 kg car is travelling at 100 km h^{-1}. The kinetic energy of the car is

A. 1.9×10^5 J.

B. 3.9×10^5 J.

C. 2.5×10^6 J.

D. 5.0×10^6 J.

Question 31

When a 300 g ball falls 6.8 m towards the ground, it

A. loses 2.9 J in gravitational potential energy.

B. gains 2.9 J in gravitational potential energy.

C. loses 20 J in gravitational potential energy.

D. gains 20 J in gravitational potential energy.

2E Vertical spring-mass systems

Question 32

A 4.0 kg ball is rolling with a speed of 3.0 m s^{-1}. How much kinetic energy does the ball have?

A. 6.0 J

B. 12 J

C. 18 J

D. 36 J

Question 33

How much *GPE* does an apple with a mass of 0.10 kg have when it's hanging 3.6 m above the ground? Take the ground as the position of zero *GPE*.

A. 0 J

B. 0.36 J

C. 3.5 J

D. 35 J

Question 34

An ideal spring with a spring constant of 5.0 N m^{-1} is compressed by 0.60 m. How much *SPE* does the spring have?

A. 0.90 J

B. 1.5 J

C. 1.8 J

D. 3.0 J

Question 35

A toy car is at the top of a hill, with 4.2 J of kinetic energy and 7.8 J of gravitational potential energy relative to the bottom of the hill. At the bottom of the hill, the cart hits a spring and all of its energy is converted to strain potential energy. How much strain potential energy does the spring have at its maximum compression?

A. 3.6 J

B. 4.2 J

C. 7.8 J

D. 12.0 J

3A Gravitational fields and forces

Question 36

Newton's third law of motion states that every action force has a reaction force that is

A. equal in magnitude and direction.

B. not equal in magnitude and direction.

C. equal in direction and different in magnitude.

D. equal in magnitude and opposite in direction.

Question 37

Which of the following correctly gives the force due to gravity acting on a 500 g ball falling 1.0 m above the ground?

A. 0.5 N

B. 4.9 N

C. 9.8 N

D. 500 N

3B Gravitational potential energy in uniform and non-uniform fields

Question 38

A rocket of mass 1.2×10^5 kg is travelling at a speed of 112 m s^{-1}. What is the kinetic energy of the rocket?

A. 6.7×10^6 J

B. 1.3×10^7 J

C. 7.5×10^8 J

D. 1.5×10^9 J

Question 39

A ball of mass 1.0 kg is dropped from a height of 10 m. What is the ball's kinetic energy when it hits the ground?

A. 9.8 J

B. 10 J

C. 98 J

D. 150 J

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Question 40

A non-uniform gravitational field

A. repels objects.

B. both repels and attracts objects.

C. is a field that has a constant magnitude and direction at all points.

D. is a field where the distance between field lines changes as distance from the centre of mass changes.

3C Orbital motion

Question 41

Yasmin is swinging a yo-yo so that it is undergoing uniform circular motion. The mass of the yo-yo is 0.10 kg and the string is 1.2 m long. If the yo-yo has a speed of 5.0 m s^{-1}, what is the net force acting on the yo-yo?

A. 0.35 N

B. 0.42 N

C. 1.7 N

D. 2.1 N

Question 42

Which of the following is incorrect about gravitational fields and forces?

A. Only planets have an associated gravitational field.

B. Field lines always point towards the centre of mass.

C. The gravitational force acting between two objects is equal and opposite.

D. Gravitational field strength decreases as distance from a planet's surface increases.

4A Electric fields

Question 43

One vector has a magnitude of 2, directed to the right, and another vector has a magnitude of 5, directed to the left. The addition of the two vectors is a vector

A. of magnitude 3, directed to the left.

B. of magnitude 3, directed to the right.

C. of magnitude 7, directed to the left.

D. of magnitude 7, directed to the right.

Question 44

The spacing of field lines indicates

A. the type of field present.

B. the direction of the field at that point.

C. the direction of the force at that point.

D. the relative strength of the field at that point.

4B Magnetic fields

Question 45

Two vectors of the same magnitude, one directed east and one directed south, are added. The resultant vector is directed

A. east.

B. south.

C. between south and east.

D. between south and west.

Question 46

When drawing field lines, it is important that

A. the field lines cross over and have arrowheads to indicate the direction of the field.

B. the field lines never cross over and have arrowheads to indicate the direction of the field.

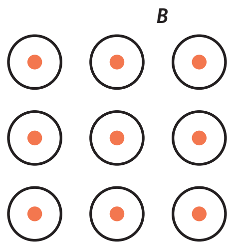
C. the field lines cross over and do not have any arrowheads to indicate the direction of the field.

D. the field lines never cross over and do not have any arrowheads to indicate the direction of the field.

4C Magnetic forces on charged particles

Question 47

The magnetic field shown is directed



A. up the page.

B. into the page.

C. down the page.

D. out of the page.

4D DC motors

Question 48

2.0 A of current runs along a single turn of 1.5 m current-carrying wire, perpendicular to the direction of a magnetic field. The strength of the magnetic field is 2.5 T. What is the magnitude of magnetic force on the current-carrying wire?

A. 2.0 N

B. 3.8 N

C. 5.0 N

D. 7.5 N

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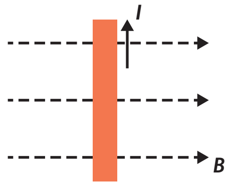
Question 49

The direction of the magnetic force on the current-carrying wire shown is



A. upwards.

B. to the left.

C. to the right.

D. into the page.

5A EMF and Faraday's law

Question 50

Which of the following best describes the direction and strength of the magnetic field near a bar magnet?

A. The magnetic field points north to south and is weaker close to the magnet.

B. The magnetic field points south to north and is weaker close to the magnet.

C. The magnetic field points north to south and is stronger close to the magnet.

D. The magnetic field points south to north and is stronger close to the magnet.

Question 51

The direction of a magnetic field represented by crosses is

A. to the left.

B. to the right.

C. into the page.

D. out of the page.

5B Direction of induced current and Lenz's law

Question 52

As a magnet moves towards a loop, the field strength through the loop is

A. uniform.

B. increasing.

C. decreasing.

D. cancelled out by the loop.

Question 53

Which rule can be used to find the direction of the magnetic field around a current carrying wire?

A. right-hand coil rule

B. right-hand slap rule

C. right-hand grab rule

D. right-hand rotation rule

Question 54

Which of the following would not induce an EMF in a loop of wire?

A. rotating the loop in a magnetic field

B. moving a magnet closer to the loop

C. moving the loop into a magnetic field

D. holding a magnet at a constant distance from the loop

5C Generators and alternators

Question 55

Which of the following best describes the primary difference between alternating current (AC) and direct current (DC)?

A. DC works on all household devices.

B. AC does not work on household devices.

C. DC alternates between positive and negative amplitudes.

D. AC alternates between positive and negative amplitudes.

Question 56

Frequency (f) can be best related to period (T) through which equation?

A. $f = \frac{1}{T}$

B. $v = f\lambda$

C. $f = T$

D. Amplitude = $\frac{f}{T}$

Question 57

According to Faraday's law, an EMF can be induced in a current carrying wire when it

A. moves.

B. is in a magnetic field.

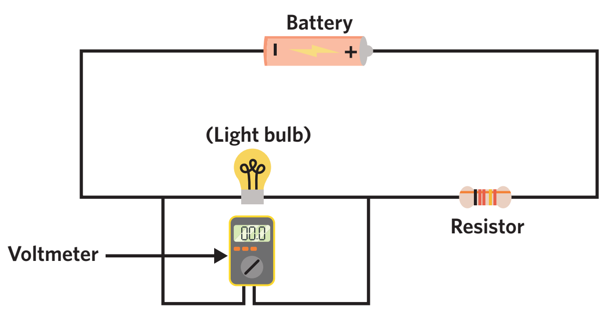
C. undergoes a magnetic flux.

D. experiences a change in magnetic flux.

5D Photovoltaic Cells

Use the following information to answer questions 58 and 59.

The diagram shows a 2 V battery connected to a resistor, light bulb, and voltmeter.



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PRIOR KNOWLEDGE

Question 58

The battery outputs direct current (DC). This means the electrons in the circuit

A. flow in one direction.
B. change direction once.
C. continuously change direction.
D. build up on the surface of the object.

Question 59

The light bulb and voltmeter are connected in

A. AC.
B. series.
C. parallel.
D. conjunction.

6B Transformers and comparing AC and DC power

Question 60

3.0 A of current runs through a 1.60 Ω resistor. What is the power dissipated by the resistor?

A. 1.6 W
B. 3.0 W
C. 4.8 W
D. 14 W

Question 61

Which of the following correctly describes voltage and current in a series circuit?

A. The current through each component and the voltage across each may vary.
B. The current through each component and the voltage across each is always the same.
C. The current through each component is the same, but the voltage across each may vary.
D. The current through each component may vary, but the voltage across each is always the same.

6C Transmission of power

Question 62

2.0 A of current runs through a resistor that dissipates power at a rate of 8.0 W. What is its resistance?

A. 2.0 Ω
B. 4.0 Ω
C. 8.0 Ω
D. 16 Ω

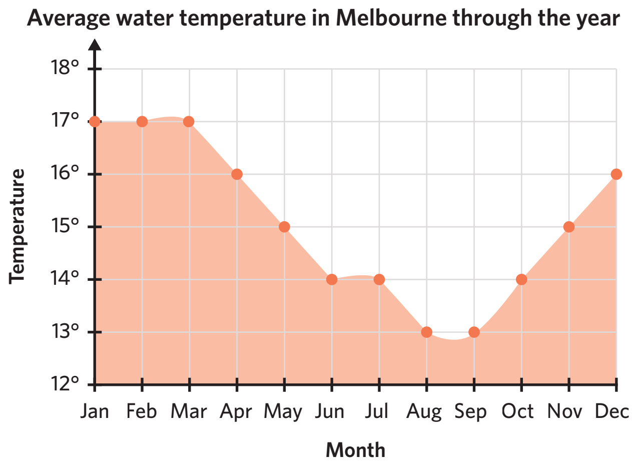
Question 63

An AC power supply, set at 200 V_{RMS}, is attached to the primary coil of a step-down transformer with turns ratio 2:1. What is the value of the RMS voltage in the secondary coil?

A. 100 V
B. 200 V
C. 300 V
D. 400 V

7A Waves recap

Question 64



Which of the following correctly identifies the month of the year with the coldest average water temperature?

A. April
B. August
C. February
D. December

7B Wave interference and path difference

Question 65

The point of maximum amplitude in a longitudinal wave is called a

A. crest.
B. trough.
C. rarefaction.
D. compression.

Question 66

The point of minimum amplitude in a transverse wave is called a

A. crest.
B. trough.
C. rarefaction.
D. compression.

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Question 67

Which of the following statements is true?
(Select all that apply)

A. Two waves in the same medium with the same frequency can have different speeds.

B. Two waves in the same medium with the same frequency must have the same speed.

C. Two waves in the same medium with the same frequency can have different wavelengths.

D. Two waves in the same medium with the same frequency must have the same wavelength.

7C Standing waves

Question 68

When the peak of one wave overlaps with the trough of another wave, what kind of interference occurs?

A. no interference

B. full interference

C. destructive interference

D. constructive interference

Question 69

Which of the following is correct? **(Select all that apply)**

A. Nodes are regions of destructive interference.

B. Nodes are regions of constructive interference.

C. Antinodes are regions of destructive interference.

D. Antinodes are regions of constructive interference.

7D Diffraction

Question 70

A speaker creates a 50 Hz sound wave. Take the speed of sound in the air to be 340 m s^{-1}. What is the wavelength of the wave?

A. 3.4 m

B. 6.8 m

C. 50 m

D. 340 m

8A Electromagnetic waves

Question 71

Which of the following is not true about transverse waves?

A. The wavelength is the length of one complete wave cycle.

B. The speed of a wave increases as the frequency increases.

C. The period is the time it takes one wavelength to pass a point.

D. The frequency is the number of waves that pass a point each second.

8B Young's double slit experiment

Question 72

Which of the following correctly gives the wavelength of a wave travelling at 54 ms^{-1} with a frequency of 65 kHz?

A. 8.3×10^{-4} m

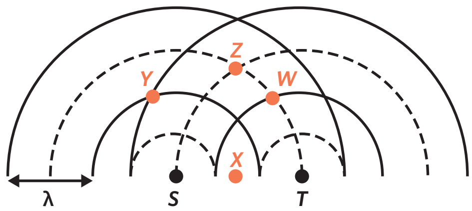
B. 8.3×10^{-1} m

C. 3.5×10^{3} m

D. 3.5×10^{6} m

Question 73

The diagram shows two wave sources, S and T, producing waves at the same frequency. The solid lines represent the crests of the waves while the dotted lines represent the troughs of the waves.



Which of the following statements is true?

A. Y is a point of destructive interference.

B. Z is a point of constructive interference.

C. W is a point of constructive interference.

D. The distance from X to Z is one wavelength.

9A Experimental design of the photoelectric effect

Question 74

Which statement correctly describes the law of conservation of energy?

A. In a closed system, energy is never conserved.

B. In a closed system, initial energy is equal to the final energy.

C. In a closed system, initial energy is less than the final energy.

D. In a closed system, initial energy is more than the final energy.

Question 75

What is the work done on a particle with a charge of 1.6×10^{-19} C by variable voltage source applying a potential difference of 7.2 V?

A. 1.4×10^{-19} J

B. 1.2×10^{-18} J

C. 1.3×10^{-18} J

D. 7.2×10^{1} J

Question 76

An ammeter is used for

A. measuring charge.

B. measuring voltage.

C. measuring current.

D. measuring frequency.

Question 77

An independent variable is

A. a variable that is measured throughout the experiment.

B. a variable that stays the same throughout the experiment.

C. a variable that is deliberately changed throughout the experiment.

D. a variable that is both changed and measured throughout the experiment.

9B Changing intensity in the photoelectric effect

Question 78

1.40×10^{-15} J converted to eV is closest to

A. 2.24×10^{-34}.

B. 8.75×10^{-34}.

C. 2.24×10^{3}.

D. 8.75×10^{3}.

Question 79

Negatively charging the collector electrode in the photoelectric experiment is useful to

A. shine light on the metal surface.

B. apply a voltage across the ammeter.

C. measure the work function of the metal.

D. measure the maximum kinetic energy of photoelectrons.

Question 80

The stopping voltage represents the voltage which

A. repels the least photoelectrons.

B. attracts the most photoelectrons.

C. attracts half of the photoelectrons.

D. repels all photoelectrons from reaching the collector electrode.

Question 81

When graphing data for a scientific experiment, which variable usually goes on the horizontal axis?

A. the control variable

B. the dependent variable

C. the independent variable

D. It doesn't matter which variable goes on the horizontal axis.

9C Changing frequency in the photoelectric effect

Question 82

2.30×10^{5} eV converted to J is closest to

A. 3.68×10^{-24}.

B. 1.44×10^{-14}.

C. 3.68×10^{-14}.

D. 1.44×10^{24}.

Question 83

In the photoelectric effect experiment, incident light on the metal surface can

A. liberate protons.

B. liberate neutrons.

C. liberate electrons.

D. cause electrons to lose energy.

Question 84

Select the incorrect statement.

The work function

A. depends on the metal surface.

B. is measured using the variable voltage source.

C. is a property of the metal that relates to how strongly electrons are held.

D. determines how much energy is required to release the most loosely bound electron.

Question 85

The horizontal axis intercept of a photocurrent-electrode potential graph represents the

A. work function.

B. stopping voltage.

C. maximum photocurrent.

D. negative value of the stopping voltage.

Question 86

When graphing data for a scientific experiment, which variable usually goes on the vertical axis?

A. the control variable

B. the dependent variable

C. the independent variable

D. It doesn't matter which variable goes on the vertical axis.

9D Explaining the photoelectric effect

Question 87

How can the maximum kinetic energy of photoelectrons be increased? **(Select all that apply)**

A. by increasing the intensity of light

B. by increasing the frequency of light

C. by reducing the work function of the metal

D. by negatively charging the collector electrode

Question 88

Increasing the intensity of light in a photoelectric experiment increases

A. the voltage of the battery.

B. the maximum photocurrent.

C. the work function of the metal.

D. the maximum kinetic energy of the photoelectrons.

Question 89

The threshold frequency represents

A. the voltage at which no photoelectrons reach the collector.

B. the minimum amount of energy required to eject photoelectrons.

C. the minimum frequency of light required to eject photoelectrons.

D. the maximum frequency of light required to produce a photocurrent.

10A Comparing light and matter

Question 90

Significant diffraction occurs when

A. $\frac{\lambda}{w} = 0$.

B. $\frac{\lambda}{w} \geq 0$.

C. $\frac{\lambda}{w} << 1$.

D. $\frac{\lambda}{w} \gtrsim 1$.

Question 91

Which of the following is true of Young's double slit experiment?

A. The two bright bands formed on the screen showed that light behaves like a wave.

B. The two bright bands formed on the screen showed that light behaves like a particle.

C. The interference pattern formed on the screen showed that light behaves like a wave.

D. The interference pattern formed on the screen showed that light behaves like a particle.

Question 92

Which formula can be used to calculate the energy of a photon?

A. $E = \frac{hc}{\lambda}$

B. $E = \frac{h}{\lambda}$

C. $E = \frac{1}{2}mv^2$

D. $E = \sqrt{2m \times KE}$

10B Absorption and emission spectra

Question 93

Which of the following best explains why standing waves form?

A. All waves are standing waves.

B. Transverse waves form standing waves the farther they travel.

C. Constructive and destructive interference cause nodes and antinodes to form.

D. Waves carry energy so when they overlap the amplitude everywhere is increased.

Question 94

What is the definition of the electromagnetic spectrum?

A. the seven colours of a rainbow

B. the range of all visible wavelengths of electromagnetic waves

C. the range of all electromagnetic waves ordered by frequency and wavelength

D. the range of all high energy electromagnetic waves order by frequency and wavelength

Question 95

Which of the following options correctly relates photon energy, frequency, and wavelength?

	Energy and frequency	Energy and wavelength
A.	$E_{ph} = hf$	$E_{ph} = hc\lambda$
B.	$E_{ph} = hf$	$E_{ph} = \frac{hc}{\lambda}$
C.	$E_{ph} = \frac{h}{f}$	$E_{ph} = hc\lambda$
D.	$E_{ph} = \frac{h}{f}$	$E_{ph} = \frac{hc}{\lambda}$

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Question 96

What does wave-particle duality refer to?

A. Something being either a wave or a particle.

B. Something being a wave most of the time and a particle some of the time.

C. Something being a particle most of the time and a wave some of the time.

D. Something exhibiting both wave and particle properties depending on the situation.

11A Special relativity concepts

Question 97

Which of the following objects is not accelerating?

A. A ball speeding up as it rolls down a hill.

B. A car travelling around a corner at a constant speed.

C. A train moving at a constant speed in a straight line.

D. A person running a 400 m race around an oval track.

11B Length contraction and time dilation

Question 98

Which of the following best describes light?

A. It travels at different speeds, dependent on the relative speeds of the observer or source of light.

B. It travels at different speeds, independent of the relative speeds of the observer or source of light.

C. It travels at a constant speed, dependent on the relative speeds of the observer or source of light.

D. It travels at a constant speed, independent of the relative speeds of the observer or source of light.

11C Relativity examples

Question 99

The Lorentz factor of a particle travelling at $0.75c$ is

A. 0.66.

B. 0.75.

C. 1.5.

D. 2.0.

Question 100

Car *X* is travelling at $0.60c$ along a straight freeway. Which of the following observers is able to measure the proper length of the freeway?

A. the person driving car *X*

B. a person driving a different car at the same velocity as car *X*

C. a stationary observer on a nearby bridge overlooking the freeway

D. a person driving a car travelling in the opposite direction to car *X*

11D Mass-energy

Question 101

The Lorentz factor of a particle moving at 2.65×10^8 m s^{-1} is closest to

A. 1.2.

B. 2.1.

C. 2.3.

D. 2.9.

12D Representing and analysing data

Question 102

A student is undertaking a photoelectric effect experiment. They are altering the frequency of the incident light, and measuring the stopping voltage. They keep the intensity of light the same throughout all tests. Which of the following correctly identifies the independent and dependent variables for this experiment, respectively?

A. the intensity of incident light, the stopping voltage

B. the frequency of incident light, the stopping voltage

C. the stopping voltage, the frequency of incident light

D. the frequency of incident light, the intensity of incident light

---

Question 103

A scientist takes a measurement of the acceleration of a block down an inclined plane. They state the value of the acceleration as 5.0 ± 0.5 m s^{-2}. Which of the following is correct?

A. The scientist believes the true value of the acceleration is 5.0 m s^{-2}.

B. The scientist believes the true value of the acceleration is incorrect by 0.5 m s^{-2}.

C. The scientist is incorrect in measuring the value of the acceleration, as they are uncertain in its value.

D. The scientist believes the true value of the acceleration is somewhere between 4.5 m s^{-2} and 5.5 m s^{-2}.

12E Communicating findings

Question 104

A difference between the aim and the hypothesis of an experiment is

A. an aim should include specific details about the experiment, whereas a hypothesis should state the purpose of the experiment.

B. an aim should include specific details about the experiment, whereas a hypothesis should include theory relevant to the experiment.

C. an aim should explain the purpose of an experiment, whereas a hypothesis should state the step-by-step procedure to carry out the experiment.

D. an aim should explain the purpose of an experiment, whereas a hypothesis should provide a testable prediction for the relationship between the variables being investigated.

Question 105

Which of the following should be included in a graph produced to show the relationship between two variables? **(Select all that apply)**

A. labels on both axes

B. the aim of the experiment

C. the hypothesis of the experiment

D. a title relating to the variables being investigated

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Essential prior knowledge answers

1A	1. A				
1B	2. D	3. A			
1C	4. C	5. D	6. B		
1D	7. B	8. B	9. C		
1E	10. D	11. B			
1F	12. C	13. C	14. A		
1G	15. C	16. D			
1H	17. A	18. C			
1I	19. C	20. C			
2A	21. D	22. D	23. D		
2B	24. C	25. B			
2C	26. D	27. C			
2D	28. B	29. B	30. A	31. C	
2E	32. C	33. C	34. A	35. D	
3A	36. D	37. B			
3B	38. C	39. C	40. D		
3C	41. D	42. A			
4A	43. A	44. D			
4B	45. C	46. B			
4C	47. D				
4D	48. D	49. D			
5A	50. C	51. C			
5B	52. B	53. A	54. D		
5C	55. D	56. A	57. D		
5D	58. A	59. C			
6B	60. D	61. C			
6C	62. A	63. A			
7A	64. B				
7B	65. D	66. B	67. B, D		
7C	68. C	69. A, D			
7D	70. B				
8A	71. B				
8B	72. A	73. B			
9A	74. B	75. B	76. C	77. C	
9B	78. D	79. D	80. D	81. C	
9C	82. C	83. C	84. B	85. D	86. B
9D	87. B, C	88. B	89. C		
10A	90. D	91. C	92. A		
10B	93. C	94. C	95. B	96. D	
11A	97. C				
11B	98. D				
11C	99. C	100. C			
11D	101. B				
12D	102. B	103. D			
12E	104. D	105. A, D			

PRIOR KNOWLEDGE

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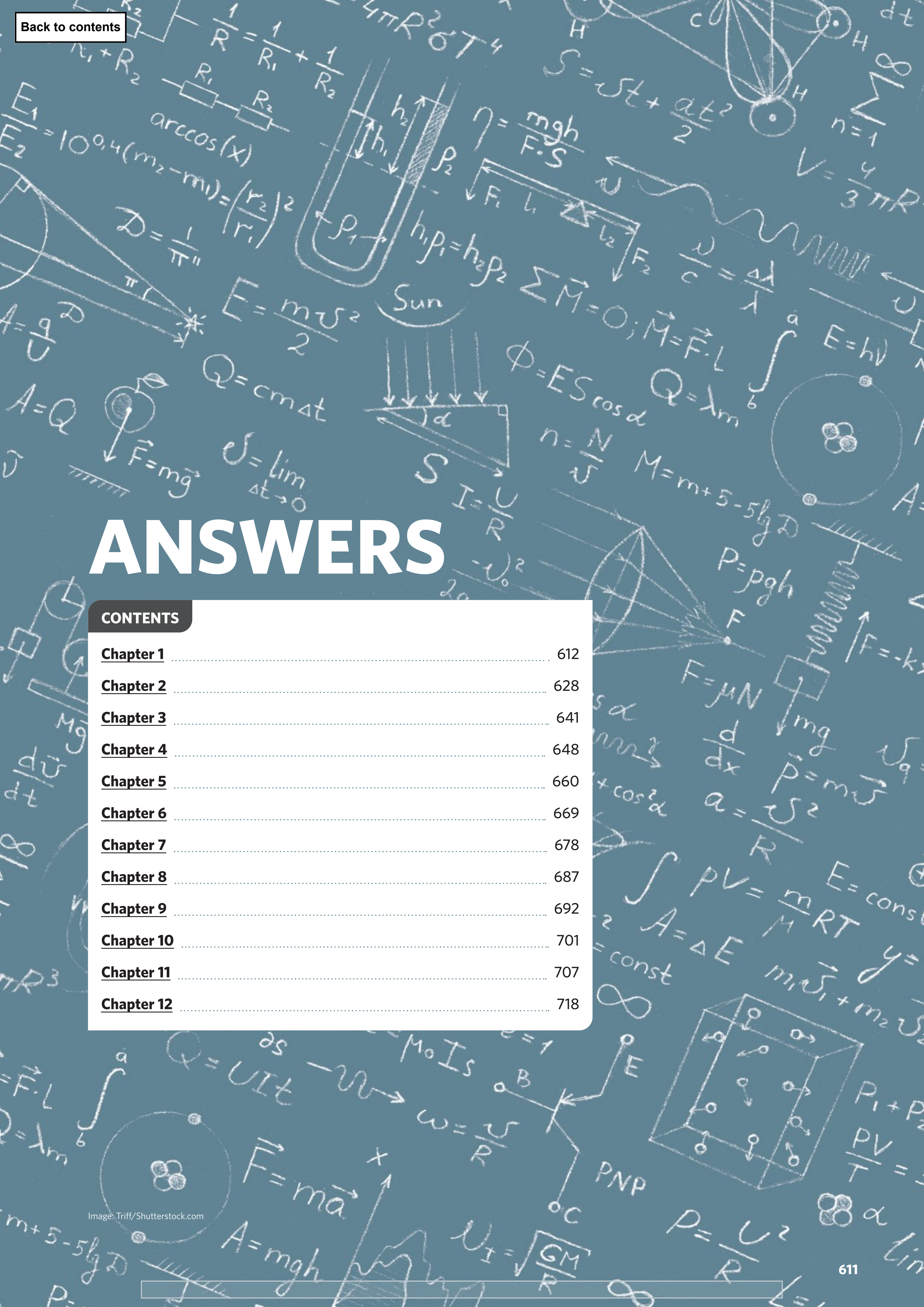

ANSWERS

CONTENTS

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1A Kinematics recap

Progress questions

1. B. A scalar quantity only has an associated magnitude.

2. A. Acceleration is a vector quantity, whereas money, distance travelled and temperature are all scalar quantities.

3. B. $d = 3$ laps $= 3 \times 25 = 75$ m, $t = 144$ s, $v = \frac{d}{t}$

$v = \frac{75}{144} = 0.521 = 0.52 \text{ m s}^{-1}$

4. A. After 3 laps, she is 25 m away from her starting position, so $s = 25$ m, $t = 144$ s, $v = \frac{\Delta s}{\Delta t}$

$v = \frac{25}{144} = 0.174 = 0.17 \text{ m s}^{-1}$

5. B. $a = \frac{\Delta v}{\Delta t} = \frac{v - u}{\Delta t} = \frac{10 - 0}{20} = 0.500 = 0.50 \text{ m s}^{-2}$

6. A. Deceleration implies slowing down, not necessarily a negative velocity. Therefore, while Sidra is still travelling in her original direction, she is slowing down.

7. D. The variable present are u, s and v, and we are looking for t, therefore a suitable equation would be one that does not contain the unknown variable a.

8. D. $s = \frac{1}{2}(u + v)t \Rightarrow 140 = \frac{1}{2} \times (20 + 0)t \Rightarrow t = 14$ s

Deconstructed exam-style

9. $v = \frac{\Delta s}{\Delta t} \Rightarrow 2.5 = \frac{600}{\Delta t}$

$\Delta t = 240 = 2.4 \times 10^2$ s

10. $v^2 = u^2 + 2as \Rightarrow v^2 = 2.5^2 + 2 \times (-0.10) \times 20$

$v = 1.50 = 1.5 \text{ m s}^{-1}$

11. $s = \frac{1}{2}(v + u)t \Rightarrow 20 = \frac{1}{2} \times (1.5 + 2.5) \times t$

$t = 10.0 = 10$ s

12. Calculate time to the bottom of the hill.

$v = \frac{\Delta s}{\Delta t} \Rightarrow 2.5 = \frac{600}{\Delta t}$

$\Delta t = 240$ s (1 MARK)

Calculate time to the top of the hill.

$v^2 = u^2 + 2as \Rightarrow v^2 = 2.5^2 + 2 \times (-0.10) \times 20$

$v = 1.50 \text{ m s}^{-1}$ (1 MARK)

$s = \frac{1}{2}(v + u)t \Rightarrow 20 = \frac{1}{2} \times (1.50 + 2.5) \times t$

$t = 10.0$ s (1 MARK)

$t_{total} = 240 + 10.0 = 250 = 2.5 \times 10^2$ s (1 MARK)

Exam-style

13. B. $v = \frac{\Delta s}{\Delta t} = \frac{50}{20} = 2.50 = 2.5 \text{ m s}^{-1}$

14. $u = 0 \text{ m s}^{-1}$, $v = \frac{36}{3.6} = 10.0 \text{ m s}^{-1}$

$a = \frac{\Delta v}{\Delta t} = \frac{10.0 - 0}{2.0 - 0}$ (1 MARK)

$a = 5.00 = 5.0 \text{ m s}^{-2}$ (1 MARK)

15. $v^2 = u^2 + 2as = 4.0^2 + 2 \times 0.50 \times 30$ (1 MARK)

$v = 6.78 = 6.8 \text{ m s}^{-1}$ (1 MARK)

85% of students answered this VCAA exam question correctly.

16. $s = vt - \frac{1}{2}at^2 = 2.0 \times 6.0 - \frac{1}{2} \times 0.30 \times 6.0^2$ (1 MARK)

$s = 6.60 = 6.6$ m (1 MARK)

17. $s = \frac{1}{2}(v + u)t \Rightarrow 30 = \frac{1}{2} \times (17 + 3.0) \times t$ (1 MARK)

$t = 3.00 = 3.0$ s (1 MARK)

18. a. $s = ut + \frac{1}{2}at^2 = 0 \times 4.0 + \frac{1}{2} \times 3.0 \times 4.0^2$ (1 MARK)

$s = 24.0 = 24$ m (1 MARK)

b. $v = u + at = 0 + 3.0 \times 4.0$ (1 MARK)

$v = 12.0 = 12 \text{ m s}^{-1}$ (1 MARK)

19. a. Using any two points from the line such as

(10, 8.0) and (2.0, 4.0), (1 MARK)

$gradient = \frac{y_2 - y_1}{x_2 - x_1} = \frac{8.0 - 4.0}{10 - 2.0} = 0.50 \text{ m s}^{-1}$ (1 MARK)

FROM LESSON 12E

b. [A gradient is a rate that indicates the change in the vertical axis per unit of the horizontal axis.[1]][In this case, that is Rory's displacement per second. This is the rate of change of displacement with respect to time, which is Rory's velocity.[2]]

I have explained what a gradient of a line is.[1]

I have explained what the gradient represents in the context of this question.[2]

FROM LESSON 12E

c. $v = 0.50 \text{ m s}^{-1}$ to the south

20. $v = \frac{60}{3.6} = 16.7 \text{ m s}^{-1}$

$s = \frac{1}{2}(v + u)t \Rightarrow 50 = \frac{1}{2} \times (16.7 + u) \times 3.6$ (1 MARK)

$u = 11.1 \text{ m s}^{-1}$

$u = 11.1 \times 3.6 = 40.0 = 40 \text{ km h}^{-1}$ (1 MARK)

21. Yasmin:

$v^2 = u^2 + 2as \Rightarrow 0^2 = 1.70^2 + 2 \times (-0.500) \times s$ (1 MARK)

$s = 2.89$ m (1 MARK)

Bill: $v^2 = u^2 + 2as \Rightarrow 0^2 = 1.60^2 + 2 \times (-0.400) \times s$ (1 MARK)

$s = 3.20$ m (1 MARK)

As 3.20 > 2.89, Bill travels further. (1 MARK)

22. Define upwards as positive.

$s = 15 \times 0.30 = 4.50$ m (1 MARK)

$s = vt - \frac{1}{2}at^2 \Rightarrow 4.50 = 0 \times 10 - \frac{1}{2} \times a \times 10^2$ (1 MARK)

$a = -0.0900 = -0.090 \text{ m s}^{-2}$ (1 MARK)

23. Ryan: $v^2 = u^2 + 2as \Rightarrow v^2 = 1.0^2 + 2 \times 0.30 \times 10$ (1 MARK)

$v = 2.64 = 2.6 \text{ m s}^{-1}$ (1 MARK)

Graham:

$v = u + at = 0.80 + 0.40 \times 5.0 = 2.80 = 2.8 \text{ m s}^{-1}$ (1 MARK)

Graham ends up running at a faster pace. (1 MARK)

24. $s = ut + \frac{1}{2}at^2 = 1.5 \times 2.0 + \frac{1}{2} \times 2.0 \times 2.0^2$

$s = 7.00 = 7.0$ m (1 MARK)

7.0 < 10, so the shark will not catch the fish. (1 MARK)

1B Forces recap

Progress questions

1. A. The vector addition of the two forces is to the right and has a magnitude less than x.

2. B. $F_x = 4.5\cos(60°) = 2.3$ N, $F_y = 4.5\sin(60°) = 3.9$ N.

3. C. The net force acting on a block is the addition of all the forces acting on it.

4. C. In the x-direction, $F_x = 240 - 210 = 30$ N. In the y-direction, $F_y = 200 - 180 = 20$ N. The net force is $F_{net} = \sqrt{(30)^2 + (20)^2} = 36.1$ N.

74% of students answered this VCAA exam question correctly.

5. D. As $F_{net} = ma$, the net force acts in the same direction as the acceleration.

6. C. $F_{A\ on\ B} = -F_{B\ on\ A}$ describes an action-reaction force pair. Objects A and B must be involved in both forces.

7. D. Newton's first law states an object in motion will remain in motion unless acted upon by an external net force.

8. D. The normal force is the force of the surface on the object. This is the reaction of the force the object applies on the surface, as $F_{A\ on\ B} = -F_{B\ on\ A}$.

9. C. Both objects exert a gravitational force toward the centre of the mass of one another.

Deconstructed exam-style

10. A. The gravitational force is the force of the Earth on Liesel.

11. B. The reaction force to F_g is the force of Liesel on the Earth, as $F_{A\ on\ B} = -F_{B\ on\ A}$.

12. [The reaction force acts upwards.[1]]

- I have stated the direction of the reaction force.[1]

13. [The reaction force to the action force, F_g, is the force of Liesel on the Earth.[1]][The direction of the reaction force is upwards,[2]] [and it has a magnitude of 500 N.[3]]

- I have identified the reaction force to the action force F_g.[1]
- I have described the direction of the reaction force.[2]
- I have described the magnitude of the reaction force.[3]

8% of students answered this VCAA exam question correctly.

Exam-style

14. B. Taking to the right as positive:

$F_{addition} = 11.0 - 6.0 = 5.0$

The addition of the two forces is 5.0 N to the right.

15. a. Vector A: $A_x = -50 \times \cos(35°) = -41.0 = -41$ N

$A_y = 50 \times \sin(35°) = 28.7 = 29$ N (1 MARK)

Vector B: $B_x = 60\cos(65°) = 25.4 = 25$ N

$B_y = 60 \times \sin(65°) = 54.4 = 54$ N (1 MARK)

b. $F_x = A_x + B_x$

$F_x = -41.0 + 25.4 = -15.6$ N (1 MARK)

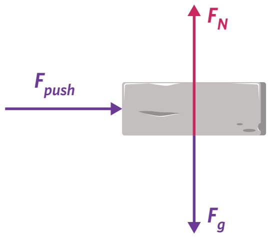
$F_y = A_y + B_y$

$F_y = 28.7 + 54.4 = 83.1$ N (1 MARK)

$F_{addition} = \sqrt{(F_x)^2 + (F_y)^2}$

$F_{addition} = \sqrt{(-15.6)^2 + (83.1)^2} = 84.5 = 85$ N (1 MARK)

16. a.



- I have drawn a pushing force to the right.
- I have drawn a normal force acting upwards.
- I have drawn a gravitational force acting downwards.

b. In the horizontal direction:

$F_{net} = ma$

$70 = 30 \times a$

$a = \frac{70}{30} = 2.33 = 2.3$ m s^{-2}

c. In the horizontal direction:

$F_{net} = ma$

$70 - F_{friction} = 30 \times (-1.5)$ (1 MARK)

$F_{friction} = 1.15 \times 10^2 = 1.2 \times 10^2$ N (1 MARK)

17. B. The force arrangement in option B is the only possible arrangement in which the net force acting on the ring may be 0, as both the horizontal and vertical components of the forces are able to add to 0.

53% of students answered this VCAA exam question correctly.

18. a. $F_g = mg$

$F_g = 1000 \times 9.8 = 9.80 \times 10^3 = 9.8 \times 10^3$ (1 MARK)

The gravitational force acting on the boat is 9.8×10^3 N, downwards. (1 MARK)

b. In the vertical direction:

$F_{net} = 0$, as the boat is not accelerating vertically. (1 MARK)

$F_g - F_N = 0$

$F_N = F_g = 9.80 \times 10^3 = 9.8 \times 10^3$ N (1 MARK)

c. [The boat exerts a contact force on the ground as a result of the gravitational force on the boat.[1]][From Newton's third law, as a result of this contact force a reaction force is exerted on the boat by the ground, known as the normal force.[2]]

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I have identified the boat exerts a contact force on the ground.[1]

I have explained why a normal force is present using Newton's third law of motion.[2]

d. [According to Newton's first law of motion, the boat in motion will remain in motion until it is acted upon by an external net force.[1]][As there is no external net force acting on the boat when the tow bar snaps, it will continue travelling at 65 km h^{-1} until one is applied.[2]]

I have related the boat's motion to Newton's first law of motion.[1]

I have explained the boat will continue moving at 65 km h^{-1} until an external net force is applied.[2]

19. C. As both blocks experience the same acceleration, the 10 kg block must experience twice the net force as the 5 kg block as $F_{net} = ma$.

49% of students answered this VCAA exam question correctly.

20. [When the rocket expels the gases it exerts a force on them. Newton's third law states this force will have an equal and opposite reaction force.[1]][The gases exert a force on the rocket in the opposite direction to the force of the rocket on the gases, which accelerates the rocket forward.[2]]

I have applied Newton's third law of motion to the question.[1]

I have explained how the expelled gases accelerate the rocket.[2]

21. In the vertical direction:

$F_{net} = 700\sin(30°) - 700\sin(30°) = 0$ (1 MARK)

In the horizontal direction:

$F_{net} = 900 + 700\cos(30°) + 700\cos(30°) - 100$

$F_{net} = 2.01 \times 10^3$ N (1 MARK)

$F_{net} = ma$

$2.01 \times 10^3 = 70 \times a$

$a = 28.7 = 29$ m s^{-2} (1 MARK)

The esky is accelerating at 29 m s^{-2} to the left. (1 MARK)

22. a. [The tension in the string causes the block to accelerate.[1]]

I have identified a tension force causes the block to accelerate.[1]

b. [The students have not drawn the normal force acting on the block.[1]][The frictional force acting on the block should be drawn at the contact between the block and the ground, not at the top of the block.[2]]

I have identified that the normal force has not been drawn.[1]

I have identified that the frictional force has been drawn at the wrong point of contact.[2]

FROM LESSON 12A

c. In the vertical direction:

$F_{net} = ma = 0$, as the mass is not accelerating in that direction.

$F_g - F_N = 0$ (1 MARK)

$0.135 \times 9.8 - F_N = 0$ (1 MARK)

$F_N = 1.32$ N

In the horizontal direction:

$F_{net} = ma$

$T - \mu F_N = ma$

$0.120 \times 9.8 - \mu \times 1.32 = 0.135 \times 3.6$ (1 MARK)

$\mu = 0.522 = 0.52$ (1 MARK)

FROM LESSON 12A

Previous lessons

23. B. The average speed and velocity of the person are only the same when they travel in a straight path.

FROM LESSON 1A

24. $v = u + at$

$200 \times 3.6 = 0 + a \times 6.6$ (1 MARK)

$a = \frac{200 \times 3.6}{6.6} = 1.09 \times 10^2 = 1.1 \times 10^2$ m s^{-2} (1 MARK)

FROM LESSON 1A

1C Inclined planes

Progress questions

1. B. Parallel to the plane, we consider friction and the parallel component of gravity. Perpendicular to the plane we consider the normal force and the perpendicular component of gravity.

2. An object on an inclined plane will always experience a force due to **gravity** and a normal force. It will also sometimes experience a force due to **friction**. In general it will tend to accelerate **down** the plane, and increasing the angle of inclination will **increase** the magnitude of this acceleration.

3. D. For there to be zero perpendicular net force, the two relevant forces, F_N and $F_{g\perp}$, have to balance each other.

Deconstructed exam-style

4. B. Resolving F_g into parallel and perpendicular components gives $F_{g\parallel} = mg\sin(\theta)$ and $F_{g\perp} = mg\cos(\theta)$.

5. C. $F_{g\parallel}$ and F_f both act down the mountain, since the boulder is moving up the mountain, and F_S acts up the mountain since Sisyphus is pushing the boulder up the mountain.

6. C. If an object is not accelerating then $F_{net} = ma$ implies that $F_{net} = 0$.

7. Take down the mountain as positive.

Since the boulder is moving at a constant velocity up the mountain, $F_{net\parallel} = 0$. (1 MARK)

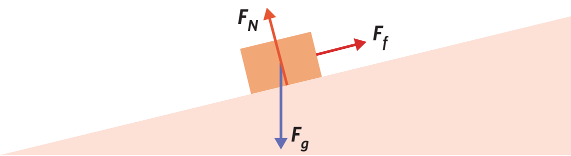
Since the boulder is moving up the mountain, and the friction force opposes the motion, the net force parallel to the mountain is given by $F_{net\parallel} = mg\sin(\theta) + F_f - F_S$. (1 MARK)

$0 = 200 \times 9.8 \times \sin(30°) + 120 - F_S$ (1 MARK)

$F_S = 1100 = 1.1 \times 10^3$ N (1 MARK)

Exam-style

8. a.



- I have drawn and labelled the gravitational force from the centre of the block pointing downwards.[1]
- I have drawn and labelled the normal force from the bottom surface of the block, pointing perpendicular to the plane, shorter than the gravitational force arrow.[2]
- I have drawn and labelled the frictional force pointing up the plane.[3]

b. $F_{net} = F_{net\parallel} = mg\sin(\theta) - F_f$

$2.3 = 1.2 \times 9.8 \times \sin(\theta) - 1.7$ (1 MARK)

$\theta = 19.9 = 20°$, as required (1 MARK)

c. $F_{g\perp} = mg\cos(\theta)$

$F_{g\perp} = 1.2 \times 9.8 \times \cos(20°)$ (1 MARK)

$F_{g\perp} = 11.05 = 11$ N into the plane.

The normal force will have be equal and opposite to $F_{g\perp}$ (1 MARK)

Therefore the normal force is $F_N = 11$ N out of the plane. (1 MARK)

d. $s = ut + \frac{1}{2}at^2$

$6.0 = 0 \times 5.0 + \frac{1}{2} \times a \times 5.0^2$

$a = 0.48$ m s^{-2} (1 MARK)

$F_{net\parallel} = ma = mg\sin(\theta) - F_f$

$0.50 \times 0.48 = 0.50 \times 9.8 \times \sin(20°) - F_f$ (1 MARK)

$F_f = 1.43 = 1.4$ N (1 MARK)

40% of students answered this VCAA exam question correctly.

9. a. [When the object is at rest it has no acceleration, so Newton's second law says that it must have no net force on it.[1]][Since it has no net force, there must be a friction force opposing the parallel component of the gravitational force, which acts down the plane.[2]][Since it opposes $F_{g\parallel}$, we have to subtract it to that rather than add it.[3]]

- I have identified the relationship between zero net force and acceleration.[1]
- I have explained how the friction force must oppose the parallel component of the gravitational force.[2]
- I have justified that the friction force must be subtracted from $F_{g\parallel}$.[3]

b. [On an inclined plane, the normal force on an object acts perpendicular to the plane.[1]][While the object is located on the plane, the net force on it will be parallel to the plane,[2]][so the normal force does not affect the block's motion.[3]]

- I have identified that the normal force acts perpendicular to the inclined plane.[1]
- I have identified that the net force will be parallel to the inclined plane.[2]
- I have explained that the normal force will not affect the block's motion.[3]

10. a. $F_{g\parallel} = mg\sin(\theta)$

$F_{g\parallel} = 5.0 \times 9.8 \times \sin(25°) = 20.7 = 21$ N

78% of students answered this VCAA exam question correctly.

b. $F_{net} = ma = mg\sin(\theta) - F_f$

$5.0 \times 2.7 = 5.0 \times 9.8 \times \sin(25°) - F_f$ (1 MARK)

$F_f = 7.20 = 7.2$ N (1 MARK)

53% of students answered this VCAA exam question correctly.

c. [Repeating the experiment and averaging the value reduces the effect of random error.[1]][This is because by taking multiple measurements and averaging them, the effect of random error on any one measurement has less effect on your final result, the averaged value.[2]]

- I have identified the type of error.[1]
- I have explained how averaging reduced the effects of random error.[2]

FROM LESSON 12C

11. B. The normal force has magnitude $F_N = mg\cos(\theta)$, and between 0 and 90°, this is greater for smaller angles of inclination.

12. a. [Since $F_{g\parallel} = mg\sin(\theta)$, larger angles of inclination have a larger parallel component of gravitational force.[1]][According to Newton's second law of motion, $F_{net} = ma$, a larger net force corresponds to a larger acceleration.[2]][Therefore since P has the greatest angle of inclination, and Q the least, Garrett's acceleration is greatest at P, in between at R, and lowest at Q.[3]]

- I have identified that increasing the angle of inclination increases the parallel component of gravitational force.[1]
- I have explained how a larger net force causes a larger acceleration.[2]
- I have determined the points where Garrett has the greatest and the least acceleration.[3]

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b. $gradient = \frac{y_2 - y_1}{x_2 - x_1} = \frac{500 - 200}{0.85 - 0.35}$

$gradient = 600$ (1 MARK)

$gradient = \frac{F_{net}}{\sin(\theta)} \Rightarrow 600 = \frac{F_{net}}{\sin(\theta)}$

$F_{net} = mg\sin(\theta) \Rightarrow \frac{F}{\sin(\theta)} = m \times 9.8$

$\Rightarrow 600 = m \times 9.8$ (1 MARK)

$m = 61.2 = 61$ kg (1 MARK)

Answers from 58–64 kg are acceptable depending on the points chosen.

FROM LESSON 12E

Previous lessons

13. a. $v^2 = u^2 + 2as$

$v^2 = 0^2 + 2 \times 4.9 \times 10.0$ (1 MARK)

$v = 9.90 = 9.9$ m s^{-1} (1 MARK)

b. $v = u + at$

$9.9 = 0 + 4.9 \times t$ (1 MARK)

$t = 2.02 = 2.0$ s (1 MARK)

c. $F = ma$

$0.75 = 0.50 \times a$ (1 MARK)

$a = 1.5$ m s^{-2} (1 MARK)

d. The force on the ground by the ball.[1]

I have identified the reaction force as the force on the ground by the ball.

FROM LESSONS 1A & 1B

1D Connected bodies

Progress questions

1. D. The tension force acts in equal magnitude and opposite direction pulling the trailer forward and the truck backward.

2. A, D. Block S is pulled up by the tension force and down by the force due to gravity.

3. C. $F_{net} = m_{sled}a \Rightarrow 400 = m_{sled} \times 3 \Rightarrow m_{sled} = 133.3$ kg

4. C. As the acceleration is the same for both blocks, the size of the net force is proportional to the mass.

5. A. The acceleration of the system is the same for each object in the system, so $F_{net} = m_F a = 75 \times 0.50 = 37.5 = 38$ N.

Deconstructed exam-style

6. $F_{g,2} = mg = 0.25 \times 9.8 = 2.45 = 2.5$ N

7. $F_{net} = F_{g,2} - F_f = (M_1 + M_2) \times a \Rightarrow (0.25 \times 9.8) - 0.50 = (0.5 + 0.25) \times a$

$a = 2.6$ m s^{-2}

8. $a_{system} = a_2 = 2.6$ m s^{-2}

9. $F_{g,2} = mg = 0.25 \times 9.8 = 2.45$ N (1 MARK)

$F_{net} = F_{g,2} - F_f = (M_1 + M_2) \times a_2 \Rightarrow 2.45 - 0.50 = (0.5 + 0.25) \times a_2$

$a_2 = 2.6$ m s^{-2} (1 MARK)

$a_{system} = a_2 = 2.6$ m s^{-2}

$F_{net,2} = F_{g,2} - T = M_2 a_2$

$2.45 - T = 0.25 \times 2.6$ (1 MARK)

$T = 1.8$ N (1 MARK)

52% of students answered this VCAA exam question correctly.

Exam-style

10. C. The frictional force must be equal and opposite to the F_x in order for the net force to be zero.

11. a. $F_{net} = (m_a + m_b)a = (700 + 800) \times 1.20 = 1.80 \times 10^3$ N

b. As tension is the only force acting on the trailer

$F_{net\ trailer} = T = m_{trailer}a$ (1 MARK)

$T = 700 \times 1.20 = 840$ N (1 MARK)

12. a. $F_{net} = ma \Rightarrow 80 = (2.0 + 6.0) \times a$

$a = 10$ m s^{-2} (1 MARK)

$F_{net\ A} = ma = 2.0 \times 10 = 20$ N

$F_{net\ A} = 80 - F_{on\ A\ by\ B} \Rightarrow 20 = 80 - F_{on\ A\ by\ B}$ (1 MARK)

$F_{on\ A\ by\ B} = 60$ N (1 MARK)

27% of students answered this VCAA exam question correctly.

b. $F_{on\ B\ by\ A} = 60$ N (1 MARK)

$F_{on\ B\ by\ A}$ is to the right by Newton's third law of motion. (1 MARK)

61% of students answered this VCAA exam question correctly.

13. C. $F_{net} = ma = mg - T \Rightarrow 3.0 \times 3.68 = 3.0 \times 9.8 - T \Rightarrow T = 18.36 = 18.4$ N

14. Having 5 cm gradations on the ruler will increase the effect of random errors due to the difficulty of measuring a moving object between each line of the ruler.[1] Its significance can be reduced by repeating the experiment multiple times and taking the average of the measurements[2] or using a more accurate measurement method such as a slow-motion camera.[3]

I have commented on the primary cause of random errors.[1]

I have explained one way to reduce the error.[2]

I have explained another way to reduce the error.[3]

FROM LESSON 12C

15. a. For block A: $F_{net} = 0 = F_{on\ A\ by\ B} - F_g$ (1 MARK)

$F_{on\ A\ by\ B} = F_g = m_A g = 2.0 \times 9.8 = 19.6 = 20$ N upwards (1 MARK)

b. $F_{on\ A\ by\ B} = 0$ N

Note that since the blocks are now accelerating at g, the only force acting on each block is $F_g = mg$, so the contact force must be zero.

16. a. $F_{net} = T_1 - F_f - F_f = 0 \Rightarrow T_1 - 100 - 100 = 0 \Rightarrow T_1 = 200$ N

56% of students answered this VCAA exam question correctly.

b. $F_{net\ pyramid\ 2} = T_2 - F_f = ma \Rightarrow T_2 - 100 = 250 \times 0.25$ (1 MARK)

$T_2 = 163 = 1.6 \times 10^2$ N (1 MARK)

$F_{net\ pyramid\ 1} = T_1 - T_2 - F_f = ma \Rightarrow T_1 - 163 - 100 = 250 \times 0.25$ (1 MARK)

$T_1 = 326 = 3.3 \times 10^2$ N (1 MARK)

59% of students answered this VCAA exam question correctly.

c. Rope 1 will break before rope 2 as it has to pull both pyramids. (1 MARK)

Consider the two pyramids: $F_{net} = T_{1\ break} - F_f - F_f = ma$

$1800 - 100 - 100 = 500 \times a$ (1 MARK)

$a = 3.20 = 3.2$ m s^{-2} (1 MARK)

36% of students answered this VCAA exam question correctly.

d. [Amy is recording qualitative data.[1]][Qualitative data can be useful for building hypotheses.[2]]

I have identified what sort of data Amy is recording.[1]

I have given a reason why this data is useful for building experiments.[2]

Other answers include:

- Qualitative data helps explain quantitative data

Previous lessons

17. A. The plane is travelling at a constant speed so there is a net force of zero acting on the plane therefore the thrust force and the resistance force must be equal in magnitude.

62% of students answered this VCAA exam question correctly.

FROM LESSON 1B

18. a. $F_{net} = ma = mg\sin(\theta) \Rightarrow 1.5 \times a = 1.5 \times 9.8 \times \sin(15°)$ (1 MARK)

$a = 2.54 = 2.5$ m s^{-2} (1 MARK)

75% of students answered this VCAA exam question correctly.

b. $s = ut + \frac{1}{2}at^2 \Rightarrow 2.8 = 0 \times 5.0 + \frac{1}{2} \times a \times 5.0^2$

$a = 0.224$ m s^{-2} (1 MARK)

$F_{net} = ma = mg\sin(\theta) - F_f \Rightarrow 1.5 \times 0.224 = 1.5 \times 9.8 \times \sin(15°) - F_f$ (1 MARK)

$F_f = 3.468 = 3.5$ N (1 MARK)

32% of students answered this VCAA exam question correctly.

FROM LESSON 1A & 1C

1E Basic circular motion

Progress questions

1. C, D. Both of these objects are travelling in circular paths, whereas a stone being thrown off a cliff and a football being kicked in the air are not.

2. An object undergoing uniform circular motion has a **constant** circular speed, with an instantaneous velocity that is always **changing** and directed **at a tangent to** the circle it is travelling in.

3. D. The centripetal force is another name given to the net force acting on an object undergoing uniform circular motion, and this always points towards the centre of the circular path the object is travelling in.

4. D. The gravitational force is providing the centripetal force.

$F_g = F_{net} = \frac{mv^2}{r} = \frac{7.35 \times 10^{24} \times (1.0 \times 10^3)^2}{3.48 \times 10^8} = 2.1 \times 10^{25}$ N.

5. B. Centripetal acceleration depends only on the radius of circular path an object is travelling in and its circular speed, whereas centripetal force is dependent on the mass of the object as well.

6. B. Circular speed has no direction as it is a scalar quantity, whereas centripetal acceleration and force are always towards the centre of the circular path it is travelling in.

Deconstructed exam-style

7. C. $F_{net} = \frac{4\pi^2 rm}{T^2} = \frac{4\pi^2 \times 4.5 \times 65}{25^2} = 18$ N

8. B. $F_{net} = \frac{4\pi^2 rm}{T^2} = \frac{4\pi^2 \times 2.0 \times 70}{25^2} = 8.8$ N

9. The direction of the centripetal force on both Markel and Fatemeh is to the right.

10. Markel:

$F_{net} = \frac{4\pi^2 rm}{T^2}$

$F_{net} = \frac{4\pi^2 \times 4.5 \times 65}{25^2}$

$F_{net} = 18.47 = 18$ N (1 MARK)

Fatemeh:

$F_{net} = \frac{4\pi^2 rm}{T^2}$

$F_{net} = \frac{4\pi^2 \times 2.0 \times 70}{25^2}$

$F_{net} = 8.84 = 8.8$ N (1 MARK)

The net force acting on Markel is greater in magnitude than that on Fatemeh, but both act to the right. (2 MARKS)

OR

Markel:

$v = \frac{2\pi r}{T}$

$v = \frac{2\pi \times 4.5}{25} = 1.13$ m s

$F_{net} = \frac{mv^2}{r}$

$F_{net} = \frac{65 \times (1.13)^2}{4.5}$

$F_{net} = 18.47 = 18$ N (1 MARK)

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Fatemeh:

$v = \frac{2\pi r}{T}$

$v = \frac{2\pi \times 2.0}{25} = 0.503 \text{ m s}^{-1}$

$F_{net} = \frac{mv^2}{r}$

$F_{net} = \frac{70 \times (0.503)^2}{2.0}$

$F_{net} = 8.84 = 8.8 \text{ N}$ (1 MARK)

The net force acting on Markel is greater in magnitude than that on Fatemeh, but both act to the right. (2 MARKS)

Exam-style

11. **a.** $v = \frac{2\pi r}{T}$

$v = \frac{2\pi \times 12.0}{\left(\frac{1}{0.125}\right)}$ (1 MARK)

$v = 9.424 = 9.42 \text{ m s}^{-1}$ (1 MARK)

b. [To the right.[1]]

I have identified the direction of the beetle's instantaneous velocity.[1]

12. $a = \frac{v^2}{r}$

$a = \frac{8.00^2}{50.0}$ (1 MARK)

$a = 1.280 = 1.28 \text{ m s}^{-2}$ (1 MARK)

OR

$v = \frac{2\pi r}{T}$

$8.00 = \frac{2\pi \times 50.0}{T}$

$T = 39.3$

$a = \frac{4\pi r^2}{T}$

$a = \frac{4\pi \times (50.0)^2}{39.3}$ (1 MARK)

$a = 1.280 = 1.28 \text{ m s}^{-2}$ (1 MARK)

13. C. At point *R*, the centre of the mass's circular path is to the left, so it is accelerating to the left.

70% of students answered this VCAA exam question correctly.

14. B. At point *Q*, the direction of the instantaneous velocity of the mass is to the right.

15. The centripetal force is provided by the tension in the rope.

$F_{net} = T = \frac{mv^2}{r}$

$3.0 = \frac{0.30 \times v^2}{0.80}$ (1 MARK)

$v = 2.83 = 2.8 \text{ m s}^{-1}$ (1 MARK)

16. **a.** $T = 30.0 \times 60 \times 60 = 1.08 \times 10^5 \text{ s}$

$v = \frac{2\pi r}{T}$

$v = \frac{2\pi \times 2.60 \times 10^7}{1.08 \times 10^5}$ (1 MARK)

$v = 1.513 \times 10^3 = 1.51 \times 10^3 \text{ m s}^{-1}$ (1 MARK)

b. [The magnitude of Deimos' velocity does not change throughout its orbit, as it is undergoing uniform circular motion.[1]][However, the direction of the velocity is constantly changing to remain tangential to the circular orbit.[2]]

I have stated the magnitude of Deimos' velocity does not change.[1]

I have described the direction of Deimos' velocity as constantly changing to remain tangential to the circular path it is travelling in.[2]

c. $a = \frac{4\pi^2 r}{T^2}$

$a = \frac{4\pi^2 \times 2.60 \times 10^7}{(1.08 \times 10^5)^2}$ (1 MARK)

$a = 8.800 \times 10^{-2} = 8.80 \times 10^{-2} \text{ m s}^{-2}$ (1 MARK)

OR

$a = \frac{v^2}{r}$

$a = \frac{(1.51 \times 10^3)^2}{2.60 \times 10^7}$ (1 MARK)

$a = 8.800 \times 10^{-2} = 8.80 \times 10^{-2} \text{ m s}^{-2}$ (1 MARK)

d. $v = \frac{2\pi r}{T}$

$2.00 \times 10^3 = \frac{2 \times \pi \times r}{8.00 \times 60 \times 60}$ (1 MARK)

$r = 9.167 \times 10^6 = 9.17 \times 10^6 \text{ m}$ (1 MARK)

17. **a.** [The mass of the rubber stopper.[1]]

I have identified a variable to be controlled.[1]

Other answers include:

- velocity of the stopper
- radius of rubber stopper's circular path

b. [The time taken for the rubber stopper to rotate around five revolutions was measured to reduce random error in the measurement taken[1]][This is likely to increase both the accuracy and precision of the data obtained[2]][as each measurement is likely to be closer to the true value and closer to the other measurements taken.[3]]

I have stated the random error in the measurement is likely to be reduced.[1]

I have stated the accuracy and precision of the data is likely to increase.[2]

I have described why the accuracy and precision of the data is likely to increase.[3]

86% of students answered this VCAA exam question correctly.

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c. [The centripetal force is provided by the gravitational force, Mg.[1]][The centripetal force can be expressed as $F = \frac{4\pi^2 rm}{T^2}$.[2]] [The relationship between the variables is $Mg = \frac{4\pi^2 rm}{T^2}$.[3]]

I have identified the centripetal force is provided by Mg.[1]

I have identified the centripetal force can be expressed as $F = \frac{4\pi^2 rm}{T^2}$.[2]

I have related the gravitational force to the net force acting on the rubber stopper.

31% of students answered this VCAA exam question correctly.

18. **a.** $F_{net} = \frac{mv^2}{r}$

$F_{net} = \frac{800 \times \left(\frac{144}{3.6}\right)^2}{80}$ (1 MARK)

$F_{net} = 1.60 \times 10^4 = 1.6 \times 10^4$ N (1 MARK)

OR

$v = \frac{2\pi r}{T}$

$\frac{144}{3.6} = \frac{2\pi \times 80}{T}$

$T = 12.6$ s

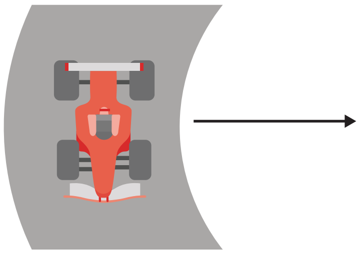
$F_{net} = \frac{4\pi^2 rm}{T^2}$

$F_{net} = \frac{4\pi^2 \times 80 \times 800}{(12.6)^2}$ (1 MARK)

$F_{net} = 1.60 \times 10^4 = 1.6 \times 10^4$ N (1 MARK)

78% of students answered this VCAA exam question correctly.

b.



I have drawn an arrow pointing to the right.[1]

84% of students answered this VCAA exam question correctly.

c. [The net force acting on the car must be perpendicular to the direction of motion of the car for it to undergo circular motion.[1]] [This means a net horizontal force is required.[2]][The ground exerts this force on the car tyres due to friction between the ground and tyres.[3]]

I have stated the net force on the car must be perpendicular to the velocity of the car.[1]

I have identified a horizontal net force is required .[2]

I have identified the friction force on the tyres provides the horizontal net force.[3]

21% of students answered this VCAA exam question correctly.

19. $F_{net} = \frac{mv^2}{r} = qvB$ (1 MARK)

$r = \frac{mv^2}{qvB}$

$r = \frac{mv}{qB}$ (1 MARK)

$r = \frac{9.1 \times 10^{-31} \times 2.4 \times 10^8}{1.6 \times 10^{-19} \times 2}$ (1 MARK)

$r = 6.8 \times 10^{-4}$ m (1 MARK)

Previous lessons

20. B. The force of the rope on each student will be the same as the force of each student on the rope, according to Newton's third law.

FROM LESSON 1B

21. Equation of motion of the trailer:

$F_{net} = ma$

$T = 2000 \times 0.50$ (1 MARK)

$T = 1.00 \times 10^3 = 1.0 \times 10^3$ N (1 MARK)

52% of students answered this VCAA exam question correctly.

FROM LESSON 1D

1F Banked circular motion

Progress questions

1. D. The hypotenuse of the triangle is the normal force, and the angle of inclination θ is the angle between the normal force and the force due to gravity.

2. A, B. The truck's speed is constant as it travels around the banked track but the direction of the speed is always changing.

3. B. There is no normal force acting on a conical pendulum as it is not in contact with any surface.

4. C. The tension is the hypotenuse in the force triangle of a conical pendulum, with its horizontal component providing the centripetal force.

Deconstructed exam-style

5. A. The radius of the bike's circular path is half the distance from side of the circular track to the other, $\frac{60}{2} = 30$ m.

6. A. The design speed can be found by analysing the force triangle of the bike.

7. $r = \frac{60}{2} = 30$ m (1 MARK)

$v = \sqrt{rg\tan(\theta)} = \sqrt{30 \times 9.8 \times \tan(35°)}$ (1 MARK)

$v = 14.3 = 14$ m s^{-1} (1 MARK)

62% of students answered this VCAA exam question correctly.

1F ANSWERS

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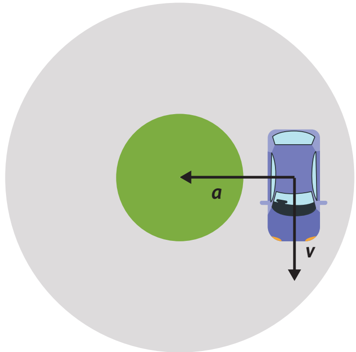
Exam-style

8. D. The magnitude of the net force is constant, given by $F_{net} = \frac{mv^2}{r}$, but is always changing direction as it must point towards the centre of the path the dice are travelling in.

9.



I have drawn an arrow towards the centre of the circle labelled *a*.

I have drawn an arrow downwards labelled *v*.

10. a. [The centripetal force is provided by the horizontal component of the normal force.[1]]

I have identified the force/component providing the centripetal force.[1]

b. [The centripetal force is provided by the horizontal component of the tension force.[1]]

I have identified the force/component providing t he centripetal force.[1]

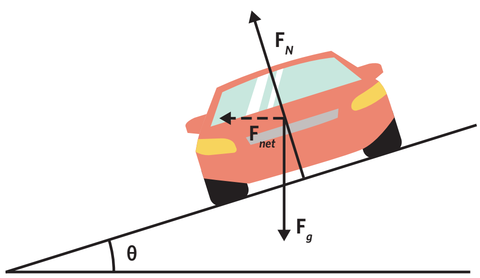
11. $r = 0.75\sin(25°) = 0.317$ m (1 MARK)

$v = \sqrt{rg\tan(\theta)} = \sqrt{0.317 \times 9.8 \times \tan(25°)}$ (1 MARK)

$v = 1.20 = 1.2$ m s^{-1} (1 MARK)

39% of students answered this VCAA exam question correctly.

12. a.



I have drawn the normal force correctly.[1]

I have drawn the net force with a dashed arrow correctly.[2]

I have drawn the gravitational force correctly.[3]

55% of students answered this VCAA exam question correctly.

b. $\theta = \tan^{-1}\left(\frac{v^2}{rg}\right) = \tan^{-1}\left(\frac{40^2}{380 \times 9.8}\right)$ (1 MARK)

$\theta = 23.3 = 23°$ (1 MARK)

67% of students answered this VCAA exam question correctly.

13. [The tension in the spring can be related to the motion of the ball using the formula $T = \frac{mv^2}{r\sin(\theta)}$ **OR** $T = \sqrt{(mg)^2 + \left(\frac{mv^2}{r}\right)^2}$.[1]]

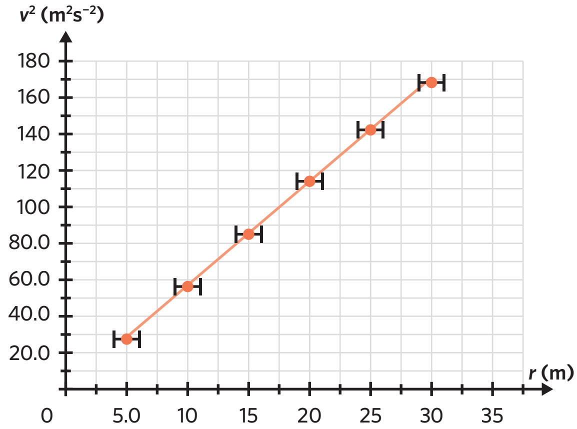
[Hitting the ball back quicker increases the speed of the ball, which will increase the tension in the string.[2]]

I have identified a relationship between tension and the speed of the ball.[1]

I have determined that increasing the speed of the ball increases the tension in the string.[2]

14. a. 28.3; 56.6; 84.8; 112; 142; 169.

b.



I have correctly labelled the horizontal and vertical axis and included correct units.

I have included an appropriate and consistent scale on the axes.

I have plotted each point of data correctly.

I have drawn correctly sized uncertainty bars.

I have drawn a straight line of best fit which passes through all uncertainty bars.

c. To find the gradient, use two points on the line of best fit that are reasonably far apart.

$gradient = \frac{y_2 - y_1}{x_2 - x_1} = \frac{170 - 30}{30 - 5} = 5.6$ (1 MARK)

Depending on the line of best fit drawn, values between 5.0 and 6.2 are acceptable.

$gradient = \frac{v^2}{r} = g\tan(\theta)$

$\theta = \tan^{-1}\left(\frac{gradient}{g}\right) = \tan^{-1}\left(\frac{5.6}{9.8}\right)$ (1 MARK)

$\theta = 29.7 = 30°$ (1 MARK)

FROM LESSONS 12C, 12D & 12E

15. a. $\theta = \sin^{-1}\left(\frac{opposite}{hypotenuse}\right) = \sin^{-1}\left(\frac{0.40}{0.70}\right) = 34.8°$ (1 MARK)

$F_{net} = F_g\tan(\theta) = mg\tan(\theta) = 0.30 \times 9.8 \times \tan(34.8°)$
$= 2.047 = 2.0$ N (1 MARK)

b. $T = \sqrt{(F_{net})^2 + (mg)^2} = \sqrt{2.047^2 + (0.30 \times 9.8)^2}$ (1 MARK)

$T = 3.58 = 3.6$ N (1 MARK)

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OR

$T = \frac{F_{net}}{\sin(\theta)} = \frac{2.047}{\sin(34.8°)}$ (1 MARK)

$T = 3.58 = 3.6$ N (1 MARK)

OR

$T = \frac{mg}{\cos(\theta)} = \frac{0.30 \times 9.8}{\cos(34.8°)}$ (1 MARK)

$T = 3.58 = 3.6$ N (1 MARK)

45% of students answered this VCAA exam question correctly.

16. C. $r = \frac{v^2}{g\tan(\theta)} = \frac{(14)^2}{9.8 \times \tan(32°)} = 32$ m

17. $r = l\sin(\theta) = 6.0 \times \sin(55°)$ (1 MARK)

$r = 4.91$ m

$v = \sqrt{rg\tan(\theta)} = \sqrt{4.91 \times 9.8 \times \tan(55°)}$ (1 MARK)

$v = 8.29$ m s^{-1}

$v = \frac{2\pi r}{T} \Rightarrow 8.29 = \frac{2\pi \times 4.91}{T}$ (1 MARK)

$T = 3.72 = 3.7$ s (1 MARK)

Previous lessons

18. C. As the mass is moving up the inclined plane, the frictional force is acting down the plane. A normal force and gravitational force are also present.

FROM LESSON 1C

19. $m_{tot} = 10 + 20 + 5.0 = 35$ kg

$F_{net} = m_{tot}a \Rightarrow 200 = 35 \times a$ (1 MARK)

$a = 5.71$ m s^{-2} (1 MARK)

$F_{on\ C\ by\ B} = m_C a = 5.0 \times 5.71$

$F_{on\ C\ by\ B} = 28.6 = 29$ N (1 MARK)

FROM LESSON 1D

1G Vertical circular motion

Progress questions

1. D. As the cart does not leave the track, the net force is downwards.

2. B. $\frac{mv^2}{r} = F_g - F_N \Rightarrow \frac{1000 \times 20^2}{500} = 1000 \times 9.8 - F_N$

$\Rightarrow F_N = 9000 = 9.0 \times 10^3$ N

3. C. $\frac{mv^2}{r} = T - F_g$

$\Rightarrow T = \frac{2.00 \times 12.0^2}{1.00} + 2.00 \times 9.8 = 3.08 \times 10^2 = 3.10 \times 10^2$ N

4. D. $v = \sqrt{gr} \Rightarrow 14 = \sqrt{9.8 \times r} \Rightarrow r = 20$ m

5. A. At the bottom of a loop, there must be a normal force acting upwards for the roller coaster to undergo circular motion.

Deconstructed exam-style

6. [The tension force is pulling upwards.[1]][The force due to gravity is acting downwards.[2]]

- I have identified the tension force and its direction.[1]
- I have identified the force due to gravity and its direction.[2]

7. [The tension force will increase.[1]]

- I have identified the change to the tension force as a result of increased speed.[1]

8. $\frac{mv^2}{r} = T - mg$

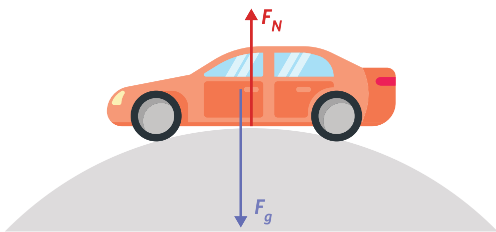
$\frac{3.2 \times 7.3^2}{1.2} = T - 3.2 \times 9.8$ (1 MARK)

$T = 1.7 \times 10^2 > 150$ N (1 MARK)

The string will break as the tension will be greater than the tension required to break it. (1 MARK)

Exam-style

9. a.



- I have drawn all forces acting upon the car.
- I have labelled all forces acting upon the car correctly.
- I have shown the force due to gravity to be greater in magnitude than the normal force.

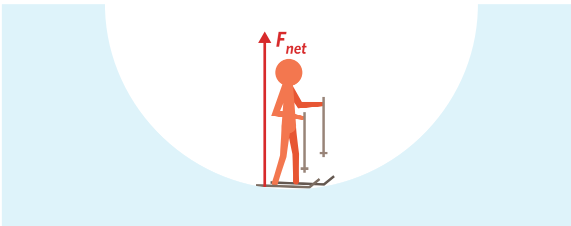
b. $v = \sqrt{gr} = \sqrt{9.8 \times 5.2}$ (1 MARK)

$v = 7.14 = 7.1$ m s^{-1} (1 MARK)

10. D. There are only two forces acting on the ball, tension and force due to gravity. The tension force is greater at the bottom of the circle.

56% of students answered this VCAA exam question correctly.

11. a.



- I have drawn the net force acting upwards.

75% of students answered this VCAA exam question correctly.

b. $F_{net} = F_N - F_g \Rightarrow \frac{mv^2}{r} = F_N - mg$

$\frac{60 \times 18^2}{15} = F_N - 60 \times 9.8$ (1 MARK)

$F_N = 1.88 \times 10^3 = 1.9 \times 10^3$ N (1 MARK)

47% of students answered this VCAA exam question correctly.

12. B. 44.72 km $h^{-1} \div 3.6 = 12.42$ m s^{-1}

$v = \sqrt{gr} \Rightarrow 12.42 = \sqrt{9.8 \times r}$

$r = 15.74 = 15.7$ m

13. a. Calculate the minimum speed the cart needs to stay on track.

$v = \sqrt{gr} = \sqrt{9.8 \times 13.0}$ (1 MARK)

$v = 11$ m $s^{-1} > 9.0$ m s^{-1} (1 MARK)

The cart will fall off the track if it is not supported by an additional upwards force. (1 MARK)

b. [Velocity should be on the vertical axis and radius should be on the horizontal axis.[1]][This is because the velocity is the dependent variable and the radius is the independent variable.[2]]

- I have identified which axes velocity and radius should be graphed on.[1]
- I have justified my answer.[2]

FROM LESSON 12A & 12D

c. $gradient = \frac{rise}{run} = \frac{v^2}{r}$. (1 MARK)

For zero normal force (when the cart loses contact with the track), $v = \sqrt{gr} \Rightarrow \frac{v^2}{r} = g$. (1 MARK)

$gradient = \frac{v^2}{r} = g = 9.8$ m s^{-2}. (1 MARK)

FROM LESSON 12E

14. a. $v = \sqrt{gr} = \sqrt{9.8 \times 35}$ (1 MARK)

$v = 18.5 = 19$ m s^{-1} (1 MARK)

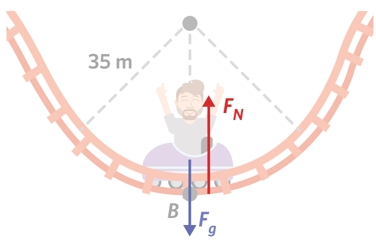
69% of students answered this VCAA exam question correctly.

b. [Zephyr experiences zero normal force at point *A* because the car is travelling at the maximum speed to maintain contact with the track without becoming airborne.[1]]

- I have explained why the cart experiences zero normal force.[1]

11% of students answered this VCAA exam question correctly.

c.



- I have drawn a solid arrow representing the normal force and included a label.
- I have drawn a solid arrow representing the force due to gravity force and included a label.

44% of students answered this VCAA exam question correctly.

15. a. The motorbike will fall off the track if the force due to gravity is greater than the centripetal force, but will stay connected if they are equal.

$\frac{mv^2}{r} = F_g = mg$ (1 MARK)

By dividing both sides by m, $\frac{v^2}{r} = g$, as required. (1 MARK)

49% of students answered this VCAA exam question correctly.

b. The condition needed to be satisfied is $\frac{v^2}{r} = g$

$\frac{20^2}{r} = 9.8$ (1 MARK)

$r = 40.82$ m

As the height equals the diameter of the circle, $h = 2r$ (1 MARK)

$h = 2 \times 40.82$

$h = 82.64 = 83$ m (1 MARK)

11% of students answered this VCAA exam question correctly.

c. [Safa will need to decrease the predicted value for the height of the loop.[1]][This is because the presence of air resistance will decrease the speed that the bike reaches at the top of the loop.[2]][According to $\frac{v^2}{r} = g$, as the speed decreases, so will the size of the loop made to suit it.[3]]

- I have identified the need to decrease the predicted height of the loop.[1]
- I have explained the relationship between speed and air resistance.[2]
- I have explained the relationship between the height of the loop and speed.[3]

27% of students answered this VCAA exam question correctly.

Previous lessons

16. $F_{net} = F_{net\parallel} = mg\sin(\theta) = 0.30 \times 9.8 \times \sin(10°) = 0.511$ N (1 MARK)

$F_{net} = ma$

$0.511 = 0.30 \times a$

$a = 1.70$ m s^{-2} (1 MARK)

$v^2 = u^2 + 2as$

$v^2 = 0 + 2 \times 1.70 \times 2.0$

$v = 2.61 = 2.6$ m s^{-1} (1 MARK)

FROM LESSON 1C

17. a. $a = \frac{4\pi^2 r}{T^2} = \frac{4 \times \pi^2 \times 0.60}{1.4^2}$ (1 MARK)

$a = 12.1 = 12$ m s^{-2} (1 MARK)

b. $F_{net} = ma = 0.20 \times 12.1 = 2.42 = 2.4$ N

FROM LESSON 1E

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1H Projectile motion

Progress questions

1. C. When the projectile is at its maximum height, the vertical velocity is zero.
2. A. The ball momentarily comes to a stop at the top of its flight as it changes direction.
3. A. At the maximum height, the vertical component of velocity is 0.
4. C. The horizontal velocity of a projectile is constant throughout its flight.
5. A. $v = \frac{s}{t} = \frac{10}{5.0} = 2.0 \text{ m s}^{-1}$
6. D. $u\cos(\theta)$ is used to find the horizontal component of the initial velocity, and $u\sin(\theta)$ is used to find the vertical component of the initial velocity.
7. A. Time is the linking factor between horizontal motion and vertical motion.
8. D. Since both balls have the same vertical component of initial velocity, they will land at the same time due to symmetry.
9. D. Air resistance decreases the maximum height and range of an object's path.

Deconstructed exam-style

10. $u_x = 10\cos(40°) = 7.66 = 7.7 \text{ m s}^{-1}$

11. $u_y = 10\sin(40°) = 6.42 = 6.4 \text{ m s}^{-1}$

12. $v_x = \frac{s_x}{t} \Rightarrow 7.66 = \frac{8.0}{t} \Rightarrow t = 1.04 = 1.0 \text{ s}$

13. B. We can use time to link the horizontal and vertical components of projectile motion, and we know the initial vertical velocity and acceleration due to gravity.

14. $v_x = \frac{s_x}{t} \Rightarrow 7.66 = \frac{8.0}{t} \Rightarrow t = 1.04 = 1.0 \text{ s}$ (1 MARK)

    $s_y = u_y t + \frac{1}{2} a_y t^2$

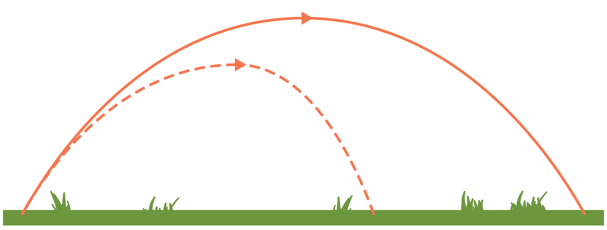
    $s_y = 10\sin(40°) \times 1.04 + \frac{1}{2} \times (-9.8) \times 1.04^2$ (1 MARK)

    $s_y = 1.37 = 1.4 \text{ m}.$

    As $s_y > 1.0$ m, the ball travels over the net. (1 MARK)

Exam-style

15.



I have drawn an arc that is asymmetrical and smaller than the arc when air resistance is ignored.

16. a. Take up as positive.

    $v_y^2 = u_y^2 + 2a_y s \Rightarrow 0 = u_y^2 + 2 \times (-9.8) \times 49$ (1 MARK)

    $u_y = \pm 31.0 = 31 \text{ m s}^{-1}.$

    Note that we take the positive value since we know the rocket is initially travelling upwards.

    $u_y = 31 \text{ m s}^{-1}$ upwards. (1 MARK)

    b. Time to max height:

    $v_y = u_y + a_y t \Rightarrow 0 = 31 + (-9.8)t$ (1 MARK)

    $t = 3.16 \text{ s}$

    Time to complete full arc is $2 \times 3.16 = 6.32$ s (1 MARK)

    $v_x = \frac{s_x}{t} \Rightarrow 5.47 = \frac{s_x}{6.32}$

    $s_x = 34.6 = 35 \text{ m}$ (1 MARK)

17. a. Taking down as positive:

    $v_y^2 = u_y^2 + 2a_y s_y = 0 + 2 \times 9.8 \times 40$

    $v_y = 28.0 \text{ m s}^{-1}$ (1 MARK)

    $v = u + a_y t \Rightarrow 28.0 = 0 + 9.8 \times t$ (1 MARK)

    $t = 2.86 = 2.9 \text{ s}$ (1 MARK)

    b. $v_x = \frac{s_x}{t} \Rightarrow 60 = \frac{s_x}{2.86}$ (1 MARK)

    $s_x = 1.71 \times 10^2 = 1.7 \times 10^2$ (1 MARK)

18. $t = \frac{s_x}{v_x} = \frac{29}{25\cos(20°)} = 1.23 \text{ s}$ (1 MARK)

    $s_y = u_y t + \frac{1}{2} a_y t^2$

    $s_y = 25\sin(20°) \times 1.23 + \frac{1}{2} \times (-9.8) \times 1.23^2$ (1 MARK)

    $s_y = 3.09 = 3.1 \text{ m}$ (1 MARK)

    40% of students answered this VCAA exam question correctly.

19. a. [If the angle of launch is directly related to the range of a projectile, then the range will increase[1]][when the angle of launch is decreased.[2]]

    I have stated the predicted change to the dependent variable.[1]

    I have stated how the change will be made to the independent variable.[2]

    FROM LESSON 12A

    b. $v_y = u_y + a_y t \Rightarrow 0 = 31\sin(53°) + (-9.8) \times t$

    $t = 2.53 = 2.5$ s, as required

    75% of students answered this VCAA exam question correctly.

    c. Time for full flight $= 2 \times 2.5 = 5.0$ s

    $u_x = \frac{s_x}{t} \Rightarrow 31\cos(53°) = \frac{s_x}{5.0}$ (1 MARK)

    $s_x = 31\cos(53°) \times 5.0 = 93.3$

    $s_x = 93 \text{ m}$ (1 MARK)

    59% of students answered this VCAA exam question correctly.

1H ANSWERS

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20. a. Taking down as positive:

$s_y = ut + \frac{1}{2}a_y t^2 = 0 \times 0.5 + \frac{1}{2} \times 9.8 \times 0.45^2$ (1 MARK)

$s_y = 0.992 = 0.99$ m (1 MARK)

66% of students answered this VCAA exam question correctly.

b. Taking down and to the right as positive:

$u_x = v_x = 2.8$ m s^{-1}

$v_y = u_y + a_y t = 0 + 9.8 \times 0.45$ (1 MARK)

$v_y = 4.41$ m s^{-1}

$v = \sqrt{{v_x}^2 + {v_y}^2} = \sqrt{2.8^2 + 4.41^2}$ (1 MARK)

$v = 5.22 = 5.2$ m s^{-1} (1 MARK)

41% of students answered this VCAA exam question correctly.

c. $\theta = \tan^{-1}\left(\frac{v_y}{v_x}\right) = \tan\left(\frac{4.41}{2.8}\right)$ (1 MARK)

$\theta = 57.6 = 58°$ (1 MARK)

21. a. $u_y = 75\sin(40°) = 48.2$ m s^{-1}

${v_y}^2 = {u_y}^2 + 2a_y s \Rightarrow 0 = 48.2^2 + 2 \times (-9.8) \times d$ (1 MARK)

$d = 1.19 \times 10^2 = 1.2 \times 10^2$ m (1 MARK)

b. $v_y = u_y + a_y t \Rightarrow 0 = 48.2 + (-9.8) \times t$

$t = 4.92$ s

Time to point A is $2 \times 4.92 = 9.84$ s (1 MARK)

$v_x = \frac{s_x}{t} \Rightarrow 75\cos(40°) = \frac{s_x}{9.84}$ (1 MARK)

$s_x = 565.8 = 5.7 \times 10^2$ m (1 MARK)

c. ${v_y}^2 = {u_y}^2 + 2a_y s$
$\Rightarrow {v_y}^2 = (48.2)^2 + 2 \times (-9.8) \times (-62)$ (1 MARK)

$v_y = \pm 59.5$ m s^{-1}. Take the negative value as we know the stone is travelling downwards.

$v^2 = {v_x}^2 + {v_y}^2 = 57.5^2 + (-59.5)^2$ (1 MARK)

$v = 82.7 = 83$ m s^{-1}

As $v > 70$ m s^{-1}, the boat will sink. (1 MARK)

22. a. $R = \frac{u^2\sin(2\theta)}{g} = \frac{15^2\sin(2 \times 40°)}{9.8}$ (1 MARK)

$R = 22.6 = 22$ m (1 MARK)

81% of students answered this VCAA exam question correctly.

b. [Air resistance cannot be ignored.[1]][The difference between the theoretical and practical data is outside the limits of uncertainty.[2]]

- I have stated that air resistance cannot be ignored.[1]
- I have identified that the difference is outside of uncertainty bounds.[2]

4% of students answered this VCAA exam question correctly.

FROM LESSON 12C

Previous lessons

23. $F_{net} = 0 = F_{on\ M\ by\ C} - F_g$ (1 MARK)

$F_{on\ M\ by\ C} = F_g = m_M g = 70 \times 9.8$

$F_{on\ M\ by\ C} = 686 = 6.9 \times 10^2$ N upwards (1 MARK)

FROM LESSON 1D

24. $\theta = \tan^{-1}\left(\frac{v^2}{rg}\right) = \tan^{-1}\left(\frac{7.0^2}{10 \times 9.8}\right)$ (1 MARK)

$\theta = 26.6 = 27°$ (1 MARK)

FROM LESSON 1F

1I Momentum and impulse

Progress questions

1. C. $p = mv = 5.0 \times 3.0 = 15$ kg m s^{-1}
2. A. The direction of momentum is the same as the direction of velocity.
3. B. In an isolated system, momentum is conserved in a collision.
4. B. $p_i = p_f = mv = 0.06 \times 12 = 0.72$ kg m s^{-1}
5. B. Impulse is the change in momentum of an object due to a force acting over a period of time.
6. D. Both cars have the same change in momentum, $I = \Delta p = m \times (80 - 0)$.

Deconstructed exam-style

7. D. $p_{car,\,i} = mu = 1100 \times 11 = 12100 = 1.2 \times 10^4$ kg m s^{-1} to the right (same direction as velocity).
8. By conservation of momentum, $\sum p_i = \sum p_f$

$p_f = 1.2 \times 10^4$ kg m s^{-1} to the right.

9. D. $p_{bus,\,f} = mv = 2300 \times 5.9 = 13570 = 1.4 \times 10^4$ kg m s^{-1} to the right (same direction as velocity).
10. Applying conservation of momentum:

$\sum p_i = \sum p_f$ (1 MARK)

$m_{car}u_{car} + m_{bus}u_{bus} = m_{car}v_{car} + m_{bus}v_{bus}$

$1100 \times 11 + 2300 \times 0 = (2300 \times 5.9) + (1100 \times v_{car})$ (1 MARK)

$1200 = 13570 + 1100 \times v_{car}$

$v_{car} = \frac{12100 - 13570}{1100}$ (1 MARK)

$v_{car} = -1.34$ m s^{-1}

After the collision, the car has a velocity of 1.3 m s^{-1} to the left (1 MARK)

77% of students answer this VCAA exam question correctly.

Exam-style

11. $p = mv = 0.25 \times 4.0$ (1 MARK)

$p = 1.00 = 1.0$ kg m s^{-1} or N s to the right (1 MARK)

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12. $p = mv \Rightarrow 0.5 = 0.20 \times v$ (1 MARK)

$v = 2.50 = 2.5 \text{ m s}^{-1}$ (1 MARK)

13. a. $I = \Delta p = m\Delta v = 1500 \times (50 - 0)$ (1 MARK)

$I = 75000 = 7.5 \times 10^4 \text{ kg m s}^{-1}$ (1 MARK)

b. $I = F_{avg}\Delta t \Rightarrow 7.5 \times 10^4 = F_{avg} \times 8.5$ (1 MARK)

$F_{avg} = \frac{7.5 \times 10^4}{8.5} = 8824 = 8.8 \times 10^3 \text{ N}$ (1 MARK)

14. D. $I = F\Delta t = 5.0 \times 6.0 = 30.0 = 30 \text{ N s}$.

87% of students answer this VCAA exam question correctly.

15. a. Due to the conservation of momentum:

$\Sigma p_i = \Sigma p_f$

$\Sigma p_f = p_{car} + p_{truck} = m_{car}u_{car} + m_{truck}u_{truck}$

$\Sigma p_f = 1.5 \times 10^3 \times 20 + 7.5 \times 10^3 \times 10$ (1 MARK)

$p_f = 1.05 \times 10^5 = 1.1 \times 10^5 \text{ kg m s}^{-1}$ to the right (1 MARK)

b. $p_f = m_{total}v$

$\Rightarrow 1.05 \times 10^5 = (1.5 \times 10^3 + 7.5 \times 10^3) \times v$ (1 MARK)

$v = 11.7 = 12 \text{ m s}^{-1}$ (1 MARK)

c. Taking to the right as positive:

$I = \Delta p = m\Delta v$ (1 MARK)

$I = 1.5 \times 10^3 \times (11.7 - 20) = -1.25 \times 10^4$ (1 MARK)

$I = 1.3 \times 10^4 \text{ kg m s}^{-1}$ to the left (1 MARK)

d. [Impulse will be equal in magnitude and opposite in direction due to Newton's third law.[1]][The impulse on the truck will be $1.3 \times 10^4 \text{ kg m s}^{-1}$ to the right.[2]]

- I have identified the link between impulse and Newton's third law of motion.[1]
- I have stated the magnitude and direction of the impulse on the truck.[2]

16. B. $m_Au_A + m_Bu_B = (m_A + m_B)v_f$

$\Rightarrow (8000 \times 4.0) + (m_B \times 0) = (8000 + m_B) \times 2.5 \Rightarrow v_B = 4800$ kg.

78% of students answer this VCAA exam question correctly.

17. a. Taking to the right as positive:

$I = \Delta p = m\Delta v$ (1 MARK)

$I = 0.4 \times (55 - (-20)) = 30.0$ (1 MARK)

$I = 30 \text{ kg m s}^{-1}$ (1 MARK)

b. $I = F_{avg}\Delta t \Rightarrow 30 = 1.2 \times 10^3 \times \Delta t$ (1 MARK)

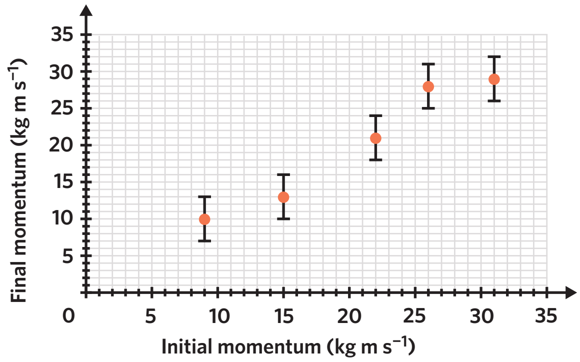
$\Delta t = 0.0250 = 2.5 \times 10^{-2} \text{ s}$ (1 MARK)

c. [The type of error is a systematic error.[1]][This can be improved by calibrating the measuring devices and re-collecting the data.[2]]

- I have identified the type of error.[1]
- I have suggested how this error can be improved.[2]

FROM LESSON 12C

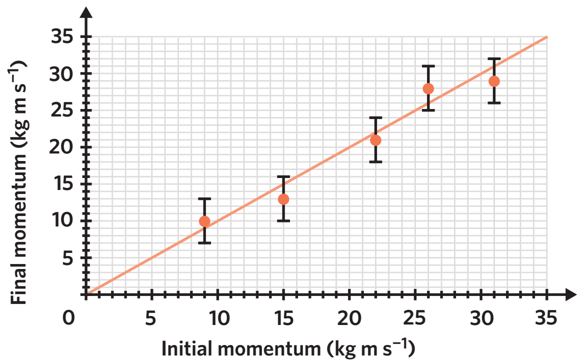
18. a.



- I have drawn initial momentum on the horizontal axis.
- I have drawn final momentum on the vertical axis.
- I have labelled both axes and included units.
- I have used an appropriate and consistent scale so the data takes up at least half of each axis.
- I have plotted each data point.
- I have included the correct uncertainty bars.

FROM LESSON 12D

b. [The students' data does support the law of conservation of momentum.[1]][It is possible to draw a line of best fit using the students' data that has a gradient of one,[2]][indicating that initial momentum is equal to the final momentum.[3]]



- I have stated whether the data supports the law of conservation of momentum.[1]
- I have identified the line of best fit has a gradient of 1.[2]
- I have explained the link between the gradient and the law of conservation of momentum.[3]

FROM LESSON 12E

19. [Zara will be safer with the airbags than Lara without.[1]] [This is because the airbags increase the time of which the collision occurs.[2]][Since both scenarios experience the same impulse, this decreases the average force experience by Zara.[3]]

- I have evaluated which driver is safer.[1]
- I have stated the use of airbags in collisions.[2]
- I have identified the result of increases the time of which a collision occurs in terms of force and impulse.[3]

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20. Taking to the right as positive:

$\Sigma p_i = \Sigma p_f$

$m_H u_H + m_p u_p = m_H v_H + m_p v_p$

$1.02 \times 7.8 \times 10^6 + 1 \times 0 = 1.02 \times v_H + 1 \times 8.1 \times 10^6$ (1 MARK)

$v_H = \dfrac{1.02 \times 7.8 \times 10^6 - 1 \times 8.1 \times 10^6}{1.02} = -1.41 \times 10^5$ (1 MARK)

$v_H = 1.4 \times 10^5$ m s^{-1} to the left (1 MARK)

Previous lessons

21. $F_{net} = (m_{Tim} + m_{trolley}) \times a = (80 + 15) \times 4.0$ (1 MARK)

$F_{net} = 380 = 3.8 \times 10^2$ N (1 MARK)

FROM LESSON 1D

22. $v = \sqrt{gr} = \sqrt{9.8 \times 4.0}$ (1 MARK)

$v = 6.26 = 6.3$ m s^{-1} (1 MARK)

FROM LESSON 1G

Chapter 1 review

Section A

1. C. $F_{net} = ma \Rightarrow 3.0 = 1.5 \times a$

$a = \dfrac{3.0}{1.5} = 2.0$ m s^{-2}

95% of students answered this VCAA exam question correctly.

2. C. In the horizontal direction: $F_{net,\,x} = 34 - 26 = 8$ N.

In the vertical direction: $F_{net,\,y} = 18 - 14 = 4$ N.

$F_{net} = \sqrt{(F_{net,x})^2 + (F_{net,y})^2} = \sqrt{(8)^2 + (4)^2} = 8.9 = 9$ N.

74% of students answered this VCAA exam question correctly.

3. C. $\theta = \tan^{-1}\left(\dfrac{v^2}{rg}\right) = \tan^{-1}\left(\dfrac{\left(\frac{60}{3.6}\right)^2}{55 \times 9.8}\right) = 27.3 = 27°$.

4. C. $v = \sqrt{rg} = \sqrt{7.0 \times 9.8} = 8.28 = 8.3$ m s^{-1}.

5. A. Considering block A: $F_{net} = 0$

$F_{on\,A\,by\,B} - F_g = 0$

$F_{on\,A\,by\,B} = F_g = 5.0 \times 9.8 = 49.0 = 49$ N.

This acts upwards, as it opposes the gravitational force.

Section B

6. Considering the combined system:

$F_{net} = m_{total}a \Rightarrow 18 = (2.0 + 4.0) \times a$

$a = \dfrac{18}{(2.0 + 4.0)} = 3.00$ m s^{-2} (1 MARK)

As the force on block Y by block X is the net force on block Y:

$F_{on\,Y\,by\,X} = F_{net,\,Y} = m_Y a$

$F_{on\,Y\,by\,X} = 4.0 \times 3.00 = 12.0 = 12$ N (1 MARK)

85% of students answered this VCAA exam question correctly.

7. **a.** $v = u + at \Rightarrow 10 = 0 + 0.50 \times t$ (1 MARK)

$t = \dfrac{10}{0.50} = 20.0 = 20$ s (1 MARK)

27% of students answered this VCAA exam question correctly.

b. Consider the trailer: $F_{net} = T - F_f = ma$

$T - 1000 = 600 \times 0.50$ (1 MARK)

$T = 1.30 \times 10^3 = 1.3 \times 10^3$ N (1 MARK)

46% of students answered this VCAA exam question correctly.

8. **a.** $s = ut + \frac{1}{2}at^2 \Rightarrow 1.5 = 0 \times 5.0 + \frac{1}{2} \times a \times 5.0^2$

$a = 0.120 = 0.12$ m s^{-2}, as required.

75% of students answered this VCAA exam question correctly.

b. $F_{net} = F_{net\parallel} = mg\sin(\theta) - F_f$

$1.5 \times 0.120 = 1.5 \times 9.8 \times \sin(20°) - F_f$ (1 MARK)

$F_f = 4.848 = 4.8$ N (1 MARK)

32% of students answered this VCAA exam question correctly.

c. [Taking the y-intercept of the graph of sin(θ) vs. a, $ma = F_{net\parallel} = mg\sin(\theta) - F_f \rightarrow a = g\sin(\theta) - \dfrac{F_f}{m}$.[1]][We can find the y-intercept by letting $a = 0$, therefore the y-intercept $= \dfrac{-F_f}{m}$.[2]][By multiplying the y-intercept of the graph by the mass of the block, the magnitude of the frictional force can be found.[3]]

- I have derived an expression for the acceleration of the block in terms of sin(θ).[1]
- I have identified the y-intercept of the graph is $\dfrac{-F_f}{m}$.[2]
- I have determined by multiplying the y-intercept by m, the frictional force can be found.[3]

FROM LESSON 12E

9. Take to the right as positive

$I = \Delta p = F\Delta t$

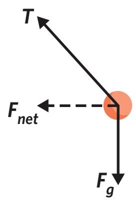
$\Delta p = m(v - u) = 1200\left(0 - \dfrac{90}{3.6}\right) = -3.00 \times 10^4$ kg m s^{-1} (1 MARK)

$-3.00 \times 10^4 = F \times 0.10$ (1 MARK)

$F = \dfrac{-3.00 \times 10^4}{0.10} = -3.00 \times 10^5 = -3.0 \times 10^5$ N

The average force on the car was 3.0×10^5 N to the left. (1 MARK)

10. **a.**



- I have drawn and labelled the gravitational and tension force correctly.
- I have drawn and labelled the net force correctly, as a dotted line.

53% of students answered this VCAA exam question correctly.

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b. $T = \sqrt{(F_{net})^2 + (F_g)^2} = \sqrt{\left(\frac{mv^2}{r}\right)^2 + (mg)^2}$ (1 MARK)

$T = \sqrt{\left(\frac{0.5 \times 1.2^2}{0.4}\right)^2 + (0.50 \times 9.8)^2}$ (1 MARK)

$T = 5.22 = 5.2$ N (1 MARK)

OR

$\sin(\theta) = \frac{0.40}{1.16} = 0.345$ (1 MARK)

$T = \frac{mv^2}{r\sin(\theta)} = \frac{0.50 \times 1.2^2}{0.40 \times 0.345}$ (1 MARK)

$T = 5.22 = 5.2$ N (1 MARK)

45% of students answered this VCAA exam question correctly.

11. a. Vertical motion:

$s_y = u_y t + \frac{1}{2} a_y t^2 \Rightarrow 1.5 = 0 \times t + \frac{1}{2} \times 9.8 \times t^2$ (1 MARK)

$t = 0.553$ s

Horizontal motion:

$s_x = u_x t + \frac{1}{2} a_x t^2 = 6.0 \times 0.553 + \frac{1}{2} \times 0 \times 0.553^2$
(1 MARK)

$s_x = 3.32 = 3.3$ m (1 MARK)

b. Vertical motion:

${v_y}^2 = u^2 + 2a_y s_y = 0^2 + 2 \times 9.8 \times 1.5$ (1 MARK)

$v_y = 5.42$ m s^{-1}

$v = \sqrt{(v_y)^2 + (v_x)^2} = \sqrt{5.42^2 + 6.0^2}$

$v = 8.09 = 8.1$ m s^{-1} (1 MARK)

The N&N will shatter when it hits the ground, as $v > 7.0$. (1 MARK)

Note: since all variables for constant acceleration are known there are multiple ways to calculate the final velocity of the N&N in the y direction.

12. a. $F_{net} = \frac{mv^2}{r} = \frac{85 \times 14^2}{45}$ (1 MARK)

$F_{net} = 3.70 \times 10^2 = 3.7 \times 10^2$ N

The net force is 3.7×10^2 N, towards the left. (1 MARK)

b. $\theta = \tan^{-1}\left(\frac{v^2}{rg}\right) = \tan^{-1}\left(\frac{14^2}{45 \times 9.8}\right)$ (1 MARK)

$\theta = 24.0 = 24°$ (1 MARK)

67% of students answered this VCAA exam question correctly.

13. a. $\Sigma p_i = \Sigma p_f$

$m_{engine} u_{engine} + m_{wagon} + u_{wagon} = m_{engine} v_{engine} + m_{wagon} v_{wagon}$

$(20 \times 10^3) \times 2.0 + (10 \times 10^3) \times 0 = (20 \times 10^3) \times v_{engine} + (10 \times 10^3) \times 2.0$ (1 MARK)

$v_{engine} = 1.0$ m s−1 (1 MARK)

The velocity of the engine after collision is 1.0 m s−1 to the right. (1 MARK)

67% of students answered this VCAA exam question correctly.

b. [The force exerted by the engine on the wagon and the force exerted by the wagon on the engine are an action-reaction force pair.[1]][According to Newton's third law, both forces will have the same magnitude,[2]][but will act in opposite directions.[3]]

- I have identified the forces are an action-reaction force pair.[1]
- I have applied Newton's third law to compare the magnitude of the forces.[2]
- I have applied Newton's third law to compare the direction of the forces.[3]

14. a. Considering the motion down the plane:

$F_{net} = F_{g\parallel} = mg\sin(\theta)$

$F_{net} = 1.50 \times 9.8 \times \sin(45°) = 10.4$ N (1 MARK)

$F_{net} = ma \Rightarrow 10.4 = 1.50 \times a$

$a = 6.93 = 6.9$ m s^{-2} (1 MARK)

b. The length of the ramp, s, is the hypotenuse of the triangle created by the ramp with the ground.

$\sin(\theta) = \frac{opposite}{hypotenuse}$

$\sin(45°) = \frac{15}{s}$ (1 MARK)

$s = 21.2$ m

$v^2 = u^2 + 2as = 0^2 + 2 \times 6.9 \times 21.2$ (1 MARK)

$v = \sqrt{2 \times 6.9 \times 21.2} = 17.1 = 17$ m s^{-1} (1 MARK)

c. $v = \sqrt{rg} = \sqrt{\left(\frac{6.0}{2}\right) \times 9.8}$ (1 MARK)

$v = 5.42 = 5.4$ m s^{-1} (1 MARK)

d. $F_{net} = F_g + F_N$

$\frac{m v^2}{r} = mg + F_N \Rightarrow \frac{1.50 \times 13^2}{3.0} = 1.50 \times 9.8 + F_N$ (1 MARK)

$F_N = 69.8 = 70$ N (1 MARK)

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2A Kinetic energy, work and power

Progress questions

1. C. $KE = \frac{1}{2}mv^2 = \frac{1}{2} \times 5.0 \times 8.0^2 = 160 = 1.6 \times 10^2$ J

2. A. When the boat is stationary, it does not have any kinetic energy.

3. D. When Jess holds the barbell, there is no displacement of the object and so work is not being done.

4. C. $W = \Delta E = E_f - E_i = 12 - 4.0 = 8$ J

5. C. $W = Fs = 35 \times 2.0 = 70 = 7.0 \times 10^1$ N

6. A. $P = \frac{\Delta E}{\Delta t} = \frac{50}{80} = 0.625 = 0.63$ W

7. C. Power is calculated using $P = \frac{\Delta E}{\Delta t}$, which is the change in energy with respect to time.

Deconstructed exam-style

8. C. $KE_i = \frac{1}{2}mu^2 = \frac{1}{2} \times 90 \times 2.5^2 = 281 = 2.8 \times 10^2$ J

9. D. $KE_f = \frac{1}{2}mv^2 = \frac{1}{2} \times 90 \times 5.0^2 = 1.13 \times 10^3 = 1.1 \times 10^3$ J

10. $KE_i = \frac{1}{2}mu^2 = \frac{1}{2} \times 90 \times 2.5^2 = 2.81 \times 10^2$ J (1 MARK)

    $KE_f = \frac{1}{2}mv^2 = \frac{1}{2} \times 90 \times 5.0^2 = 1.13 \times 10^2$ J (1 MARK)

    $W = \Delta E = E_f - E_i = 1.13 \times 10^3 - 2.81 \times 10^2$

    $W = 844 = 8.4 \times 10^2$ J (1 MARK)

Exam-style

11. C. Area under graph $= \frac{9 + (6-2)}{2} \times 8 = 52$

12. a. $W = KE_f - KE_i = \frac{1}{2}mv^2 - \frac{1}{2}mu^2$

    $W = \frac{1}{2} \times 900 \times 10^2 - \frac{1}{2} \times 900 \times 0^2$ (1 MARK)

    $W = 4.50 \times 10^4 = 4.5 \times 10^4$ J (1 MARK)

    b. $W = KE_f - KE_i = \frac{1}{2}mv^2 - \frac{1}{2}mu^2$

    $W = \frac{1}{2} \times 900 \times 20^2 - \frac{1}{2} \times 900 \times 10^2$ (1 MARK)

    $W = 1.35 \times 10^5 = 1.4 \times 10^5$ J (1 MARK)

13. B. $W = KE_f - KE_i = \frac{1}{2}mv^2 - \frac{1}{2}mu^2$

    $\Rightarrow 10\,240 = \frac{1}{2} \times 80 \times v^2 - \frac{1}{2} \times 80 \times 12^2$

    $v = 20 = 2.0 \times 10^1$ m s^{-1}

14. a. $P = \frac{W}{\Delta t} \Rightarrow 300 = \frac{W_{rem}}{30.0}$

    $W_{rem} = 9000$ J (1 MARK)

    $W = Fs \Rightarrow 9000 = F_{rem} \times 15.0$ (1 MARK)

    $F_{rem} = 600$ N, as required

    b. $E_{heat} = W_f = F_f s = 550 \times 15.0$ (1 MARK)

    8.25×10^3 J lost as heat. (1 MARK)

15. Use the area under the graph:

    $W = \frac{100 + (60 - 30)}{2} \times 1000 = 65\,000$ J (1 MARK)

    $W = KE_f - KE_i = \frac{1}{2}mv^2 - \frac{1}{2}mu^2$

    $65\,000 = \frac{1}{2} \times 1600 \times v^2 - \frac{1}{2} \times 1600 \times 8.0^2$ (1 MARK)

    $v = 12.1 = 12$ m s^{-1} (1 MARK)

16. a. $W = Fs = KE_f - KE_i$

    $130 \times s = 13\,540 - 6000$ (1 MARK)

    $s = 58.0$ m (1 MARK)

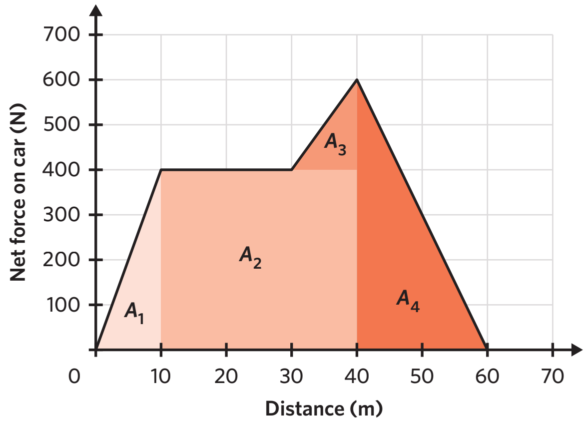
    b. $W = Fs = KE_f - KE_i$

    $F \times 70 = 4900 - 9400$ (1 MARK)

    $F = -64.3 = -64$ N

    The magnitude of the breaking force is 64 N. (1 MARK)

17. Use the area under the graph:



    $Area = W = A_1 + A_2 + A_3 + A_4$

    $W = \frac{1}{2} \times 10 \times 400 + 30 \times 400 + \frac{1}{2} \times 10 \times 200 + \frac{1}{2} \times 20 \times 600$
    $= 21\,000$ J (1 MARK)

    $W = KE_f - KE_i = \frac{1}{2}mv^2 - \frac{1}{2}mu^2$

    $21\,000 = \frac{1}{2} \times 1300 \times v^2 - \frac{1}{2} \times 1300 \times \left(\frac{36}{3.6}\right)^2$ (1 MARK)

    $v = 11.5 = 12$ m s^{-1} (1 MARK)

18. a. $W = KE_f - KE_i \Rightarrow Fs = \frac{1}{2}mv^2 - \frac{1}{2}mu^2$

    $800 \times s = \frac{1}{2} \times 1500 \times 14^2 - \frac{1}{2} \times 1500 \times 9.0^2$ (1 MARK)

    $s = 1.08 \times 10^2 = 1.1 \times 10^2$ m

    The car accelerates over a distance of 1.1×10^2 m. (1 MARK)

    b. $W = KE_f - KE_i \Rightarrow Fs = \frac{1}{2}mv^2 - \frac{1}{2}mu^2$

    $F \times 64 = \frac{1}{2} \times 1200 \times 12^2 - \frac{1}{2} \times 1200 \times 20^2$ (1 MARK)

    $F = 2.4 \times 10^3$ N (1 MARK)

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19. [Mikaela is correct. Sergio and Liam are incorrect.[1]][Random errors are unpredictable variations in the measurement process which create a spread of measured values and their effect can be reduced by taking an average of multiple measurements.[2]] [Systematic errors cause measurements to differ from the true value by a consistent amount every time and can not be reduced by taking multiple measurements.[3]][The uncertainty in each measurement is determined by the smallest deviations on the measuring instrument, so it cannot be changed by taking multiple measurements.[4]]

- I have stated who is correct and who is incorrect.[1]
- I have identified the relationship between random errors and taking multiple measurements.[2]
- I have identified the relationship between systematic errors and taking multiple measurements.[3]
- I have identified the relationship between uncertainty and taking multiple measurements.[4]

FROM LESSON 12C

20. $W = KE_f - KE_i = \frac{1}{2}mv^2 - \frac{1}{2}mu^2$

$W = \frac{1}{2} \times 80.0 \times \left(\frac{15.0}{3.6}\right)^2 - \frac{1}{2} \times 80.0 \times \left(\frac{10.0}{3.6}\right)^2$ (1 MARK)

$W = 385.8$ J

$P = \frac{W}{\Delta t} = \frac{385.8}{3.00 \times 60}$ (1 MARK)

$P = 2.143 = 2.14$ W (1 MARK)

21. [Let the kinetic energy for trial A be: $KE_A = \frac{1}{2}mv^2$. Then, kinetic energy for trial B is $KE_B = \frac{1}{2}m(3v)^2 = 9 \times \frac{1}{2}mv^2 = 9 \times KE_A$.[1]] [Work is equal to the change in energy so the work done for trial B is 9 times the work done for trial A.[2]][Work is also given by $W = Fs$.[3]][Since the value of F (brake force) is the same for both cars, s (brake distance) must be 9 times greater for trial B.[4]]

- I have compared trial A to trial B.[1]
- I have stated that work is the change in energy.[2]
- I have stated that work is the product of force and displacement.[3]
- I have explained why the stopping distance needs to be 9 times greater for trial B.[4]

Previous lessons

22. $F_{net} = \frac{mv^2}{r} = \frac{1200 \times 40^2}{20}$

$F_{net} = 9.60 \times 10^4 = 9.6 \times 10^4$ N (1 MARK)

The net force is 9.6×10^4 N towards the centre of the circle of motion (1 MARK)

FROM LESSON 1E

23. $v_x = \frac{s_x}{t} \Rightarrow 28 \times \cos(30°) = \frac{50}{t}$ (1 MARK)

$t = 2.06 = 2.1$ s (1 MARK)

FROM LESSON 1H

2B Elastic and inelastic collisions

Progress questions

1. B. Momentum is conserved in all collisions, but kinetic energy is only conserved in elastic collisions.

2. A. The collision cannot be elastic if kinetic energy is not conserved.

3. B. The dissipated energy is the energy lost in the collision. 3 J − 2 J = 1 J

4. D. Some kinetic energy is converted to sound. Kinetic energy is not conserved and the collision is inelastic.

Deconstructed exam-style

5. A. $p_i = m_Au_A + m_Bu_B = 110 \times 8.00 + 130 \times (-5.00)$ $= 2.30 \times 10^2$ kg m s^{-1} to the right.

6. A. $p_i = p_f = (m_A + m_B) \times v_f \Rightarrow 2.30 \times 10^2 = (110 + 130) \times v_f$ $\Rightarrow v_f = 0.958$ m s^{-1}

7. A. $KE_f = \frac{1}{2}(m_A + m_B)v_f^2 = \frac{1}{2}(110 + 130) \times 0.958^2 = 1.10 \times 10^2$ J

8. $p_i = m_Au_A + m_Bu_B = 110 \times 8.00 + 130 \times (-5.00)$ (1 MARK)

$p_i = 2.30 \times 10^2$ kg m s^{-1}

$p_i = p_f$

$p_i = (m_A + m_B) \times v_f \Rightarrow 2.30 \times 10^2 = (110 + 130) \times v_f$ (1 MARK)

$v_f = 0.958$ m s^{-1}

$KE_f = \frac{1}{2}(m_A + m_B)v_f^2 = \frac{1}{2}(110 + 130) \times 0.958^2$ (1 MARK)

$KE_f = 1.10 \times 10^2$ J

$KE_i \neq KE_f$, so the collision is inelastic. (1 MARK)

Exam-style

9. C. Since a sound can be heard and deformation occurs, some kinetic energy is lost but momentum is conserved in all collisions.

71% of students answered this VCAA exam question correctly.

10. a. Take to the right as positive.

Initial total momentum: $p_i = m_Xu_X + m_Yu_Y$ $= 10 \times 10^3 \times 6.0 + 5.0 \times 10^3 \times 3.0$

$p_i = 7.50 \times 10^4$ kg m s^{-1} or N s (1 MARK)

By conservation of momentum $p_i = p_f$

Final total momentum: $p_f = m_{XY}v_{XY} = 15 \times 10^3 \times v_{XY}$ $= 7.50 \times 10^4$ (1 MARK)

$v_{XY} = 5.00 = 5.0$ m s^{-1} (1 MARK)

86% of students answered this VCAA exam question correctly.

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b. $KE_i = \frac{1}{2}m_X{u_X}^2 + \frac{1}{2}m_Y{u_Y}^2$

$= \frac{1}{2} \times 10 \times 10^3 \times 6.0^2 + \frac{1}{2} \times 5.0 \times 10^3 \times 3.0^2$ (1 MARK)

$KE_i = 2.03 \times 10^5$ J

$KE_{final} = \frac{1}{2}m_{XY}{v_{XY}}^2 = \frac{1}{2} \times 15 \times 10^3 \times 5.0^2 = 1.88 \times 10^5$ J (1 MARK)

Since $KE_i \neq KE_f$, the collision is inelastic. (1 MARK)

c. [Kinetic energy may have been lost to sound.[1]]

- I have stated where kinetic energy has been dissipated.[1]

Other appropriate answers:

- Heat
- Deformation of cars

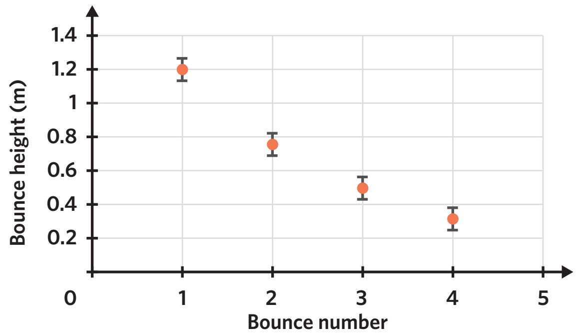
11. By the conservation of momentum, if ball A is stationary after the collision, and the balls have equal mass, then ball B will have a speed of 4.0 m s^{-1}. (1 MARK)

$KE_{initial} = \frac{1}{2}m{u_A}^2 = \frac{1}{2} \times 0.35 \times 4.0^2 = 2.8$ J

$KE_{final} = \frac{1}{2}m{v_B}^2 = \frac{1}{2} \times 0.35 \times 4.0^2 = 2.8$ J (1 MARK)

Since $KE_i = KE_f$, the collision is elastic. (1 MARK)

12. a.



- I have plotted the number of bounces on the horizontal axis and the bounce height on the vertical axis.
- I have included axis labels and appropriate units.
- I have included an appropriate and consistent scale on the axes.
- I have correctly plotted all the data points with appropriate error bars.

FROM LESSON 12D

b. [The ball does not return to the same height after each bounce because of energy dissipation.[1]][The ball's kinetic energy may be transformed into sound, heat, and the deformation of the ball.[2]]

- I have identified why the ball does not return to the same height.[1]
- I have identified the forms of energy that kinetic energy may be converted into.[2]

c. [Repeating the experiment and taking the average will reduce the effect of random errors.[1]][This will likely improve the accuracy of the data.[2]]

- I have identified that repetition reduced random errors.[1]
- I have identified how this will impact the precision of the data.[2]

FROM LESSON 12C

13. a. Take to the right as positive.

$p_i = m_Xu_X + m_Yu_Y = 3.34 \times 10^{-27} \times 9.48 \times 10^6$
$+ 3.34 \times 10^{-27} \times 0$ (1 MARK)

$p_i = 3.166 \times 10^{-20}$ kg m s^{-1}

$p_i = p_f$

$p_f = m_Xv_X + m_Yv_Y \Rightarrow 3.166 \times 10^{-20} = 3.34 \times 10^{-27}$
$\times v_X + 3.34 \times 10^{-27} \times 5.96 \times 10^6$ (1 MARK)

$v_X = 3.520 \times 10^6 = 3.52 \times 10^6$ m s^{-1} (1 MARK)

The velocity of the particle X after collision is 3.52×10^6 m s^{-1} to the right (1 MARK)

77% of students answered this VCAA exam question correctly.

b. $KE_i = \frac{1}{2}m_X{u_X}^2 = \frac{1}{2} \times 3.34 \times 10^{-27} \times (9.48 \times 10^6)^2$

$KE_i = 1.501 \times 10^{-13} = 1.50 \times 10^{-13}$ J (1 MARK)

$KE_f = \frac{1}{2}m_X{v_X}^2 + \frac{1}{2}m_Y{v_Y}^2 = \frac{1}{2} \times 3.34 \times 10^{-27} \times (3.52 \times 10^6)^2$
$+ \frac{1}{2} \times 3.34 \times 10^{-27} \times (5.96 \times 10^6)^2$

$KE_f = 8.001 \times 10^{-14} = 8.00 \times 10^{-14}$ J (1 MARK)

$KE_i \neq KE_f$, so the collision is inelastic, as required. (1 MARK)

52% of students answered this VCAA exam question correctly.

c. [No, this does not violate the law of energy conservation.[1]] [Kinetic energy is not conserved because of energy dissipation.[2]] [Kinetic energy is transformed into other forms of energy such as sound, heat, or light.[3]]

- I have stated that the collision does not violate the law of energy conservation.[1]
- I have stated that kinetic energy is not conserved because of energy dissipation.[2]
- I have identified what kinetic energy is transformed into.[3]

14. $KE_{ball,f} = \frac{1}{2}mv^2 = \frac{1}{2} \times 0.048 \times 54.74^2 = 71.915$ J (1 MARK)

$\Delta KE_{club} = 71.915$ J

$\Delta KE_{club} = KE_{club,i} - KE_{club,f} = \frac{1}{2}m_{club}{u_{club}}^2 - \frac{1}{2}m_{club}{v_{club}}^2$ (1 MARK)

$71.915 = \frac{1}{2} \times m_{club} \times 30.00^2 - \frac{1}{2} \times m_{club} \times 24.74^2$ (1 MARK)

$m_{club} = 0.4995$ kg $= 5.0 \times 10^2$ g (1 MARK)

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OR

$p_i = m_{club}u_{club} = 30.00 \times m_{club}$ (1 MARK)

$p_f = m_{club}v_{club} + m_{ball}v_{ball} = 24.74 \times m_{club} + 54.74 \times 0.048$ (1 MARK)

$p_i = p_f$

$24.74 \times m_{club} + 54.74 \times 0.048 = 30.00 \times m_{club}$ (1 MARK)

$m_{club} = 0.4995 \text{ kg} = 5.0 \times 10^2 \text{ g}$ (1 MARK)

Previous lessons

15. $F = \frac{mv^2}{r} \Rightarrow 12 = \frac{0.40 \times v^2}{0.75}$ (1 MARK)

$v = 4.74 = 4.7 \text{ m s}^{-1}$ (1 MARK)

FROM LESSON 1E

16. $v = \frac{\Delta s}{\Delta t} \Rightarrow 17 = \frac{\Delta s}{1.8}$ (1 MARK)

$\Delta s = 28.9 = 29 \text{ m}$

The distance jumped (29 m) is greater than the distance to the building (20 m). Therefore, Jim will make the jump. (1 MARK)

FROM LESSON 1H

2C Gravitational potential energy

Progress questions

1. C. To calculate ΔGPE, we need to use the change in height between points W and X.

2. A. Points X and Y are at the same height and so will have the same gravitational potential energy.

3. B. $\Delta GPE = mg\Delta h = 15 \times 9.8 \times (2 - 6) = 588 = -5.9 \times 10^2 \text{ J}$

4. C. Since energy is conserved, all the ball's GPE will be converted to KE.

5. D. All of the roller coaster cart's initial energy will be converted to kinetic energy. $KE_i + GPE_i = KE_f \Rightarrow 5 + 58.8 = 63.8 \text{ kJ}$

6. B. $mgh = \frac{1}{2}mv^2 \Rightarrow 800 \times 9.8 \times 30 = \frac{1}{2} \times 800 \times v^2$
$\Rightarrow v^2 = 24 \text{ m s}^{-1}$

Deconstructed exam-style

7. C. $GPE_i = mgh_i = 100 \times 9.8 \times 7.0 = 6.9 \times 10^3 \text{ J}$

8. C. By the conservation of energy, the kinetic energy at point Q will be equal to the gravitational potential energy at point P.

9. $GPE_i = KE_f$ (1 MARK)

$mgh_i = \frac{1}{2}mv^2 \Rightarrow 100 \times 9.8 \times 7.0 = \frac{1}{2} \times 100 \times v^2$ (1 MARK)

$v = 11.7 = 12 \text{ m s}^{-1}$ (1 MARK)

35% of students answered this VCAA exam question correctly

Exam-style

10. D. The total energy of the ball is constant. As point C is higher than point A, the ball would need to gain extra energy to reach it.

11. a. The change in GPE is the area under a force-height graph.

$GPE = base \times height = 8.0 \times 9.0 = 72 \text{ J}$

b. The change in GPE when launching the rock to a height of 8.0 m is 72 J.

$GPE = mg\Delta h \Rightarrow 72 = m \times 9.8 \times (8.0 - 0)$ (1 MARK)

$m = 0.918 = 0.92 \text{ kg}$ (1 MARK)

12. a. $KE_i = \frac{1}{2}mv^2 = \frac{1}{2} \times 1800 \times 30^2$ (1 MARK)

$KE_i = 8.10 \times 10^5 = 8.1 \times 10^5 \text{ J}$ (1 MARK)

b. $GPE_f = mgh_f = 1800 \times 9.8 \times 15$ (1 MARK)

$GPE_f = 2.64 \times 10^5 = 2.6 \times 10^5 \text{ J}$ (1 MARK)

c. $KE_i = KE_f + GPE_f$

$\frac{1}{2}mu^2 = \frac{1}{2}mv^2 + mgh_f \Rightarrow \frac{1}{2} \times 1800 \times 30^2$
$= \frac{1}{2} \times 1800 \times v^2 + 1800 \times 9.8 \times 15$ (1 MARK)

$v = 24.6 = 25 \text{ m s}^{-1}$ (1 MARK)

OR

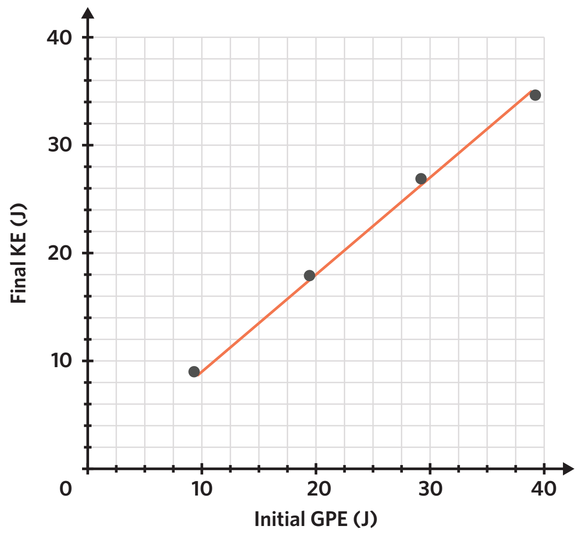
$v = \sqrt{u^2 - 2g\Delta h} = \sqrt{30^2 - 2 \times 9.8 \times (15 - 0)}$ (1 MARK)

$v = 24.6 = 25 \text{ m s}^{-1}$ (1 MARK)

13. a.

Height from which the ball is dropped (m)	Initial gravitational potential energy (J)	Final kinetic energy (J)
2	9.8	9.5
4	19.6	18
6	29.4	27
8	39.2	35

b.



- I have plotted the data correctly
- I have labelled the axes correctly and used an appropriate scale.
- I have included units on both axes.
- I have drawn a linear line of best fit.

FROM LESSON 12D

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c. [Yes, energy was dissipated,[1]] [because the final kinetic energy for all the different heights is less than the initial GPE.[2]]

I have identified that energy was dissipated.[1]

I have justified my answer.[2]

14. $GPE_A = GPE_B + KE_B \Rightarrow mgh_A = mgh_B + \frac{1}{2}mv^2$ (1 MARK)

$0.300 \times 9.8 \times h_A = 0.300 \times 9.8 \times 0.5 + \frac{1}{2} \times 0.300 \times 4.0^2$ (1 MARK)

$h_A = 1.32 = 1.3$ m (1 MARK)

46% of students answered this VCAA exam question correctly.

15. a. $E_{total,\,i} = KE_i + GPE_i$

$= \frac{1}{2}mv^2 + mgh = \frac{1}{2} \times 0.50 \times 5.0^2 + 0.50 \times 9.8 \times 35$ (1 MARK)

$E_{total,\,i} = 1.78 \times 10^2 = 1.8 \times 10^2$ J (1 MARK)

b. $KE_i + GPE_i = KE_f$

$\frac{1}{2}mu^2 + mgh_i = KE_f \Rightarrow \frac{1}{2} \times 0.50 \times 5.0^2 + 0.5 \times 9.8 \times 35 = KE_f$ (1 MARK)

$KE_f = 1.78 \times 10^2 = 1.8 \times 10^2$ J (1 MARK)

OR

Though conservation of energy $E_{total,\,i} = E_{total,\,f}$ (1 MARK)

$E_{total,\,f} = KE_f = 1.78 \times 10^2 = 1.8 \times 10^2$ J (1 MARK)

c. $KE_i + GPE_i = KE_f + GPE_f$

$\frac{1}{2}mu^2 + mgh_i = \frac{1}{2}mv^2 + mgh_f$

$\Rightarrow \frac{1}{2} \times 0.5 \times 5.0^2 + 0.5 \times 9.8 \times 35$

$= \frac{1}{2} \times 0.5 \times v^2 + 0.5 \times 9.8 \times 10$ (1 MARK)

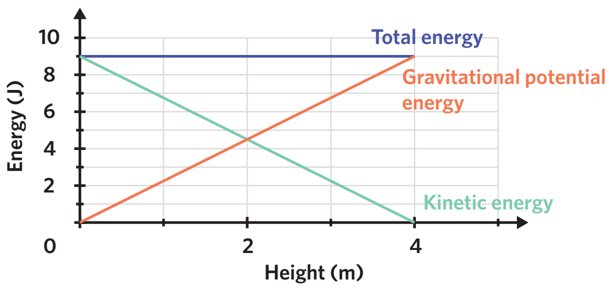
$v = 22.7 = 23$ m s^{-1} (1 MARK)

OR

$v = \sqrt{u^2 - 2g\Delta h} = \sqrt{5.0^2 - 2 \times 9.8 \times (10 - 35)}$ (1 MARK)

$v = 22.7 = 23$ m s^{-1} (1 MARK)

16.



I have drawn a straight line for GPE that starts at 9 J and meets the horizontal axis at 4 m.

I have drawn a straight line for KE that starts at 0 J and finishes at 9 J when the height is 4 m.

I have drawn the total energy as a straight horizontal line at 9 J.

FROM LESSON 12D

17. a. $GPE_A = KE_B$

$mgh_A = \frac{1}{2}mv_B{}^2 \Rightarrow 9.8 \times 20 = \frac{1}{2} \times v_B{}^2$ (1 MARK)

$v = 19.8 = 20$ m s^{-1} (1 MARK)

53% of students answered this VCAA exam question correctly.

b. $GPE_A = KE_C + GPE_C$

$mgh_A = \frac{1}{2}mv_C{}^2 + mgX$ (1 MARK)

Since $v^2 = rg$,

$mgh_A = \frac{1}{2}mrg + mgX \Rightarrow h_A = \frac{1}{2}r + X$ (1 MARK)

Since $X = 2r \Rightarrow r = \frac{X}{2}$,

$h_A = \frac{X}{4} + X \Rightarrow h_A = 1.25X$

$X = \frac{20}{1.25} = 16$ m (1 MARK)

OR

$v = \sqrt{u^2 - 2g\Delta h} \Rightarrow v^2 = u^2 - 2g\Delta h$ (1 MARK)

Since $v^2 = rg$,

$rg = u^2 - 2g\Delta h$ (1 MARK)

Since $X = 2r \Rightarrow r = \frac{X}{2}$

$\frac{X}{2} \times 9.8 = 0^2 - 2 \times 9.8 \times (X - 20)$ (1 MARK)

$X = \frac{40}{2.5} = 16$ m (1 MARK)

11% of students answered this VCAA exam question correctly.

18. a. $W = Fs = 560 \times 18.2 = 1.019 \times 10^4$ J (1 MARK)

$W = \Delta GPE = mg\Delta h$

$1.019 \times 10^4 = 64 \times 9.8 \times \Delta h$ (1 MARK)

$\Delta h = 16.3 = 16$ m (1 MARK)

b. [When moving over the dirt patch the skier's kinetic energy would be dissipated, for example into thermal energy.[1]] [Since no energy has been created or destroyed (just transformed), energy is conserved.[2]]

I have identified that the energy would be dissipated.[1]

I have explained my answer.[2]

19. B. $GPE = mg\Delta h = (250 + 810) \times 9.8 \times 90 \times \sin(10°) = 1.62 \times 10^5$ J

Previous lessons

20. a. $v = \sqrt{rg\tan(\theta)} = \sqrt{50 \times 9.8 \times \tan(25°)}$ (1 MARK)

$v = 15.1 = 15$ m s^{-1} (1 MARK)

b. $\theta = \tan^{-1}\left(\frac{v^2}{rg}\right) = \tan^{-1}\left(\frac{30^2}{50 \times 9.8}\right) = 61.4 = 61°$

$\theta = 61.4 = 61°$ (1 MARK)

FROM LESSON 1F

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21. a. $I = \Delta p = p_i - p_f = 0.250 \times 13.0 - 0.250 \times 0$

$I = 3.25 \text{ kg m s}^{-1}$, as required

b. $I = F\Delta t \Rightarrow 3.25 = F \times 0.150$ (1 MARK)

$F = 21.67 = 21.7 \text{ N}$ (1 MARK)

FROM LESSON 1I

2D Strain potential energy

Progress questions

1. C. The spring's force-displacement graph is always a straight line with a non-zero gradient.

2. A. The force in the spring is equal to the gravitational force acting on the mass.

3. A. $SPE = \frac{1}{2}k(\Delta x)^2 \Rightarrow 1.6 = \frac{1}{2} \times 3.5 \times (\Delta x)^2$

$\Delta x = 0.956 = 0.96$ m.

4. C. Initially the ball has kinetic and gravitational potential energy. When it has compressed the string, it only has spring potential energy as it is not moving and is at the same height as the reference height.

5. A. $SPE_B = KE_A + GPE_A = \frac{1}{2}mv_A{}^2 + mg\Delta h_a$

$= \frac{1}{2} \times 0.50 \times 2.0^2 + 0.50 \times 9.8 \times 0.70 = 4.4$ J.

Deconstructed exam-style

6. [Gravitational potential energy.[1]]

I have stated *GPE* is present when the gymnast is at their maximum height.[1]

7. [Spring potential energy.[1]]

I have stated *SPE* is present when the gymnast is at the bottom of their motion.[1]

8. B. Initially gravitational potential energy is present and finally spring potential energy is present.

9. $GPE_i + KE_i + SPE_i = GPE_f + KE_f + SPE_f$

$GPE_i = SPE_f \Rightarrow mg\Delta h = \frac{1}{2}k(\Delta x)^2$ (1 MARK)

$64 \times 9.8 \times 6.0 = \frac{1}{2} \times 4.3 \times 10^5 \times (\Delta x)^2$ (1 MARK)

$\Delta x = 0.132 = 0.13$ m (1 MARK)

Exam-style

10. a. k is the gradient of a force-displacement graph.

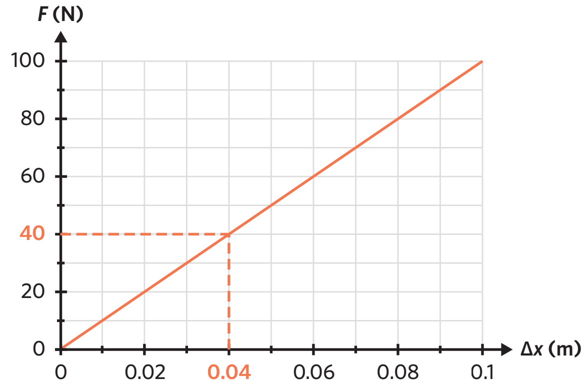
$k = \frac{y_2 - y_1}{x_2 - x_1} = \frac{100 - 0}{0.1 - 0}$ (1 MARK)

$k = 1.0 \times 10^3 \text{ N m}^{-1}$ (1 MARK)

63% of students answered this VCAA exam question correctly.

FROM LESSON 12E

b. From the graph, $F_s = 40$ N when $\Delta x = 0.04$ m.



c. $SPE = \frac{1}{2}k(\Delta x)^2 = \frac{1}{2} \times 1.0 \times 10^3 \times (0.04)^2$ (1 MARK)

$SPE = 0.80$ J (1 MARK)

OR

$SPE = \frac{1}{2}bh = \frac{1}{2} \times 0.04 \times 40$ (1 MARK)

$SPE = 0.80$ J (1 MARK)

68% of students answered this VCAA exam question correctly.

11. a. $F_x = k\Delta x = 15 \times 0.010$ (1 MARK)

$F_x = 0.150 = 0.15$ m (1 MARK)

b. $GPE_i + KE_i + SPE_i = GPE_f + KE_f + SPE_f$

$SPE_i = KE_f \Rightarrow \frac{1}{2}k(\Delta x)^2 = \frac{1}{2}mv^2$

$\frac{1}{2} \times 15 \times (0.010)^2 = \frac{1}{2} \times (80 \times 10^{-3}) \times v^2$ (1 MARK)

$v = 0.137 = 0.14 \text{ m s}^{-1}$ (1 MARK)

12. a. When one mass has been placed on the system:

$mg = k\Delta x$ (1 MARK)

$(1 \times 25 \times 10^{-3}) \times 9.8 = k \times (0.40 - 0.30)$ (1 MARK)

$k = 2.45 = 2.5 \text{ N m}^{-1}$, as required.

61% of students answered this VCAA exam question correctly.

b. $SPE = \frac{1}{2}k(\Delta x)^2 = \frac{1}{2} \times 2.5 \times (0.50 - 0.30)^2$ (1 MARK)

$SPE = 0.0500 = 0.050$ J (1 MARK)

13. D. The maximum acceleration of the mass upwards occurs when the force on the mass upwards is at a maximum. This is when the spring has been extended by the maximum amount, at the bottom of motion. All other options are false.

14. C. $KE_i = SPE_f = \frac{1}{2}bh = \frac{1}{2}(0.50) \times (2.0 \times 10^2) = 50$ J.

58% of students answered this VCAA exam question correctly.

FROM LESSON 12D

15. Taking the initial point before the car compresses the spring and final as the spring returns to natural length:

$GPE_i + KE_i + SPE_i = GPE_f + KE_f + SPE_f$

$KE_i = KE_f \Rightarrow 50 = KE_f$

$50 = \frac{1}{2} \times (1.25) \times v^2$ (1 MARK)

$v = 8.94 = 8.9 \text{ m s}^{-1}$ (1 MARK)

The velocity of the car is 8.9 m s^{-1} to the left. (1 MARK)

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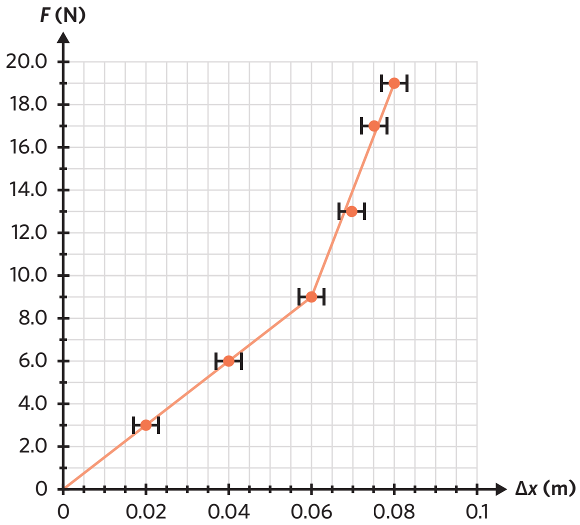
16. a.

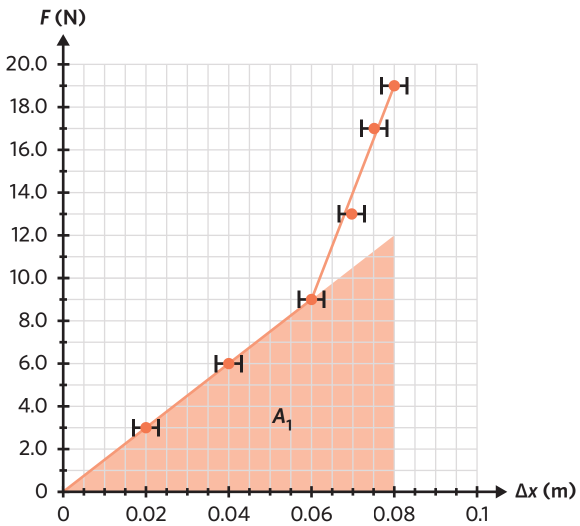


- I have drawn compression on the horizontal axis and force on the vertical axis.
- I have labelled both axes and included units.
- I have used an appropriate and consistent scale.
- I have plotted each point of data.
- I have included the correct uncertainty bars.
- I have included a straight line of best fit which passes through all uncertainty bars for the effects of spring *A* alone and the effect of spring *A* and spring *B*.

17% of students answered this VCAA exam question correctly.

FROM LESSON 12D

b. To find the energy stored just in spring *A* when it is compressed by 80 mm, the area underneath just the line of best fit for spring *A* up to that point needs to be considered. This can be done through a triangle:



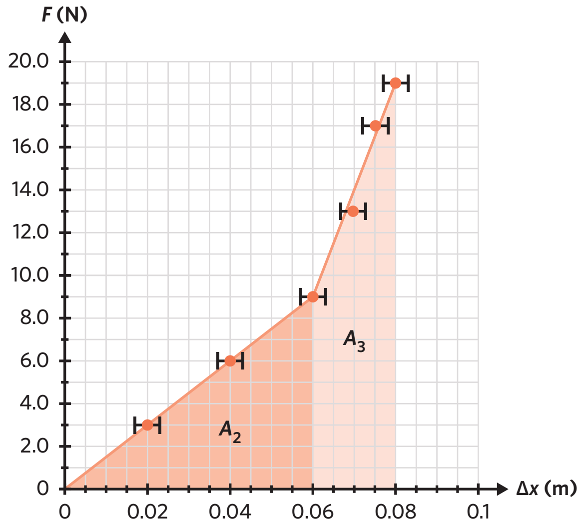
$SPE_A = A_1 = \frac{1}{2}bh$

$SPE_A = \frac{1}{2} \times 0.08 \times 12.0 = 0.48$ J

41% of students answered this VCAA exam question correctly.

FROM LESSON 12D

c. To find the work done (energy stored) on spring *B* when it is compressed by 80 mm, the area underneath the total graph needs to be found, and the energy stored in spring *A* subtracted:



$A_{total} = SPE_A + SPE_B \Rightarrow A_2 + A_3 = SPE_A + SPE_B$ (1 MARK)

$\frac{1}{2} \times 0.06 \times 9.0 + \frac{(9.0 + 19.0)}{2} \times (0.08 - 0.06) = 0.48 + SPE_B$
(1 MARK)

$SPE_B = 0.07$ J (1 MARK)

15% of students answered this VCAA exam question correctly.

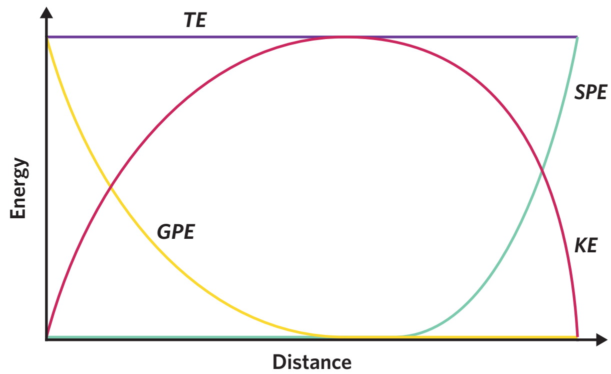
FROM LESSON 12D

d. [The single spring (*A*) could provide suspension for small bumps.[1]][The combined spring system (*A* + *B*) could provide suspension for more severe bumps.[2]]

- I have identified that just spring *A* is used for small bumps.[1]
- I have identified that both spring *A* and spring *B* are used for more severe bumps.[2]

36% of students answered this VCAA exam question correctly.

17.



- I have drawn the graph of *GPE* vs. distance correctly.
- I have drawn the graph of *KE* vs. distance correctly.
- I have drawn the graph of *SPE* vs. distance correctly.
- I have drawn the graph of *TE* vs. distance correctly.

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Previous lessons

18. D. As the normal force is the hypotenuse of the force triangle involving F_g and F_{net} it is greater in magnitude than F_g, and normal forces always act perpendicular to the contact between two surfaces.

FROM LESSON 1F

19. [As $KE = \frac{1}{2}mv^2$, the value of the KE is not affected by changes to the direction of v but only its magnitude.[1]] [As the speed of an object undergoing uniform circular motion does not changed, its KE will not change.[2]]

- I have identified that KE does not depend upon the direction of velocity of an object.[1]
- I have stated that the KE of an object undergoing uniform circular motion does not change.[2]

FROM LESSON 2A

2E Vertical spring-mass systems

Progress questions

1. A. $SPE_{max} = \frac{1}{2}k(\Delta x^2) = \frac{1}{2} \times 100 \times 0.350^2 \Rightarrow SPE_{max} = 6.13$ J

2. A. Using conservation of energy $GPE_i = SPE_{max} = 6.13$ J

3. A. $mg = k\Delta x \Rightarrow 1.5 \times 9.8 = 100 \times \Delta x \Rightarrow \Delta x = 0.147 = 0.15$ m

4. C. The strain potential energy will be a maximum when the spring is at maximum extension.

5. B. The kinetic energy will be a maximum when the mass is travelling the fastest, this occurs at the equilibrium position.

Deconstructed exam-style

6. B. $E_{total} = GPE_{top} = mg\Delta x = 2.50 \times 9.8 \times 0.500 = 12.25$ J

OR

$E_{total} = SPE_{bot} = \frac{1}{2}k(\Delta x)^2 = \frac{1}{2} \times 98 \times 0.500^2 = 12.25$ J

7. B. $GPE_{mid} = mgy = 2.50 \times 9.8 \times 0.250 = 6.125$ J

OR

$GPE_{mid} = \frac{1}{2} \times E_{total} = \frac{1}{2} \times 12.25 = 6.125$ J

8. A. $SPE_{mid} = \frac{1}{2}k(\Delta x)^2 = \frac{1}{2} \times 98.0 \times 0.250^2 = 3.0625$ J

OR

$SPE_{mid} = \frac{1}{4} \times E_{total} = \frac{1}{4} \times 12.25 = 3.0625$ J

9. Total energy of the system:

$E_{total} = GPE_{top} = mg\Delta x = 2.50 \times 9.8 \times 0.500$ (1 MARK)

$E_{total} = 12.25$ J

The maximum velocity occurs at the midpoint, where $\Delta x = \frac{0.500}{2} = 0.250$ m.

$GPE_{mid} = mg\Delta x = 2.50 \times 9.8 \times 0.250$ (1 MARK)

$GPE_{mid} = 6.125$ J

$SPE_{mid} = \frac{1}{2}k(\Delta x)^2 = \frac{1}{2} \times 98 \times 0.250^2$ (1 MARK)

$SPE_{mid} = 3.0625$ J

$KE_{mid} = 12.25 - (6.125 + 3.0625) = 3.0625$ J

$KE = \frac{1}{2}mv^2 \Rightarrow 3.0625 = \frac{1}{2} \times 2.50 \times v^2$

$v = 1.57 = 1.6$ m s^{-1} (1 MARK)

OR

$E_{total} = GPE_{top} = mg\Delta x = 2.50 \times 9.8 \times 0.500$ (1 MARK)

$E_{total} = 12.25$ J

$KE = \frac{1}{4} \times E_{total} = \frac{1}{4} \times GPE_i = \frac{1}{4} \times 12.25 = 3.0625$ J (1 MARK)

$KE = \frac{1}{2}mv^2 \Rightarrow 3.0625 = \frac{1}{2} \times 2.50 \times v^2$ (1 MARK)

$v = 1.57 = 1.6$ m s^{-1} (1 MARK)

Exam-style

10. a. At the top of the oscillation all the energy in the system is in gravitational potential energy. Therefore $GPE = 12$ J.

b. At the bottom of the oscillation all the energy in the system is in strain potential energy. Therefore $SPE = 12$ J.

11. A. The mass is at equilibrium when moving at max speed, $mg = k\Delta x$. From the graph $F = k\Delta x = 45$ N. Therefore, $k\Delta x = mg \Rightarrow 45 = m \times 10 \Rightarrow m = 4.5$ kg.

12. a. $GPE_{top} = SPE_{bot} \Rightarrow mgh_{top} = \frac{1}{2}k(\Delta x_{bot})^2$ (1 MARK)

Since $h_{top} = \Delta x_{bot}$

$0.800 \times 9.8 \times \Delta x_{bot} = \frac{1}{2} \times 12 \times (\Delta x_{bot})^2$ (1 MARK)

$\Delta x_{bot} = 1.31 = 1.3$ m (1 MARK)

b. Maximum speed occurs at the middle of the oscillation, when $\Delta x = 0.65$ m.

$SPE_{mid} + KE_{mid} + GPE_{mid} = SPE_{bot}$

$\Rightarrow \frac{1}{2}k\Delta x_{mid}{}^2 + \frac{1}{2}mv_{mid}{}^2 + mg\Delta x_{mid} = \frac{1}{2}k\Delta x_{bot}{}^2$ (1 MARK)

$\frac{1}{2} \times 12 \times 0.65^2 + \frac{1}{2} \times 0.800 \times v_{mid}^2 + 0.800 \times 9.8 \times 0.65 = \frac{1}{2} \times 12 \times 1.3^2$ (1 MARK)

$v_{mid} = 2.50$ m s^{-1} (1 MARK)

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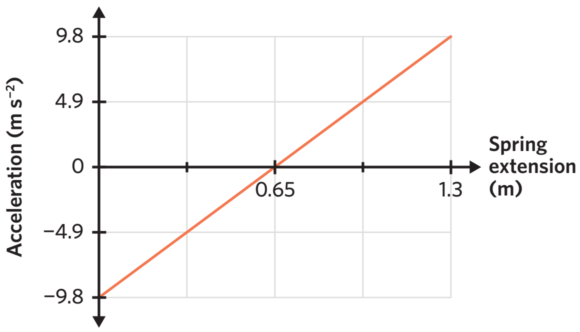
c.



I have shown the acceleration to be -9.8 m s^{-2} when the spring is unstretched.

I have shown the acceleration to be $+9.8$ m s^{-2} at maximum extension (1.3 m).

I have shown the acceleration to change linearly between the top and bottom of the motion.

I have labelled each axis including units and used appropriate scales.

13. **a.** $GPE_i = SPE_f$

$mgh = \frac{1}{2}k(\Delta x)^2 \Rightarrow 3.0 \times 9.8 \times 3.25 = \frac{1}{2} \times k \times 0.75^2$ (1 MARK)

$k = 339.7 = 340$ N m^{-1} as required (1 MARK)

45% of students answered this VCAA exam question correctly.

b. [The acceleration of the ball will be zero when it reaches its maximum velocity.[1]][This is because the net force on the ball is zero, $mg = kx$.[2]]

I have stated the acceleration of the ball.[1]

I have explained my answer.[2]

6% of students answered this VCAA exam question correctly.

c. $mg = kx \Rightarrow 3.0 \times 9.8 = 340 \times x$ (1 MARK)

$x = 0.086 = 8.6 \times 10^{-2}$ m (1 MARK)

13% of students answered this VCAA exam question correctly.

14. **a.** $k = gradient = \frac{rise}{run} = \frac{30-0}{0.25-0} = 120$ N m^{-1}, as required.

b. $\Delta SPE = SPE_Y - SPE_X$ (1 MARK)

$\Delta SPE = \frac{1}{2}k(\Delta x_Y)^2 - \frac{1}{2}k(\Delta x_X)^2$

$\Delta SPE = \frac{1}{2} \times 120 \times (0.4)^2 - \frac{1}{2} \times 120 \times (0.2)^2 = 7.2$ J, as required (1 MARK)

OR

$\Delta SPE = area\ under\ the\ graph = \frac{48+24}{2} \times (0.4 - 0.2)$ (1 MARK)

$\Delta SPE = \frac{48+24}{2} \times (0.4 - 0.2) = 7.2$ J, as required (1 MARK)

c. $SPE_i = GPE_f + SPE_f$ (1 MARK)

$\frac{1}{2}k(\Delta x_Y)^2 = mgh + \frac{1}{2}k(\Delta x_X)^2$

$\frac{1}{2} \times 120 \times (0.40)^2 = 0.50 \times 9.8 \times h + \frac{1}{2} \times 120 \times (0.20)^2$ (1 MARK)

$h = 1.47 = 1.5$ m (1 MARK)

d. $SPE_i = GPE_f + KE_f + SPE_f$ (1 MARK)

$\frac{1}{2} \times 120 \times (0.40)^2 = 0.50 \times 9.8 \times 0.20 + \frac{1}{2} \times 0.50 \times v^2 + \frac{1}{2} \times 120 \times (0.20)^2$ (1 MARK)

$v = 4.99 = 5.0$ m s^{-1} (1 MARK)

e. [The total energy of the mass-spring system remains constant.[1]] [Kinetic energy of the ball increases as the ball is launched.[2]] [Strain potential energy decreases as the ball is launched.[3]] [Gravitational potential energy increases as the ball is launched.[4]]

I have stated that the total energy remains constant.[1]

I have identified how kinetic energy changes.[2]

I have identified how strain potential energy changes.[3]

I have identified how gravitational potential energy changes.[4]

15. [Yokabit, Valeriy, and JL have all suggested incorrect maximum heights.[1]][The highest and lowest position are equidistant from the equilibrium position[2]][which means the highest position must be 1.0 cm above the equilibrium position.[3]]

I have identified who is correct and who is incorrect.[1]

I have identified the highest and lowest positions in relation to the equilibrium position.[2]

I have identified where the highest position is.[3]

16. [Total energy should remain constant.[1]][The students' mistake was to take the strain potential energy to be zero where it was released, rather than from the unstretched length (which is important since SPE is not linear – it is proportional to $(\Delta x)^2$).[2]] [Since the mass was released from 20 cm below its unstretched length, it would have initially had a non-zero strain potential energy.[3]]

I have stated that the total energy remains constant.[1]

I have explained the mistake the students have made.[2]

I have identified the correct initial strain potential energy.[3]

7% of students answered this VCAA exam question correctly.

2E ANSWERS

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Previous lessons

17. $v_{top} = \sqrt{rg}$

$80.0 = \sqrt{r \times 9.8}$ (1 MARK)

$r = 653$ m

$F_{N,\,bot} = \frac{mv_{bot}^2}{r} + mg = \frac{60.0 \times 100^2}{653} + 60.0 \times 9.8$ (1 MARK)

$F_{N,\,bot} = 1.51 \times 10^3 = 1.5 \times 10^3$ N (1 MARK)

FROM LESSON 1G

18. $KE_i = \frac{1}{2}m_{ball}u_{ball}^2 + \frac{1}{2}m_{bat}u_{bat}^2 = \frac{1}{2} \times 0.145 \times 36^2 + \frac{1}{2} \times 0.96 \times 31^2$ (1 MARK)

$KE_i = 5.55 \times 10^2$ J

$KE_f = \frac{1}{2}m_{ball}v_{ball}^2 + \frac{1}{2}m_{bat}v_{bat}^2 = \frac{1}{2} \times 0.145 \times 49^2 + \frac{1}{2} \times 0.96 \times 18^2$ (1 MARK)

$KE_f = 3.30 \times 10^2$ J

$KE_i > KE_f$ So the collision was inelastic. (1 MARK)

FROM LESSON 2B

Chapter 2 review

Section A

1. C. $W = Fs = 100 \times 3.0 = 3.0 \times 10^2$ J

2. C. $k = gradient = \frac{rise}{run} = \frac{40}{0.08} = 500$ N m^{-1}

63% of students answered this VCAA question correctly

3. B. $E = \frac{1}{2}kx^2 \Rightarrow 0.9 = \frac{1}{2} \times \frac{40}{0.08} \times x^2 \Rightarrow x = 0.06$ m

72% of students answered this VCAA question correctly

4. B. $KE_i = \frac{1}{2}m_{15.0\,kg}{u_{15.0\,kg}}^2 + \frac{1}{2}m_{40.0\,kg}{u_{40.0\,kg}}^2$

$= \frac{1}{2} \times 15.0 \times 50.0^2 + \frac{1}{2} \times 40.0 \times (-4.00)^2 = 1.91 \times 10^4$ J

$KE_f = \frac{1}{2}m_T{v_T}^2 = \frac{1}{2} \times 55.0 \times 10.7^2 = 3.15 \times 10^3$ J

$E_{conserved} = \frac{KE_f}{KE_i} \times 100 = \frac{3.15 \times 10^3}{1.91 \times 10^4} \times 100 = 16.5\%$.

5. B. The photon goes from having momentum p_{ph} to momentum $-p_{ph}$, as it reflects elastically in the opposite direction when it hits the sail. By the law of conservation of momentum, $\Delta p_{sail} = 2p_{ph}$.

11% of students answered this VCAA question correctly

Section B

6. [The PE teacher is incorrect.[1]][Work is given by $W = Fs$, and since $s = 0$ for stationary objects, the PE teacher is not doing work on the book.[3]]

- I have identified the teacher is incorrect.[1]
- I have described how work done on stationary objects is zero.[2]

7. **a.** The energy, E, that can be delivered to the light is the same as the change in GPE as the sandbag lowers.

$E = \Delta GPE = mg\Delta h = 30 \times 9.8 \times 2.0$ (1 MARK)

$E = 588 = 5.9 \times 10^2$ J (1 MARK)

b. $P = \frac{\Delta E}{t} \Rightarrow 1.5 = \frac{588}{t}$ (1 MARK)

$t = 3.92 \times 10^2 = 3.9 \times 10^2$ s (1 MARK)

8. **a.** $KE_i + GPE_i = KE_f + GPE_f \Rightarrow KE_i + GPE_i = KE_f$

$6.25 + 0.50 \times 9.8 \times h = \frac{1}{2} \times 0.50 \times 31^2$ (1 MARK)

$h = 47.8 = 48$ m (1 MARK)

b. $KE_i = \frac{1}{2}m_b{v_i}^2 = \frac{1}{2} \times 0.50 \times 5.0^2$ (1 MARK)

$KE_i = 6.25$ J

$KE_f = \frac{1}{2}(m_b + m_s){v_f}^2 = \frac{1}{2} \times (0.50 + 0.70) \times 2.1^2$ (1 MARK)

$KE_f = 2.65$ J

$E_{loss} = KE_f - KE_i = 6.25 - 2.65 = 3.60 = 3.6$ J (1 MARK)

c. [This was an inelastic collision,[1]][since the initial kinetic energy of the system is not equal to the final kinetic energy of the system.[2]]

- I have identified the collision is inelastic.[1]
- I have justified my answer with the condition for an inelastic collision.[2]

9. **a.** $W = \frac{1}{2}bh = \frac{1}{2} \times 1.5 \times 120$ (1 MARK)

$W = 90.0 = 90$ J (1 MARK)

b. $KE = \frac{1}{2}mv^2 \Rightarrow 90 = \frac{1}{2} \times 0.450 \times v^2$ (1 MARK)

$v = 20.0 = 20$ m s^{-1} (1 MARK)

10. $p_{A,\,i} + p_{B,\,i} = p_{A,\,f} + p_{B,\,f} \Rightarrow m_A u_A + m_B u_B = (m_A + m_B)v$

$400 \times 15.0 + 1200 \times 10.0 = (400 + 1200)v_f$ (1 MARK)

$v = 11.25$ m s^{-1}

$KE_i = \frac{1}{2}m_A{u_A}^2 + \frac{1}{2}m_B{u_B}^2 = \frac{1}{2} \times 400 \times 15.0^2 + \frac{1}{2} \times 1200 \times 10.0^2$ (1 MARK)

$KE_i = 1.050 \times 10^5$ J

$KE_f = \frac{1}{2}(m_A + m_B)v = \frac{1}{2} \times (400 + 1200) \times 11.25$ (1 MARK)

$KE_f = 1.013 \times 10^5$ J

The collision is inelastic, as $KE_i \neq KE_f$ (1 MARK)

64% of students answered this VCAA question correctly

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11. a. [As the mass descends from the top to the bottom the GPE starts at a maximum and then decreases.[1]][The SPE starts at a minimum and then increases.[2]][The KE starts at zero, it then increases until the middle point and then decreases back to zero at the bottom.[3]][The total energy of the system remains constant due to the law of conservation of energy.[4]]

- I have described how the GPE changes.[1]
- I have described how the SPE changes.[2]
- I have described how the KE changes.[3]
- I have described how total energy is conserved.[4]

46% of students answered this VCAA question correctly.

b. $KE_{top} + GPE_{top} + SPE_{top} = KE_{bot} + GPE_{bot} + SPE_{bot}$
$\Rightarrow GPE_{top} = SPE_{bot}$

$4.8 \times 9.8 \times \Delta x = \frac{1}{2} \times 50 \times \Delta x^2$ (1 MARK)

$\Delta x = 1.88 = 1.9$ m (1 MARK)

12. a. $W = Fs = 60 \times 0.65$ (1 MARK)

$W = 39.0 = 39$ J (1 MARK)

b. $SPE = \frac{1}{2}kx^2 \Rightarrow 39 = \frac{1}{2} \times k \times 0.65^2$ (1 MARK)

$k = 184.6 = 1.8 \times 10^2$ N m^{-1} (1 MARK)

c. $t = \frac{d}{v} = \frac{25}{1.0} = 25$ s (1 MARK)

$P = \frac{\Delta E}{t} \Rightarrow 1800 = \frac{\Delta E}{25}$ (1 MARK)

$\Delta E = 4.50 \times 10^4 = 4.5 \times 10^4$ J

Since they maintain a constant speed, $E_{dis} = \Delta E = 4.5 \times 10^4$ J. (1 MARK)

13. a. $GPE_i = KE_f + E_{loss}$

$70.0 \times 9.8 \times (7661 - 61) = \frac{1}{2} \times 70.0 \times \left(\frac{240}{3.6}\right)^2 + E_{loss}$ (1 MARK)

$E_{loss} = 5.06 \times 10^6 = 5.1 \times 10^6$ J (1 MARK)

b. $KE_{top} + GPE_{top} + SPE_{top} = KE_{bot} + GPE_{bot} + SPE_{bot}$
$\Rightarrow KE_{top} + GPE_{top} = SPE_{bot}$

$\frac{1}{2} \times 70.0 \times \left(\frac{240}{3.6}\right)^2 + 70.0 \times 9.8 \times 61 = \frac{1}{2} \times k \times 61^2$ (1 MARK)

$k = 106 = 1.1 \times 10^2$ N m^{-1} (1 MARK)

14. a. $KE_i + GPE_i + SPE_i = KE_f + GPE_f + SPE_f \Rightarrow SPE_f = GPE_i$

$SPE_f = mg\Delta h = 1.5 \times 9.8 \times 5.6$ (1 MARK)

$SPE_f = 82.3 = 82$ J (1 MARK)

b. The ball reaches its maximum speed when its acceleration, and therefore the net force on it, is zero. (1 MARK)

$F_{net} = 0 \Rightarrow mg = k\Delta x \Rightarrow 1.5 \times 9.8 = 457 \times \Delta x$ (1 MARK)

$\Delta x = 3.22 \times 10^{-2} = 3.2 \times 10^{-2}$ m (1 MARK)

14% of students answered this VCAA question correctly

c. $KE_i + GPE_i + SPE_i = KE_f + GPE_f + SPE_f$
$\Rightarrow GPE_i = KE_f + SPE_f$

$1.5 \times 9.8 \times (5.0 + 7.35 \times 10^{-2})$
$= KE_f + \frac{1}{2} \times 200 \times (7.35 \times 10^{-2})^2$ (1 MARK)

$KE_f = 74.0 = 74$ J (1 MARK)

Unit 3 AOS 1 review

Section A

1. B. $s = ut + \frac{1}{2}at^2 = 12 \times 6.0 + \frac{1}{2} \times (-2.0) \times 6.0^2 = 36.0$
$= 3.6 \times 10^1$ m

85% of students answered this VCAA exam question correctly.

2. B. Acceleration requires a change in the magnitude of velocity or a change in direction of velocity.

3. A. The law of conservation of energy states that energy must always be conserved.

4. B. $E_i = E_f \Rightarrow GPE_i = KE_f \Rightarrow mg\Delta h = \frac{1}{2}mv^2 \Rightarrow 20 \times 9.8 \times 1.5$
$= \frac{1}{2} \times 20 \times v^2 \Rightarrow v = 5.4$ m s^{-1}

5. D. The kinetic energy is not a vector quantity, but the momentum is. As the direction of the velocity changes, the direction of the momentum changes, but the magnitude of the velocity remains the same.

31% of students answered this VCAA exam question correctly.

Section B

6. Take up the page as positive.

$F_{net} = ma \Rightarrow F_{on\ Y\ by\ Z} - mg = 0 \Rightarrow F_{on\ Y\ by\ Z} - 30 \times 9.8 = 0$ (1 MARK)

$F_{on\ Y\ by\ Z} = 980 = 9.8 \times 10^2$ N (1 MARK)

27% of students answered this VCAA exam question correctly.

7. Kinetic energy is at a maximum just before the cannonball hits the ground.

$KE_f = KE_i + GPE_i = \frac{1}{2}mu^2 + mgh$ (1 MARK)

$KE_f = \frac{1}{2} \times 2.0 \times 530^2 + 2.0 \times 9.8 \times 5.3$ (1 MARK)

$KE_f = 2.81 \times 10^5 = 2.8 \times 10^5$ J (1 MARK)

8. a. $F_{g,1} = m_1 g = 9.8 \times \left(\frac{500}{1000}\right) = 4.90 = 4.9$ N (1 MARK)

$F_{g,2} = m_2 g = 9.8 \times \left(\frac{300}{1000}\right) = 2.94 = 2.9$ N (1 MARK)

b. Taking anticlockwise around the pulley as the positive direction, consider the combined system:

$F_{net} = F_{g,1} - F_{g,2} = m_{tot}a$

$4.90 - 2.94 = (0.500 + 0.300) \times a$ (1 MARK)

$a = 2.45 = 2.5$ m s^{-2} (1 MARK)

52% of students answered this VCAA exam question correctly.

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c. Taking up the page as positive, consider m_2:

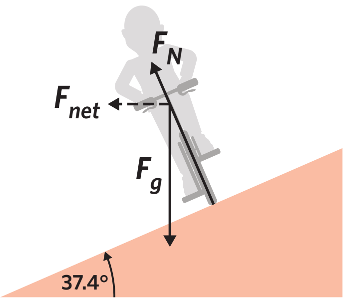
$F_{net} = T - F_{g,2} = m_2 a$

$T - 2.94 = 0.300 \times 2.45$ (1 MARK)

$T = 3.68 = 3.7$ N (1 MARK)

54% of students answered this VCAA exam question correctly.

9. a.



I have drawn the normal force correctly and the force due to gravity correctly.

I have drawn the net force vector with a dashed arrow correctly

57% of students answered this VCAA exam question correctly.

b. $v = \sqrt{rg\tan(\theta)} = \sqrt{30 \times 9.8 \times \tan(37.4°)}$ (1 MARK)

$v = 14.99$ m s^{-1}

$KE = \frac{1}{2}mv^2 = \frac{1}{2} \times 120 \times 14.99^2$ (1 MARK)

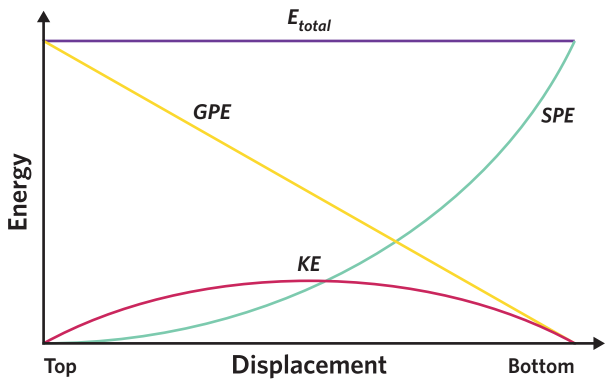
$KE = 1.349 \times 10^4 = 1.3 \times 10^4$ J (1 MARK)

c. [The rider has to travel faster than before.[1]][As design speed of the track is given by $v = \sqrt{rg\tan(\theta)}$, when the angle of inclination on the track increases the design speed also increases.[2]]

I have identified the rider has to travel faster than before.[1]

I have justified my answer using $v = \sqrt{rg\tan(\theta)}$.[2]

10.



I have drawn the graph of KE correctly.

I have drawn the graph of GPE correctly.

I have drawn the graph of SPE correctly.

I have drawn the graph of the total energy of the system correctly.

16% of students answered this VCAA exam question correctly.

FROM LESSON 12D

11. a. The minimum speed for the string to remain under tension is given by:

$v = \sqrt{gr} = \sqrt{9.8 \times 0.50}$ (1 MARK)

$v = 2.21 = 2.2$ m s^{-1} (1 MARK)

As $6.0 > 2.2$ m s^{-1}, the string will remain under tension. (1 MARK)

b. Take the zero of GPE at the bottom of the ball's motion.

$KE_{top} + GPE_{top} = KE_{bot} \Rightarrow \frac{1}{2}mu^2 + mgh = \frac{1}{2}mv^2$ (1 MARK)

$\frac{1}{2} \times 1.5 \times 6.0^2 + 1.5 \times 9.8 \times 1.0 = \frac{1}{2} \times 1.5 \times v^2$ (1 MARK)

$v = 7.46 = 7.5$ m s^{-1} (1 MARK)

12. a. Due to conservation of momentum:

$p_i = p_f \Rightarrow m_{club}u_{club} + m_{ball}u_{ball} = m_{club}v_{club} + m_{ball}v_{ball}$

$0.330 \times 70 + 0.045 \times 0 = 0.330 \times 60 + 0.045 \times v_{ball}$

$v_{ball} = 73.3 = 73$ m s^{-1}, as required.

b. $KE_i = \frac{1}{2}m_{club}u_{club}^2 + \frac{1}{2}m_{ball}u_{ball}^2 = \frac{1}{2} \times 0.330 \times 70^2 + 0$ (1 MARK)

$KE_i = 8.09 \times 10^2 = 8.1 \times 10^2$ J

$KE_f = \frac{1}{2}m_{club}v_{club}^2 + \frac{1}{2}m_{ball}v_{ball}^2$

$= \frac{1}{2} \times 0.330 \times 60^2 + \frac{1}{2} \times 0.045 \times 73^2$ (1 MARK)

$KE_f = 7.14 \times 10^2 = 7.1 \times 10^2$ J

As $KE_i \neq KE_f$, the collision was not elastic. (1 MARK)

13. a. The spring constant can be found from the gradient of the force-displacement graph:

$k = \frac{rise}{run} = \frac{y_2 - y_1}{x_2 - x_1} = \frac{250-0}{0.50-0}$ (1 MARK)

$k = 500 = 5.0 \times 10^2$ N m^{-1} (1 MARK)

FROM LESSON 12D

b. $SPE = \frac{1}{2}k(\Delta x)^2 = \frac{1}{2} \times 5.0 \times 10^2 \times 0.40^2$ (1 MARK)

$SPE = 40$ J (1 MARK)

c. Take the zero of GPE at the top of the launcher.

$SPE_i = GPE_f \Rightarrow 40 = mg\Delta h = 0.40 \times 9.8 \times \Delta h$ (1 MARK)

$\Delta h = 10.2 = 10$ m (1 MARK)

Above the launcher, the ball reaches $10.2 - 0.40 = 9.8$ m. (1 MARK)

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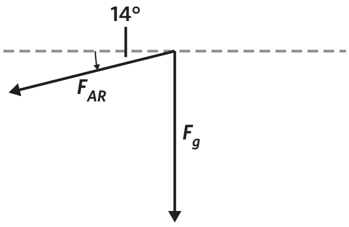
14. a. $F_{AR} = 1.0 \times 10^{-3} \times 25^2 = 0.625$ N (1 MARK)



Take down the page and to the left as positive.

In the x-direction:
$F_{net} = 0.625 \times \cos(14) = 0.606$ N (1 MARK)

In the y-direction:
$F_{net} = F_g + F_{AR,y}$ N (1 MARK)

$F_{net} = \sqrt{(F_{net,x})^2 + (F_{net,y})^2} = \sqrt{(0.606)^2 + (0.720)^2}$
(1 MARK)

$F_{net} = 0.941 = 0.94$ N (1 MARK)

b. [The force of the projectile on the air particles.[1]]

I have identified the reaction force as the force of the projectile on the air particles.[1]

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3A Gravitational fields and forces

Progress questions

1. B. In the diagram the field lines are not evenly spaced apart.

2. A. The gravitational force is always attractive.

3. C. Gravitational field lines around a planet always point towards the centre of the planet.

4. A. $g = G\frac{M}{r^2} = 6.67 \times 10^{-11} \times \frac{3.45 \times 10^{25}}{(7.91 \times 10^7)^2} = 0.37 \text{ N kg}^{-1}$.

5. A. $F = G\frac{m_1 m_2}{r^2} = 6.67 \times 10^{-11} \times \frac{2.11 \times 10^3 \times 3.45 \times 10^{25}}{(7.91 \times 10^7)^2}$
$= 776$ N.

6. D. r is the distance from the centre of one planet to the centre of the other. $6.5 \times 10^5 + 1.3 \times 10^5 + 2.4 \times 10^6 = 3.2 \times 10^6$ m

7. D. Gravitational field strength is proportional to the distance from the source squared. $g_a = g_s\left(\frac{R}{(4R)^2}\right) \Rightarrow g_a = g_s\left(\frac{1}{16}\right)$.

8. D. $g_2 = g_1\left(\frac{r_1}{r_2}\right)^2 \Rightarrow g_2 = 1.5 \times \left(\frac{r}{0.5r}\right)^2 = 6.0 \text{ N kg}^{-1}$.

9. B. $g_2 = g_1\left(\frac{r_1}{r_2}\right)^2 \Rightarrow 0.05 = 0.1 \times \frac{(2.0 \times 10^5)^2}{{r_2}^2}$
$\Rightarrow r_2 = 2.0 \times 10^5 \times \sqrt{\frac{0.1}{0.05}} = 2.8 \times 10^5$m.

Deconstructed exam-style

10. D. $r = 6.37 \times 10^6 + 4.00 \times 10^5 = 6.77 \times 10^6$ m

11. C. The correct equation to find the mass of Earth is $F = G\frac{m_1 m_2}{r^2}$

12. $r = 6.37 \times 10^6 + 4.00 \times 10^5 = 6.77 \times 10^6$ m (1 MARK)
$F = G\frac{m_E m_{ISS}}{r^2} \Rightarrow 3.65 \times 10^6 = 6.67 \times 10^{-11} \times \frac{m_E \times 4.19 \times 10^5}{(6.77 \times 10^6)^2}$
(1 MARK)
$m_E = 5.986 \times 10^{24} = 5.99 \times 10^{24}$ kg (1 MARK)

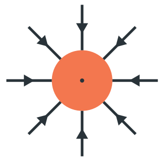
Exam-style

13. B. $g = \frac{6.67 \times 10^{-11} \times 7.34 \times 10^{22}}{(1.74 \times 10^6)^2} = 1.617 = 1.62 \text{ m s}^{-2}$
86% of students answered this VCAA exam question correctly.

14. a. $F = G\frac{m_1 m_2}{r^2} = 6.67 \times 10^{-11} \times \frac{480 \times 5.98 \times 10^{24}}{(7.00 \times 10^6)^2}$ (1 MARK)
$F = 3.907 \times 10^3 = 3.91 \times 10^3$ N (1 MARK)

b. Acceleration of the spacecraft due to Earth's gravity is equivalent to the Earth's gravitational field strength.
$g = G\frac{M}{r^2} = 6.67 \times 10^{-11} \times \frac{5.98 \times 10^{24}}{(7.00 \times 10^6)^2}$ (1 MARK)
$g = 8.140 = 8.14 \text{ m s}^{-2}$ or N kg^{-1} (1 MARK)
OR
$F = mg \Rightarrow 3.907 \times 10^3 = 480 \times g$ (1 MARK)
$g = 8.140 = 8.14 \text{ m s}^{-2}$ or N kg^{-1} (1 MARK)

15. $F = G\frac{m_s m_p}{r^2} \Rightarrow 50 = 6.67 \times 10^{-11} \times \frac{250 \times m_p}{(4.0 \times 10^6)^2}$ (1 MARK)
$m_p = 4.80 \times 10^{22} = 4.8 \times 10^{22}$ kg (1 MARK)

16. a.


I have drawn a planet with equally spaced field lines pointing towards the centre

b. Acceleration of the probe due to Mars' gravity is equivalent to Mars' gravitational field strength.
$g = G\frac{M_M}{r^2} = 6.67 \times 10^{-11} \times \frac{6.39 \times 10^{23}}{(3.39 \times 10^6 + 3.00 \times 10^5)^2}$
$g = 3.130 = 3.13 \text{ m s}^{-2}$, as required

c. $F = m_{sp} g = 1.12 \times 10^3 \times 3.130$ (1 MARK)
$F = 3.506 \times 10^3 = 3.51 \times 10^3$ N (1 MARK)
OR
$F = G\frac{m_M m_{sp}}{r^2}$
$= 6.67 \times 10^{-11} \times \frac{6.39 \times 10^{23} \times 1.12 \times 10^3}{(3.39 \times 10^6 + 3.00 \times 10^5)^2}$ (1 MARK)
$F = 3.506 \times 10^3 = 3.51 \times 10^3$ N (1 MARK)

d. $F = G\frac{m_M m_p}{r^2} = 6.67 \times 10^{-11} \times \frac{6.39 \times 10^{23} \times 80}{(3.39 \times 10^6)^2}$ (1 MARK)
$F = 2.97 \times 10^2 = 3.0 \times 10^2$ N (1 MARK)

17. $F = G\frac{m_E m_s}{r^2} \Rightarrow 340 = 6.67 \times 10^{-11} \times \frac{5.98 \times 10^{24} \times 2.00 \times 10^3}{r^2}$
(1 MARK)
$r = 4.844 \times 10^7$ m (1 MARK)
The orbital radius is the addition of the radius of Earth and the altitude of the satellite:
$r = r_e + altitude \Rightarrow 4.844 \times 10^7 = 6.37 \times 10^6 + altitude$ (1 MARK)
$altitude = 4.207 \times 10^7 = 4.21 \times 10^7$ m (1 MARK)
56% of students answered this VCAA exam question correctly.

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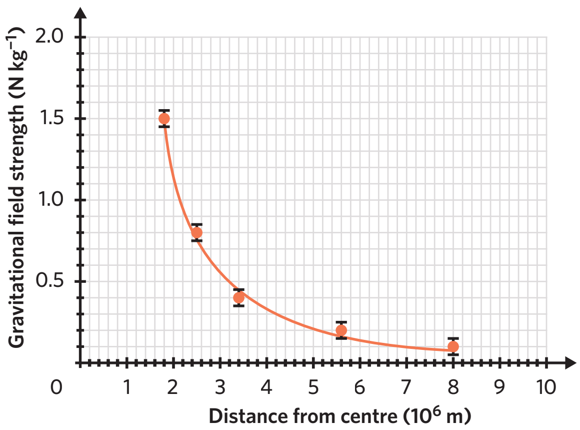
18. a.



- I have correctly labelled the axes
- I have included the correct units.
- I have included an appropriate and consistent scale on the axes.
- I have correctly plotted each data point.
- I have correctly drawn uncertainty bars in the vertical direction and to scale.
- I have drawn a non-linear line of best fit which passes through all uncertainty bars.

FROM LESSON 12D

b. Maximum mass of the Moon will be calculated using the maximum possible gravitational field strength. (1 MARK)

$g = G\frac{M}{r^2} \Rightarrow 1.55 = 6.67 \times 10^{-11} \times \frac{M}{(1.8 \times 10^6)^2}$ (1 MARK)

$M = 7.53 \times 10^{22} = 7.5 \times 10^{22}$ kg (1 MARK)

FROM LESSON 12D

19. a. [Increased.[1]]

- I have correctly identified that Mariner 10 increased its altitude.[1]

b. The factor of change will be the ratio of r_2 to r_1.

$g_2 = g_1\left(\frac{r_1}{r_2}\right)^2 \Rightarrow 0.089 = 0.80 \times \left(\frac{r_1}{r_2}\right)^2$ (1 MARK)

$\frac{r_2}{r_1} = 3.00 = 3$ (1 MARK)

Mariner 10 changed its distance from the centre of Mercury by a factor of 3. (1 MARK)

20. B. $g = G\frac{M}{r^2} \Rightarrow r \propto \sqrt{\frac{M}{g}} \Rightarrow r \propto \sqrt{\frac{5}{1.5}} = 1.83$

44% of students answered this VCAA exam question correctly.

Previous lessons

21. $F_N + mg = \frac{mv^2}{r} \Rightarrow F_N + 90 \times 9.8 = \frac{90 \times 13^2}{14}$ (1 MARK)

$F_N = \frac{90 \times 13^2}{14} - 90 \times 9.8$ (1 MARK)

$F_N = 204 = 2.0 \times 10^2$ N (1 MARK)

48% of students answered this VCAA exam question correctly.

FROM LESSON 1G

22. $\Delta GPE = mg\Delta h = 91 \times 9.8 \times (24 - 0)$ (1 MARK)

$\Delta GPE = 2.14 \times 10^4 = 2.1 \times 10^4$ J (1 MARK)

FROM LESSON 2C

3B Gravitational potential energy in uniform and non-uniform fields

Progress questions

1. A. $\Delta GPE = mg\Delta h = 0.199 \times 3.71 \times (4.00 - 0) = 2.95$ J

2. D. Since Sam is not near the surface of any planets, the gravitational field is non-uniform and we cannot use $\Delta GPE = mg\Delta h$ to calculate Sam's change in gravitational potential energy.

3. C. On the vertical axis of the graph, the units are measured in 10^2 N, so when the distance is 4×10^7 m, the force is 3.5×10^3 N

4. C. Counting the squares that are 50% or more under the line between 4×10^7 m and 12×10^7 m gives 8 squares.

5. D. Area of one square $= 2 \times 10^7 \times 5 \times 10^2 = 1.0 \times 10^{10}$ J

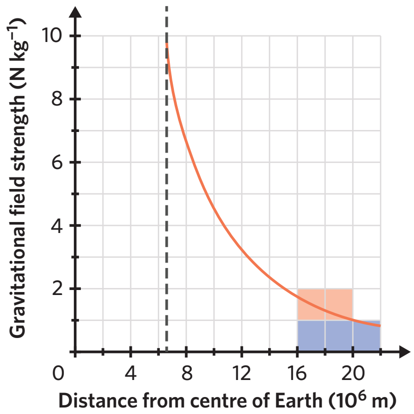
6. C. The area under a field-distance graph needs to be multiplied by mass in order to determine the gravitational potential energy.

Deconstructed exam-style

7. C. There are three squares that are 50% or more below the line between 16×10^6 m and 22×10^6 m from the centre of Earth.

8. D. Area of square $= (2 \times 10^6 \text{ m}) \times (1 \text{ N kg}^{-1}) = 2 \times 10^6 \text{ J kg}^{-1}$

9. There are 3 squares under the graph.



Area of square $= (2 \times 10^6 \text{ m}) \times (1 \text{ N kg}^{-1}) = 2 \times 10^6 \text{ J kg}^{-1}$ (1 MARK)

ΔGPE = *area under field-distance graph × mass* $= 3 \times 2 \times 10^6 \times 550$ (1 MARK)

$\Delta GPE = 3.30 \times 10^9 = 3.3 \times 10^9$ J (1 MARK)

Exam-style

10. C. As the spacecraft gets closer to the surface of a planet, the altitude decreases and gravitational potential energy is converted to kinetic energy.

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11. $\Delta GPE = mg\Delta h = 75 \times 1.9 \times (4.0 - 0)$ (1 MARK)

$\Delta GPE = 570 = 5.7 \times 10^2$ J (1 MARK)

12. a. The work done is calculated using the area under the force-distance graph.

There are approximately 15 squares under the graph (between 14 and 16 is acceptable).

Area of each square $= (2.0 \times 10^7 \text{ m}) \times (2.0 \times 10^3 \text{ N})$
$= 4.0 \times 10^{10}$ J (1 MARK)

$W = \textit{Area under the graph} = 15 \times 4.0 \times 10^{10}$ (1 MARK)

$W = 6.0 \times 10^{11}$ J (between 5.6×10^{11} J and 6.4×10^{11} J is acceptable) (1 MARK)

b. [As distance from the centre of Saturn decreases, the gravitational potential energy of an object also decreases.[1]] [Therefore the gravitational potential energy of Cassini would decrease.[2]]

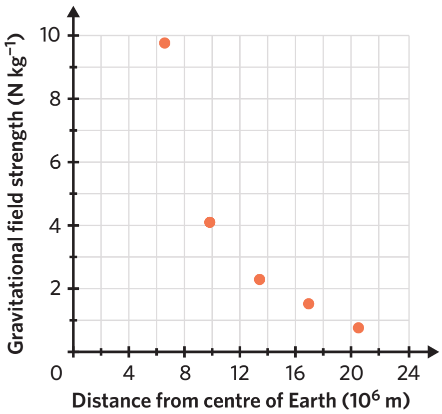
- I have identified that gravitational potential energy decreases as distance decreases.[1]
- I have related my answer to the context of the question.[2]

c. Using the graph we can see that at 8.0×10^7 m from the centre of Saturn, Casini experiences a force of approximately 14×10^3 N.

$F_g = mg \Rightarrow 14 \times 10^3 = 5700 \times g$ (1 MARK)

$g = 2.46 = 2.5$ m s^{-2} (1 MARK)

13. a.



- I have correctly labelled the horizontal and vertical axes and included correct units.
- I have included an appropriate and consistent scale on the axes so that the data takes up more than half of each axis.
- I have plotted each data point.

FROM LESSON 12D

b. [Kat's results are more accurate[1]] [because they were consistently closer than Al's data to the true values.[2]]

- I have stated who has more accurate results.[1]
- I have explained why Kat's results are more accurate.[2]

FROM LESSON 12C

14. The increase in gravitational potential energy is calculated using the area under the field-distance graph, multiplied by the mass of Wheeler.

Area under the graph is given by:

$\textit{Area} = \frac{a+b}{2} \times h = \frac{11.15 + 10.75}{2} \times 600 \times 10^3$

$\textit{Area} = 6.570 \times 10^6$ (1 MARK)

$\Delta GPE = \textit{area under field-distance graph} \times \textit{mass}$
$= 6.570 \times 10^6 \times 311$ (1 MARK)

$\Delta GPE = 2.043 \times 10^9 = 2.04 \times 10^9$ J (1 MARK)

OR

Area under the graph is given by:

$\textit{Area} = (\textit{base} \times \textit{height}) + \left(\frac{1}{2} \times \textit{base} \times \textit{height}\right)$

$= (600 \times 10^3 \times 10.75) + \left(\frac{1}{2} \times 600 \times 10^3 \times 0.4\right)$

$\textit{Area} = 6.570 \times 10^6$ (1 MARK)

$\Delta GPE = \textit{area under field-distance graph} \times \textit{mass}$
$= 6.570 \times 10^6 \times 311$ (1 MARK)

$\Delta GPE = 2.043 \times 10^9 = 2.04 \times 10^9$ J (1 MARK)

21% of students answered this VCAA exam question correctly

15. C. $F_g = mg \Rightarrow g = \frac{3.405 \times 10^3}{311} = 10.95$ m s^{-2}. Using the graph, we can see that this corresponds with an altitude of 300 km.

16. a. The change in gravitational potential energy is calculated using the area under the field-distance graph, multiplied by the mass of the Parker Solar Probe.

There are approximately 7 squares under the graph (between 6 and 7 is acceptable)

Area of each square $= (1.0 \text{ N kg}^{-1}) \times (1.0 \times 10^9 \text{ m})$
$= 1.0 \times 10^9$ J kg^{-1} (1 MARK)

$\Delta GPE = 6 \times 1.0 \times 10^9 \times 555$ (1 MARK)

$\Delta GPE = 3.33 \times 10^{12} = 3.3 \times 10^{12}$ J (1 MARK)
(between 3.3×10^{12} J and 3.9×10^{12} J is acceptable)

33% of students answered this VCAA exam question correctly

b. When distance from the Sun is 8.0×10^9 m, gravitational field strength is approximately 2.0 N kg^{-1}

$F_g = mg = 555 \times 2.0$ (1 MARK)

$F_g = 1.11 \times 10^3 = 1.1 \times 10^3$ N (1 MARK)

57% of students answered this VCAA exam question correctly

17. a. The change in gravitational potential energy is calculated using the area under the field-distance graph, multiplied by the mass of the spacecraft.

The area under the graph between 300 km to 540 km is given by:

$\textit{Area} = \frac{a+b}{2} \times h = \frac{3.2 + 2.8}{2} \times (540 \times 10^3 - 300 \times 10^3)$

$\textit{Area} = 7.200 \times 10^5$ (1 MARK)

$\Delta GPE = \textit{area under field-distance graph} \times \textit{mass}$
$= 7.200 \times 10^5 \times 600$

$\Delta GPE = 4.320 \times 10^8 = 4.32 \times 10^8$ J (1 MARK)

OR

$Area = (base \times height) + \left(\frac{1}{2} \times base \times height\right)$

$= (240 \times 10^3 \times 2.8) + \left(\frac{1}{2} \times 240 \times 10^3 \times 0.4\right)$

$Area = 7.200 \times 10^5$ (1 MARK)

$\Delta GPE = area\ under\ field\text{-}distance\ graph \times mass$
$= 7.200 \times 10^5 \times 600$

$\Delta GPE = 4.320 \times 10^8 = 4.32 \times 10^8$ J (1 MARK)

17% of students answered this VCAA exam question correctly.

b. [As the capsule descends, the gravitational potential energy is converted to kinetic energy.[1]][The kinetic energy is then converted to light/sound/heat energy[2]][due to friction between the capsule and Mercury's atmosphere.[3]]

- I have stated what the gravitational potential energy is converted to.[1]
- I have stated what the kinetic energy is converted to.[2]
- I have identified why the mechanical energy is lost.[3]

6% of students answered this VCAA question correctly.

18. a. The gravitational potential energy is calculated using the area under the field-distance graph, multiplied by the mass of the object.

There are approximately 26 squares (between 24 and 28 is acceptable)

Area of each square $= (2.0 \times 10^5\ \text{m}) \times (0.02\ \text{N kg}^{-1})$
$= 4.0 \times 10^3\ \text{J kg}^{-1}$ (1 MARK)

$\Delta GPE = \Delta KE = 26 \times 4.00 \times 10^3 \times 500 = 5.20 \times 10^7$ J (1 MARK)

$\Delta KE = 5.20 \times 10^7$ J (between 4.8×10^7 and 5.6×10^7 J is acceptable) (1 MARK)

b. $\Delta KE = KE_f - KE_i = \frac{1}{2}mv^2 - \frac{1}{2}mu^2$

$5.20 \times 10^7 = \frac{1}{2} \times 500 \times v^2 - \frac{1}{2} \times 500 \times 50.0^2$ (1 MARK)

$v = 458.8 = 459\ \text{m s}^{-1}$ (between 441 and 476 m s^{-1} is acceptable, dependent on part **a.**) (1 MARK)

19. The increase in gravitational potential energy is calculated using the area under the field-distance graph, multiplied by the mass of the person.

$\Delta GPE = \left(\frac{1}{2} \times 5.82 \times 10^7 \times 10.44\right) \times 80$ (1 MARK)

$\Delta GPE = 2.430 \times 10^{10} = 2.43 \times 10^{10}$ J (1 MARK)

25% of students answered this VCAA exam question correctly.

Previous lessons

20. $v = \frac{\Delta s}{\Delta t} \Rightarrow 20 \times \cos(40°) = \frac{25}{t} \Rightarrow 1.63\ s$

$s = ut + \frac{1}{2}at^2 = 20 \times \sin(40°) \times 1.63 + \frac{1}{2} \times (-9.8) \times 1.63^2$
(1 MARK)

$s = 7.93$ (1 MARK)

Since the ball is launched from a height of 2.0 m:
$h = 2.0 + 7.93 = 9.93 = 9.9$ m (1 MARK)

FROM LESSON 1H

21. $GPE_i = KE_f$

$KE_f = mgh_i = 252 \times 1.214 \times 5.00$ (1 MARK)

$KE = 1.529 \times 10^3 = 1.53 \times 10^3$ J (1 MARK)

FROM LESSON 2C

3C Orbital motion

Progress questions

1. D. The force causing a satellite to stay in orbit is the force due to gravity.

2. D. If the satellite is too fast, it will no longer be at the orbital speed and will travel away from the body it orbits.

3. B. $v = \sqrt{\frac{GM}{r}} = \sqrt{\frac{6.67 \times 10^{-11} \times 5.98 \times 10^{24}}{4.56 \times 10^7}} = 2.96 \times 10^3\ \text{m s}^{-1}$

4. D. $a = \frac{v^2}{r} = \frac{(1.59 \times 10^3)^2}{8.05 \times 10^6} = 0.314 = 3.14 \times 10^{-1}\ \text{m s}^{-2}$

5. B. When r increase, as $v \propto = \frac{1}{\sqrt{r}}$, speed decreases, and as $T \propto \sqrt{r^3}$, the period increases.

6. C. $4\pi^2 r^3 = GMT^2 \Rightarrow 4\pi^2 \times (3.55 \times 10^8)^3 = 6.67 \times 10^{-11} \times 1.02 \times 10^{26} \times T^2$

$T = 5.10 \times 10^5$ s

7. A. Geostationary satellites must orbit around the centre of mass, i.e. around the equator of Earth.

Deconstructed exam-style

8. $r = 6.37 \times 10^6 + 700 \times 10^3 = 7.07 \times 10^6$ m

9. D. We know the mass of Earth and the orbital radius so the most suitable equation to find the orbital period of CALIPSO is $4\pi^2 r^3 = GMT^2$.

10. $r = 6.37 \times 10^6 + 700 \times 10^3 = 7.07 \times 10^6$ m (1 MARK)
$4\pi^2 r^3 = GMT^2$

$4\pi^2 \times (7.07 \times 10^6)^3 = 6.67 \times 10^{-11} \times 5.98 \times 10^{24} \times T^2$
(1 MARK)

$T = 5.914 \times 10^3 = 5.91 \times 10^3$ s (1 MARK)

38% of students answered this VCAA exam question correctly.

Exam-style

11. D. The orbital period of the satellite must be the same as day on Saturn:
$T = (10 \times 60 \times 60) + (41 \times 60) + 57 = 3.85 \times 10^4 = 3.9 \times 10^4$ s

12. $4\pi^2 r^3 = GMT^2$

$4\pi^2 r^3 = 6.67 \times 10^{-11} \times 5.98 \times 10^{24} \times (2.376 \times 10^6)^2$ (1 MARK)

$r = 3.849 \times 10^8 = 3.85 \times 10^8$ m (1 MARK)

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13. [Georgina is correct, and both Alistair and Zev are incorrect.[1]] [A satellite's orbital radius is independent of its mass.[2]] [The radius of a satellite's orbit is determined by only the mass of the object being orbited, and the period (or speed) of the satellite in orbit, which is given by the relationship $r = \sqrt[3]{\frac{GMT^2}{4\pi^2}}$ (or $r = \frac{GM}{v^2}$).[3]]

- I have identified which statements are correct and which are incorrect.[1]
- I have stated that orbital radius is independent of mass.[2]
- I have supported my answer with a relevant formula.[3]

23% of students answered this VCAA exam question correctly

14. a. $T = 365 \text{ days} \times 24 \text{ hr/day} \times 60 \text{ min/hr} \times 60 \text{ s/min}$
$= 3.154 \times 10^7 \text{ s}$ (1 MARK)

$4\pi^2 r^3 = GMT^2$

$4\pi^2 r^3 = 6.67 \times 10^{-11} \times 1.99 \times 10^{30} \times (3.154 \times 10^7)^2$ (1 MARK)

$r = 1.495 \times 10^{11} = 1.50 \times 10^{11} \text{ m}$ (1 MARK)

b. $v = \sqrt{\frac{GM}{r}} = \sqrt{\frac{6.67 \times 10^{-11} \times 1.99 \times 10^{30}}{1.495 \times 10^{11}}}$ (1 MARK)

$v = 2.979 \times 10^4 = 2.98 \times 10^4 \text{ m s}^{-1}$ (1 MARK)

OR

$v = \frac{2\pi r}{T} = \frac{2\pi \times 1.495 \times 10^{11}}{3.154 \times 10^7}$ (1 MARK)

$v = 2.979 \times 10^4 = 2.98 \times 10^4 \text{ m s}^{-1}$ (1 MARK)

15. a. $4\pi^2 r^3 = GMT^2$

$4\pi^2 \times (1.81 \times 10^8)^3 = 6.67 \times 10^{-11} \times M \times (4.32 \times 10^4)^2$ (1 MARK)

$M = 1.881 \times 10^{27} = 1.88 \times 10^{27} \text{ kg}$ (1 MARK)

55% of students answered this VCAA exam question correctly.

b. $a = \frac{4\pi^2 r}{T^2} = \frac{4\pi^2 \times (1.881 \times 10^8)}{(4.32 \times 10^4)^2}$ (1 MARK)

$a = 3.829 = 3.83 \text{ m s}^{-2}$ (1 MARK)

16. a. $gradient = \frac{y_2 - y_1}{x_2 - x_1} = \frac{300 \times 10^{13} - 0}{10 \times 10^{33} - 0}$

$gradient = 3.0 \times 10^{-19} \text{ s}^2 \text{ m}^{-3}$, as required.

37% of students answered this VCAA exam question correctly.

FROM LESSON 12D

b. $gradient = \frac{T^2}{r^3} = 3.0 \times 10^{-19}$

$4\pi^2 r^3 = GMT^2 \Rightarrow \frac{T^2}{r^3} = \frac{4\pi^2}{GM}$ (1 MARK)

$3.0 \times 10^{-19} = \frac{\pi^2}{6.67 \times 10^{-11} \times M}$ (1 MARK)

$M = 2.0 \times 10^{30} \text{ kg}$ (1 MARK)

34% of students answered this VCAA exam question correctly.

17. a. [The centripetal force is Earth's gravity acting on the satellite.[1]] [This acts towards the centre of the Earth.[2]]

- I have identified the only force acting on a satellite.[1]
- I have described the direction that the centripetal force acts.[2]

38% of students answered this VCAA exam question correctly.

b. $r = 6.37 \times 10\ 6 + 2.02 \times 10\ 7 = 2.657 \times 10\ 7 \text{ m}$ (1 MARK)

$4\pi^2 r^3 = GMT^2\ 4\pi^2 \times (2.657 \times 10^7)^3$
$= 6.67 \times 10^{-11} \times 5.98 \times 10^{24} \times T^2$ (1 MARK)

$T = 4.309 \times 10^4 = 4.31 \times 10^4 \text{ s}$ (1 MARK)

33% of students answered this VCAA exam question correctly.

18. [The satellite's speed must increase.[1]] [According to the formula $v = \sqrt{\frac{GM}{r}}$,[2]] [if the radius of the orbit decreases, the speed of the spacecraft must increase.[3]]

- I have identified that the satellite's speed will increase.[1]
- I have identified the relationship between speed and radius.[2]
- I have justified my answer.[3]

19. $r = 1.74 \times 10^6 + 121 \times 10^3 = 1.86 \times 10^6 \text{ m}$ (1 MARK)

$4\pi^2 r^3 = GMT^2$

$4\pi^2 \times (1.86 \times 10^6)^3 = 6.67 \times 10^{-11} \times 7.36 \times 10^{22} \times T^2$ (1 MARK)

$T = 7.199 \times 10^3 = 7.20 \times 10^3 \text{ s}$ (1 MARK)

20. a. [In order for the satellite to remain stationary above a point on Earth, the centripetal force must be directed towards the centre of Earth[1]] [and so the satellite must orbit above the equator to remain in the same plane as the Earth's rotation.[2]]

- I have described the direction of the centripetal force.[1]
- I have identified that the satellite must orbit the equator to remain in the same axis/plane of rotation as the Earth.[2]

2% of students answered this VCAA exam question correctly.

b. $4\pi^2 r^3 = GMT^2$

$4\pi^2 r^3 = 6.67 \times 10^{-11} \times 4.867 \times 10^{24} \times (2.10 \times 10^7)^2$ (1 MARK)

$r = 1.537 \times 10^9 \text{ m}$

Let R_V be the radius of Venus, and let d be the altitude of the geostationary orbit

$r = R_V + d \Rightarrow 1.537 \times 10^9 = 6.05 \times 10^6 + d$ (1 MARK)

$d = 1.531 \times 10^9 = 1.53 \times 10^9 \text{ m}$ (1 MARK)

56% of students answered this VCAA exam question correctly.

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c. $v = \frac{2\pi r}{T} = \frac{2\pi \times 1.537 \times 10^9}{2.10 \times 10^7}$

$v = 460.0 = 460 \text{ m s}^{-1}$

OR

$v = \sqrt{\frac{GM}{r}} = \sqrt{\frac{6.67 \times 10^{-11} \times 4.876\ 10^{24}}{1.537 \times 10^9}}$ (1 MARK)

$v = 460 = 460 \text{ m s}^{-1}$ (1 MARK)

54% of students answered this VCAA exam question correctly.

Previous lessons

21. **a.** Take upwards as positive. $u_y = 30 \times \sin(20°) = 10.3 = 10 \text{ m s}^{-1}$, as required.

b. Take upwards as positive. Vertical velocity is zero at maximum height.

$v^2 = u^2 + 2as \Rightarrow 0^2 = 10^2 + 2 \times (-9.8) \times s$ (1 MARK)

$s = 5.10 = 5.1 \text{ m}$ (1 MARK)

FROM LESSON 1H

22. **a.** Kinetic energy is a maximum at the bottom of the ramp, before colliding with the crash mat.

$KE_{bot} = GPE_{top}$

$\frac{1}{2}mv^2 = mgh_{top} \Rightarrow \frac{1}{2} \times 67 \times v^2 = 67 \times 9.8 \times 13$ (1 MARK)

$v = 15.96 = 16 \text{ m s}^{-1}$ (1 MARK)

b. Compression is a maximum when the skateboarder has (momentarily) come to rest at the end of the ramp.

$GPE_{end} + KE_{end} + SPE_{end} = GPE_{top} + KE_{top} + SPE_{top}$

$SPE_{end} = GPE_{top}$

$\frac{1}{2}k(\Delta x)^2 = mgh_{top} \Rightarrow \frac{1}{2} \times 500 \times (\Delta x)^2 = 67 \times 9.8 \times 13$
(1 MARK)

$x = 5.84 = 5.8 \text{ m}$ (1 MARK)

FROM LESSON 2D

Chapter 3 review

Section A

1. C. Gravity acts all throughout space, not just within the atmosphere of planets.

2. B. Since $4\pi^2r^3 = GMT^2$, to decrease T, r would need to decrease.

3. C. Since $v = \sqrt{\frac{GM}{r}}$, the speed of a satellite is independent of its mass and hence, the speed will not change if the mass of the satellite is reduced.

4. D. $F = G\frac{m_1m_2}{r^2} = 6.67 \times 10^{-11} \times \frac{100 \times 10^{-3} \times 1000 \times 10^{-3}}{(10 \times 10^{-3})^2}$
$= 6.67 \times 10^{-8} = 6.7 \times 10^{-8} \text{ N}$

84% of students answered this VCAA exam question correctly.

5. D. $F_2 = F_1\left(\frac{r_1}{r_2}\right)^2 = 450 \times \left(\frac{R}{\frac{1}{4}R}\right)^2 = 7.20 \times 10^3 \text{ N}$

Section B

6. **a.** $4\pi^2r^3 = GMT^2$

$4\pi^2r^3 = 6.67 \times 10^{-11} \times 4.87 \times 10^{24} \times (8.64 \times 10^4)^2$

$r = 3.946 \times 10^7 = 3.95 \times 10^7$ m, as required.

b. $F = G\frac{m_1m_2}{r^2} = 6.67 \times 10^{-11} \times \frac{4.87 \times 10^{24} \times 517}{(3.95 \times 10^7)^2}$ (1 MARK)

$F = 107.6 = 108 \text{ N}$ (1 MARK)

c. $v = \frac{2\pi r}{T} = \frac{2\pi \times 3.95 \times 10^7}{8.64 \times 10^4}$ (1 MARK)

$v = 2.872 \times 10^3 = 2.87 \times 10^3 \text{ m s}^{-1}$ (1 MARK)

7. **a.** The change in gravitational potential energy is calculated using the area under the field-distance graph, multiplied by the mass of the Falcon 9 rocket.

Area under the graph is estimated as 45 boxes (between 43 and 47 is acceptable).

Each box $= (1.0 \times 10^5 \text{ m}) \times (1.0 \text{ N kg}^{-1}) = 1.0 \times 10^5 \text{ J kg}^{-1}$
(1 MARK)

$\Delta GPE = 45 \times 1.0 \times 10^5 \times 4.49 \times 10^5$ (1 MARK)

$\Delta GPE = 2.02 \times 10^{12} = 2.0 \times 10^{12}$ J (between 1.9×10^{12} J and 2.1×10^{12} J is acceptable) (1 MARK)

OR

Area under the graph can be calculated using the area of a trapezium.

$Area = \left(\frac{9.8 + 8.5}{2}\right) \times 5 \times 10^5 = 45.75 \times 10^5 \text{ J kg}^{-1}$ (1 MARK)

$\Delta GPE = 45.75 \times 10^5 \times 4.9 \times 10^5$ (1 MARK)

$\Delta GPE = 2.02 \times 10^{12} = 2.0 \times 10^{12} \text{ J}$ (1 MARK)

b. $v = \sqrt{\frac{GM}{r}} = \sqrt{\frac{6.67 \times 10^{-11} \times 5.98 \times 10^{24}}{5.00 \times 10^5 + 6.37 \times 10^6}}$ (1 MARK)

$v = 7620 \text{ m s}^{-1}$

$KE = \frac{1}{2}mv^2 = \frac{1}{2} \times 4.49 \times 10^5 \times 7620^2$ (1 MARK)

$KE = 1.303 \times 10^{13} = 1.30 \times 10^{13} \text{ J}$ (1 MARK)

8. **a.** From graph $F_g = 0.6 \times 10^2$ N (1 MARK)

Values between 0.5×10^2 N and 0.75×10^2 N acceptable.

$F_g = mg \Rightarrow 0.6 \times 10^2 = 450 \times g$

$g = 0.133 = 0.13 \text{ m s}^{-2}$ or N kg^{-1} (between 0.11 m s^{-2} and 0.17 m s^{-2} is acceptable) (1 MARK)

FROM LESSON 12D

b. The change in kinetic energy is calculated using the area under the force-distance graph.

Area under the graph is estimated as 7 boxes (between 6 and 8 is acceptable).

Each box $= (2.0 \times 10^6 \text{ m}) \times (0.5 \times 10^2 \text{ N}) = 1.0 \times 10^8 \text{ J}$
(1 MARK)

$\Delta KE = 7 \times 1.0 \times 10^8 = 7 \times 10^8$ J (between 6×10^8 J and 8×10^8 J is acceptable) (1 MARK)

c. $g = G\frac{M}{r^2} = 6.67 \times 10^{-11} \times \frac{1.35 \times 10^{23}}{(2.57 \times 10^6)^2}$ (1 MARK)

$g = 1.363 = 1.36 \text{ N kg}^{-1}$ (or m s^{-2}) (1 MARK)

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9. **a.** $g = G\frac{M}{r^2} = 6.67 \times 10^{-11} \times \frac{5.98 \times 10^{24}}{(6.37 \times 10^6 + 400 \times 10^3)^2}$
(1 MARK)

$g = 8.703 = 8.70 \text{ N kg}^{-1}$ (1 MARK)

b. [No, the force of gravity is not zero.[1]][Astronauts on the ISS experience zero normal force (the force of gravity is the only force acting on them)[2]][which feels like gravity is not acting on them.[3]]

- I have stated that the gravity force is not zero.[1]
- I have identified that there is no normal force.[2]
- I have identified why astronauts do not feel gravity acting on them.[3]

42% of students answered this VCAA exam question correctly.

10. Use inverse square law to find gravitational field strength at distance $10R_X$.

$g_2 = g_1\left(\frac{r_1}{r_2}\right)^2 = 50 \times \left(\frac{R_X}{10R_X}\right)^2$ (1 MARK)

$g_2 = 0.50 \text{ N kg}^{-1}$ (1 MARK)

$F_g = mg = 4.0 \times 10^3 \times 0.50 = 2.0 \times 10^3 \text{ N}$ (1 MARK)

11. **a.** $T = 24$ hours

$T = 24 \times 60 \times 60 = 8.64 \times 10^4 \text{ s}$ (1 MARK)

b. $4\pi^2 r^3 = GMT^2$

$4 \times \pi^2 \times r^3 = 6.67 \times 10^{-11} \times 5.98 \times 10^{24} \times (8.64 \times 10^4)^2$
(1 MARK)

$r = 4.225 \times 10^7 \text{ m}$ (1 MARK)

Distance above surface $= r - R_E = 4.225 \times 10^7 - 6.37 \times 10^6 = 3.588 \times 10^7 = 3.59 \times 10^7 \text{ m}$ (1 MARK)

c. [The period of the orbit must equal the period of rotation of the Earth ($T = 24$ hours).[1]][The satellite must orbit directly above the equator.[2]][The satellite must orbit in the same direction as Earth's rotation.[3]]

- I have stated the satellite's period of orbit must be 24 hours.[1]
- I have stated the satellite must orbit directly above the equator.[2]
- I have stated the satellite must orbit in the same direction as the Earth's rotation.[3]

12. $v = \sqrt{\frac{GM}{r}} \Rightarrow \frac{57\,936}{3.6} = \sqrt{\frac{6.67 \times 10^{-11} \times 1.30 \times 10^{22}}{r}}$ (1 MARK)

$r = 3.348 \times 10^3 = 3.35 \times 10^3 \text{ m}$

3.35×10^3 m is less than the radius of Pluto.
Therefore, New Horizons cannot orbit Pluto. (1 MARK)

OR

$v = \sqrt{\frac{GM}{r}} = \sqrt{\frac{6.67 \times 10^{-11} \times 1.30 \times 10^{22}}{1.19 \times 10^6}}$ (1 MARK)

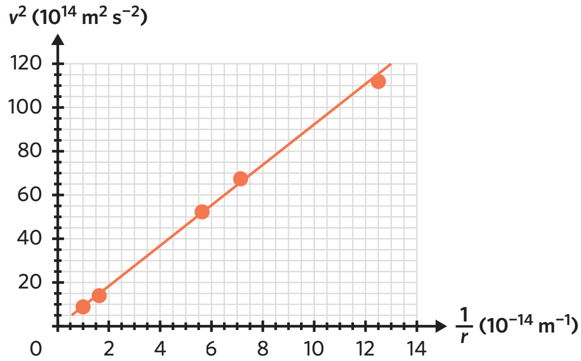
$v = 853.6 \text{ m s}^{-1} = 3073 \text{ km h}^{-1}$ in order to orbit at the surface of the planet.

At 57 936 km h^{-1}, New Horizons would need to be orbiting inside Pluto. (1 MARK)

13. **a.** $v = \frac{2\pi r}{T} \Rightarrow 3.8 \times 10^7 = \frac{2\pi \times 6.4 \times 10^{13}}{T}$ (1 MARK)

$T = 1.06 \times 10^7 = 1.1 \times 10^7\text{s}$ (1 MARK)

b.



- I have correctly labelled the horizontal axis and included correct units.
- I have correctly labelled the vertical axis and included correct units.
- I have included an appropriate and consistent scale on the axes.
- I have plotted each point of data.
- I have drawn a straight line of best fit.

FROM LESSON 12D

68% of students answered this VCAA exam question correctly.

c. $gradient = \frac{rise}{run} = \frac{(93 - 5) \times 10^{14}}{(10 - 0.5) \times 10^{-14}}$

Any substitution using two points from the line of best fit is acceptable.

$gradient = 9.26 \times 10^{28} = 9.3 \times 10^{28} \text{ m}^3 \text{ s}^{-2}$, as required.

37% of students answered this VCAA exam question correctly.

FROM LESSON 12D

d. $v^2 = GM \times \frac{1}{r} \Rightarrow \text{gradient} = GM$ (1 MARK)

$9.3 \times 10^{28} = 6.67 \times 10^{-11} \times M$ (1 MARK)

$M = 1.39 \times 10^{39} = 1.4 \times 10^{39} \text{ kg}$ (1 MARK)

34% of students answered this VCAA exam question correctly.

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4A Electric fields

Progress questions

1. B. $E = k\frac{Q}{r^2} = 8.99 \times 10^9 \times \frac{3.0 \times 10^{-17}}{(3.5)^2} = 2.2 \times 10^{-8}$ N C^{-1}.

2. A. As electrons are like charges, they repel. $F_E = k\frac{q_1 q_2}{r^2}$

$= 8.99 \times 10^9 \times \frac{1.6 \times 10^{-19} \times 1.6 \times 10^{-19}}{\left(\frac{45}{100}\right)^2} = 1.1 \times 10^{-27}$ N.

3. C. The electric field line at point X is orientated in the direction of C.

4. F. The direction of the electric force on a negatively charged particle is opposite to the direction the electric field is oriented at that point.

5. A. When a potential difference is applied between two parallel plates, the resulting electric field is static and uniform.
$E = \frac{V}{d} = \frac{5.0}{\left(\frac{55}{100}\right)} = 9.1$ V m^{-1}.

6. B. The electron will only be accelerated to the right if the plate on the right is positive and the plate on the left is negative. Applying a greater voltage between the plates increases the speed of the electron, as $\frac{1}{2}mv^2 = qV$.

Deconstructed exam-style

7. $m_e = 9.1 \times 10^{-31}$ kg, $q_e = 1.6 \times 10^{-19}$ C.

8. $\frac{1}{2}mv^2 = qV_0$.

9. $\frac{1}{2}mv^2 = qV_0$

$\frac{1}{2} \times 9.1 \times 10^{-31} \times (2.0 \times 10^7)^2 = 1.6 \times 10^{-19} \times V_0$ (1 MARK)

$V_0 = 1.14 \times 10^3 = 1.1 \times 10^3$ V (1 MARK)

The accelerating voltage is 1.1 kV. (1 MARK)

Exam-style

10. D. A dipole is created when electric field lines are directed both towards and away from charged particles. This is possible when two oppositely charged particles are placed close together.

11. a. $E = k\frac{Q}{r^2} = 8.99 \times 10^9 \times \frac{1.6 \times 10^{-19}}{\left(\frac{12}{100}\right)^2}$ (1 MARK)

$E = 9.99 \times 10^{-8} = 1.0 \times 10^{-7}$ N C^{-1} or V m^{-1}. (1 MARK)

b. $F = qE = 1.6 \times 10^{-19} \times 9.99 \times 10^{-8}$

$F = 1.60 \times 10^{-26} = 1.6 \times 10^{-26}$ N (1 MARK)

The direction of the electric force on the proton is to the left, as it is attracted to the electron. (1 MARK)

OR

$F = k\frac{q_1 q_2}{r^2} = 8.99 \times 10^9 \times \frac{1.6 \times 10^{-19} \times 1.6 \times 10^{-19}}{\left(\frac{12}{100}\right)^2}$

$F = 1.60 \times 10^{-26} = 1.6 \times 10^{-26}$ N (1 MARK)

The direction of the electric force on the proton is to the left, as it is attracted to the electron. (1 MARK)

12. C. Electric field lines point toward negative charges. In between two equally charged particles the electric field strength of the charged particles is zero.

13. a. $E = \frac{V}{d} = \frac{5000}{\left(\frac{10}{100}\right)}$

$E = 5.00 \times 10^4 = 5.0 \times 10^4$ (1 MARK)

The electric field between the plates is 5.0×10^4 N C^{-1} or V m^{-1}. (1 MARK)

b. $F = qE = 1.6 \times 10^{-19} \times 5.0 \times 10^4$ (1 MARK)

$F = 8.00 \times 10^{-15} = 8.0 \times 10^{-15}$ N (1 MARK)

c. $\frac{1}{2}mv^2 = qV$

$\frac{1}{2} \times 9.1 \times 10^{-31} \times v^2 = 1.6 \times 10^{-19} \times 5000$ (1 MARK)

$v = 4.19 \times 10^7 = 4.2 \times 10^7$ m s^{-1} (1 MARK)

14. A. The electric field is uniform between the plates.

56% of students answered this VCAA exam question correctly.

15.

I have drawn a horizontal arrow to the right.

63% of students answered this VCAA exam question correctly.

16. a. [The direction of the electric field is to the right.[1]]

I have identified the direction of the electric field is to the right.[1]

b. $F = k\frac{q_1 q_2}{r^2} = 8.99 \times 10^9 \times \frac{3.4 \times 10^{-8} \times (-5.4 \times 10^{-9})}{(3.0 \times 10^{-3})^2}$

$F = -0.183 = -0.18$N (1 MARK)

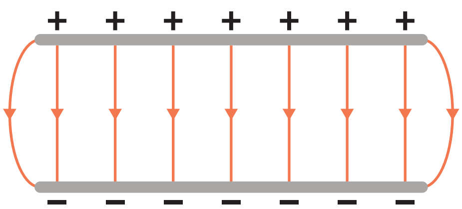
The force on the larger sphere is 0.18 N to the left. (1 MARK)

c. From the inverse square law:

$F_2 = F_1\left(\frac{r_1}{r_2}\right)^2 = 0.183 \times \left(\frac{3.0 \times 10^{-3}}{3 \times 3.0 \times 10^{-3}}\right)^2$ (1 MARK)

$F_2 = 2.00 \times 10^{-2} = 2.0 \times 10^{-2}$ N (1 MARK)

17. a.



I have drawn electric field lines that do not touch or cross and arrowheads to show direction.

I have drawn parallel field lines between the two plates, with two curved lines on either end.

b. $E = \frac{V}{d} = \frac{1.67 \times 10^3}{0.30}$

$E = 5.57 \times 10^3 = 5.6 \times 10^3$ V m^{-1} or N C^{-1}

54% of students answered this VCAA exam question correctly.

c. The gravitational force on the sphere is equivalent to the electric force on it.

$mg = qE \Rightarrow m \times 9.8 = 4.00 \times 10^{-5} \times 5.6 \times 10^{3}$ (1 MARK)

$m = 2.29 \times 10^{-2} = 2.3 \times 10^{-2}$ kg (1 MARK)

18. a. $W = \Delta KE = \frac{1}{2}m(\Delta v)^2$

$W = \frac{1}{2} \times 9.1 \times 10^{-31} \times (6.3 \times 10^{6} - 1.2 \times 10^{6})^2$ (1 MARK)

$W = 1.18 \times 10^{-17}$ J

$W = qEd$

$1.18 \times 10^{-17} = 1.6 \times 10^{-19} \times 2.0 \times 10^{3} \times d$ (1 MARK)

$d = 3.70 \times 10^{-2} = 3.7 \times 10^{-2}$ m (1 MARK)

b. [As the electric field in the particle accelerator is uniform, the electric field is constant in magnitude and direction.[1]] [As a result, the electric force acting on the electron, $F = qE$, is also constant in magnitude and direction as it is accelerated.[2]]

- I have identified the electric field has a constant magnitude and direction in the particle accelerator.[1]
- I have determined the electric force acting on the electron as a result is also constant in magnitude and direction.[2]

19. D. As the right hand charge has four times the magnitude of the left hand charge, the point at which the electric field is zero is when the location of the point is twice as far from the right hand charge than the left hand charge. This occurs at $d = \frac{1}{3} \times 12 = 4$ cm.

18% of students answered this VCAA exam question correctly.

20. a. $E = k\frac{Q}{r^2}$

$4.4 \times 10^{6} = 8.99 \times 10^{9} \times \frac{Q}{(0.50)^2}$ (1 MARK)

$Q = 1.22 \times 10^{-4}$ C

The number of protons that would produce the same electric field strength must have the same overall charge as the Van de Graaf generator:

$Q = n_p q_p \Rightarrow 1.22 \times 10^{-4} = n_p \times 1.6 \times 10^{-19}$ (1 MARK)

$n_p = 7.63 \times 10^{14} = 7.6 \times 10^{14}$ (1 MARK)

b. [Given the current is only a few microamperes and the severity of electric shock is determined by the size of current, the demonstration is unlikely to pose any serious risk to the students.[1]] [However, some students may have undiagnosed heart conditions or other medical issues that make the shock dangerous.[2]] [Even though the chances of a student having an undiagnosed heart condition is small it still outweighs any benefit students' might get from the demonstration, therefore the demonstration is not safe to use in the classroom.[3]]

- I have identified one reason why the demonstration might be safe for the classroom.[1]
- I have identified one reason why the demonstration is not safe for the classroom.[2]
- I have used the information to determine that the demonstration is not safe for the classroom.[3]

FROM LESSON 12A

Previous lessons

21. [Newton's third law of motion states that every force has an equal and opposite reaction force.[1]] [As the forces acting on each car is an action-reaction pair, the cars will experience the same magnitude of force in the opposite direction to one another.[2]] [As $I = F\Delta t$, both cars experience an impulse equal in magnitude but opposite in direction, as the force is exerted on one another for the same period of time.[3]]

- I have identified Newton's third law of motion.[1]
- I have determined both cars experience the same magnitude of force in the opposite directions to one another.[2]
- I have determined both cars experience the same magnitude of impulse in the opposite directions to one another, as $I = F\Delta t$.[3]

FROM LESSON 1I

22. D. As $F_{net} = ma$, the acceleration is zero when there is no net force acting on the mass. This occurs when $F_s = F_g$.

FROM LESSON 2E

4B Magnetic fields

Progress questions

1. D. The dots can be thought of as representing the point of an arrow coming out of the page.
2. B. Like poles repel while opposite poles attract.
3. D. Magnetic field lines run from north poles to south poles.
4. C. As magnetic field lines point out of the top and into the bottom of the magnet, the top must be a north pole and the bottom must be a south pole.
5. C. We can apply the right-hand grip rule to find the magnetic field produced by a current-carrying wire.
6. C. Applying the right-hand grip rule, the current runs clockwise when viewed from the left.
7. C. We can apply the right-hand coil rule to find the magnetic field produced by a solenoid.
8. A. The current must run to the right through the battery, out of the positive terminal.

Deconstructed exam-style

9. [Two magnets will attract each other if two opposite poles are placed close to one another.[1]]

- I have described the conditions in which two magnets attract.[1]

10. B. If the magnetic field around the solenoid points to the right at the bar magnet, it can be modelled as a north pole. This would mean the two would attract each other.

11. [Using the right-hand coil rule, the direction of the solenoid's magnetic field points to the right through the solenoid.[1]]

I have stated the direction of the magnetic field through the solenoid.[1]

12. [By the right-hand coil rule, the direction of the solenoid's magnetic field points to the right through the solenoid.[1]] [This means the right-hand side of the solenoid close to the bar magnet can be modelled as its north pole.[2]] [As opposite poles attract one another, the south pole of the bar magnet and the north pole of the solenoid will attract each other.[3]]

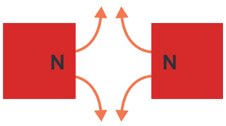
I have determined the direction of the solenoid's magnetic field using the right-hand coil rule.[1]

I have determined that the solenoid can be modelled with a north pole on the right-hand side.[2]

I have explained that the bar magnet and solenoid will attract each other.[3]

Exam-style

13. a. i.



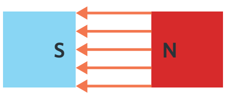
I have drawn four field lines that do not touch or cross.

I have drawn a non-uniform magnetic field directed away from the north poles.

ii. [Non-uniform.[1]]

I have identified the magnetic field as non-uniform.[1]

b. i.



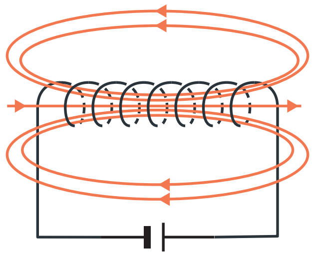
I have drawn five field lines that do not touch or cross.

I have drawn a uniform magnetic field directed from the north pole to the south pole.

ii. [Changing.[1]]

I have identified the magnetic field as changing.[1]

c. i.



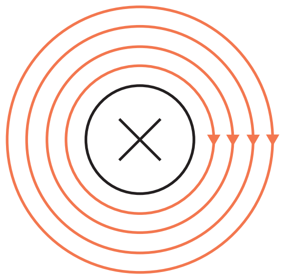
I have drawn four field lines that do not touch or cross.

I have drawn a magnetic field in the direction determined by the right-hand coil rule.

ii. [Non-uniform.[1]]

I have identified the magnetic field as non-uniform.[1]

d. i.



I have drawn four field lines that do not touch or cross.

I have drawn a circular magnetic field lines around the wire, with direction determined by the right-hand grip rule.

ii. [Changing.[1]]

I have identified the magnetic field as changing.[1]

14. A. Using the right hand grip rule, the magnetic field is anticlockwise when viewed from the left.

90% of students answered this VCAA exam question correctly.

15. [Since *W* and *X* are repelling each other, they must be the same pole. Since the field lines are going into the poles, both *W* and *X* are south poles.[1]] [Since the field lines are uniform and running from *Y* to *Z*, *Y* is a north pole and *Z* is a south pole.[2]]

I have identified that both *W* and *X* are south poles.[1]

I have identified that *Y* is a north pole, and *Z* is a south pole.[2]

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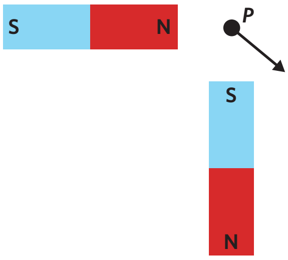
16. [The north point of the compass would point in direction *W*.[1]] [Using the right-hand coil rule, the magnetic field of the solenoid would be pointing to the left, which is the direction of *W*.[2]]

- I have determined that the north point of the compass would point in direction *W*.[1]
- I have justified my answer.[2]

17. [By the right-hand grip rule, the current is travelling upwards.[1]]

- I have determined the current is travelling upwards, using the right-hand grip rule.[1]

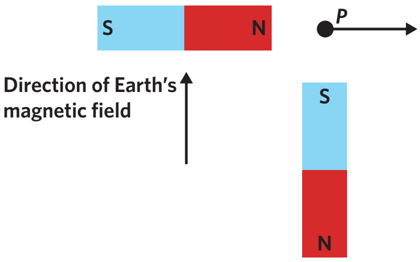
18. a.



- I have drawn an arrow at *P* pointing downwards and to the right.

44% of students answered this VCAA exam question correctly.

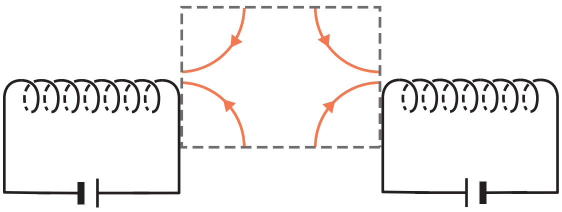
b.



- I have drawn an arrow at *P* pointing to the right.

37% of students answered this VCAA exam question correctly.

19.



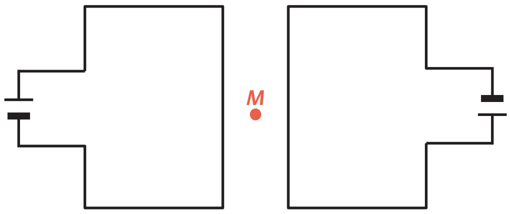
- I have drawn four field lines that do not touch or cross.
- I have drawn a magnetic field in the direction determined by the right-hand coil rule applied to each solenoid.

20. a. [When current is directed in opposite directions around each loop of wire, by applying the right-hand grip rule to each side of the loop closest to point *M*, we find the direction of the magnetic field at that point due to each loop is opposite to one another.[1]] [As the magnetic fields are vector fields, the magnetic field due to each wire cancels out with one another.[2]] [As a result, there is no detected change to the strength of the magnetic field at point *M*.[3]]

- I have used the right-hand grip rule to identify the direction of the magnetic field due to both loops of wire are in opposite directions.[1]
- I have determined the resultant magnetic field at point *M* due to the loops of wire is zero.[2]
- I have explained why there is no change to the strength of the magnetic field at point *M*.[3]

FROM LESSON 12A

b.



- I have drawn the power supply connected to the left-hand side wire correctly.
- I have drawn the power supply connected to the right-hand side loop correctly.

FROM LESSON 12A

Previous lessons

21. $I = \Delta p = m\Delta v$

$I = 50 \times 10^{-3} \times (13 - (-14))$ (1 MARK)

$I = 1.35 = 1.4$ N s (1 MARK)

FROM LESSON 1I

22. $F_2 = F_1\left(\frac{r_1}{r_2}\right)^2$

$F_2 = 30 \times \left(\frac{r}{2r + r}\right)^2$ (1 MARK)

$F_2 = 3.33 = 3.3$ N (1 MARK)

FROM LESSON 3A

4C Magnetic forces on charged particles

Progress questions

1. C. Using the right-hand palm rule, the direction of the force on particle *X* is out of the page.

2. C. As the particle is moving perpendicular to the direction of the magnetic field, the magnetic force is found using $F = qvB = 1 \times 1.4 \times 10^5 \times 0.60 = 8.4 \times 10^4$ N.

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3. A. As the particle is moving parallel to the direction of the magnetic field, the magnetic force on particle Z is 0 N.

4. D. Applying the right-hand grip rule, the magnetic force on the proton is down the page as it enters the magnetic field. This causes the proton to undergo a circular path rotating clockwise.

5. D. $r = \frac{mv}{qB} \Rightarrow \frac{35}{100} = \frac{1.67 \times 10^{-27} \times 1.5 \times 10^{6}}{1.6 \times 10^{-19} \times \mathrm{B}}$

$B = 4.47 \times 10^{-2} = 4.5 \times 10^{-2}$ T

6. C. $F = nBIL = 1 \times 1.5 \times 3.0 \times \left(\frac{20}{100}\right) = 0.90$ N

7. B. Using the right-hand palm rule, the direction of the magnetic force on the current-carrying wire is up the page.

Deconstructed exam-style

8. [The magnitude of the magnetic force acting on the charged particle does not change when it is within the magnetic field, $F = qvB$, as the magnetic field is uniform.[1]]

I have identified the magnitude of the magnetic force on the charged particle is constant.[1]

9. [The direction of the magnetic force on the charged particle is constantly changing to remain perpendicular to both the direction of motion of the charge and direction of the magnetic field.[1]]

I have identified the direction of the magnetic force on the charged particle is always perpendicular to the direction of motion of the charge.[1]

10. [The charged particle in the magnetic field follows a circular path as the force acting on the charged particle is constant in magnitude,[1]][and the direction of the magnetic force is perpendicular to the direction of motion of the charge.[2]]

I have identified the magnitude of the magnetic force on the charged particle is constant.[1]

I have identified the direction of the magnetic force on the charged particle is always perpendicular to the direction of motion of the charge.[2]

Exam-style

11. a. $F = qvB = 1.6 \times 10^{-19} \times 2000 \times 0.030$ (1 MARK)

$F = 9.60 \times 10^{-18} = 9.6 \times 10^{-18}$ N (1 MARK)

b. [Using the right-hand palm rule, the direction of the magnetic force on the proton is down the page.[1]]

I have determined the direction of the magnetic force on the proton is down the page.[1]

c. [Using the right-hand palm rule, with direction of motion reversed, the direction of the magnetic force on the electron is up the page.[1]]

I have determined the direction of the magnetic force on the electron is up the page.[1]

12. $F = nBIL = 1 \times 0.400 \times 1.50 \times \left(\frac{10.0}{100}\right)$ (1 MARK)

$F = 6.00 \times 10^{-2}$ N (1 MARK)

13. C. Using the right-hand palm rule, the magnetic force on the current-carrying wire acts into the page.

14. a. $F = qvB \Rightarrow 2.00 \times 10^{-11} = 1.6 \times 10^{-19} \times v \times 3.00$

$v = 4.17 \times 10^{7} = 4.2 \times 10^{7}$ m s^{-1}, as required

b. $r = \frac{mv}{qB} = \frac{9.1 \times 10^{-31} \times 4.2 \times 10^{7}}{1.6 \times 10^{-19} \times 3.00}$ (1 MARK)

$r = 7.96 \times 10^{-5} = 8.0 \times 10^{-5}$ m (1 MARK)

65% of students answered this VCAA exam question correctly.

c. [Increasing the magnetic field strength will decrease the radius of the electron's path.[1]][This is because radius of the electron's path in a magnetic field is found using $r = \frac{qv}{mB}$, and magnetic field strength is in the denominator of the equation.[2]]

I have predicted the radius of the electron's path will decrease.[1]

I have justified my answer.[2]

FROM LESSON 12A

15. a. [Sides XY and WZ experience a force,[1]][as the current in these sides runs perpendicular to the direction of the magnetic field.[2]]

I have identified that sides XY and WZ experience a magnetic force.[1]

I have explained the current in sides XY and WZ runs perpendicular to the direction of the magnetic field.[2]

b. $F = nBIL = 10 \times 6.50 \times 10^{-6} \times 2.50 \times 2.00$ (1 MARK)

$F = 3.250 \times 10^{-4} = 3.25 \times 10^{-4}$ N for each side (1 MARK)

48% of students answered this VCAA exam question correctly.

c. [Using the right-hand palm rule, the side XY experiences an upward force[1]][and the side WZ experiences a downward force.[2]]

I have determined the side XY experiences an upwards force.[1]

I have determined the side WZ experiences a downward force.[2]

d. [The upward and downward force on the loop have equal magnitude and opposite direction.[1]][As a result, there is no net force acting on the loop of wire.[2]]

I have identified the upward and downward force on the loop have equal magnitude and opposite direction.[1]

I have determined there is no net force acting on the loop of wire.[2]

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16. B. Using the right-hand palm rule with fingers pointing out of the page and palm pointing towards the centre of the circle. This gives clockwise motion for a positive charge, which means anticlockwise motion for an electron.

17. [As the radius of an electron is found using $r = \frac{mv}{qB}$, the outer electron is travelling at a faster speed.[1]] [As the magnetic force on an electron is given by $F = qvB$, the outer electron is experiencing a greater magnetic force than the inner electron.[2]]

- I have identified that the outer electron is travelling at a faster speed.[1]
- I have determined that the outer electron is experiencing a greater magnetic force.[2]

18. $r = \frac{mv}{qB} = \frac{9.1 \times 10^{-31} \times 2.3 \times 10^{4}}{1.6 \times 10^{-19} \times 4.0 \times 10^{-3}}$ (1 MARK)

$r = 3.27 \times 10^{-5}$ m

$d = 2r = 2 \times 3.27 \times 10^{-5}$ (1 MARK)

$d = 6.54 \times 10^{-5} = 6.5 \times 10^{-5}$ m (1 MARK)

19. a. [By the right-hand grip rule, the field due to the upper wire is into the page at the location of the lower wire. The right-hand palm rule predicts an upwards force on the lower wire.[1]] [By the right-hand grip rule, the field due to the lower wire is out of the page at the location of the upper wire. The right-hand palm rule predicts a downwards force on the upper wire.[2]] [As a result, the wires are attracted to each other in this situation.[3]]

- I have determined the direction of the magnetic force on the lower wire, due to the upper wire.[1]
- I have determined the direction of the magnetic force on the upper wire, due to the lower wire.[2]
- I have identified that the two wires attract each other.[3]

b. [By the right-hand grip rule, the field due to the upper wire is into the page at the location of the lower wire. The right-hand palm rule predicts a downwards force on the lower wire.[1]] [By the right-hand grip rule, the field due to the lower wire is into the page at the location of the upper wire. The right-hand palm rule predicts an upwards force on the upper wire.[2]] [As a result, the wires are repelled from each other in this situation.[3]]

- I have determined the direction of the magnetic force on the lower wire, due to the upper wire.[1]
- I have determined the direction of the magnetic force on the upper wire, due to the lower wire.[2]
- I have identified that the two wires repel each other.[3]

20. a. $a = \frac{v^2}{r} \Rightarrow 6.25 \times 10^{10} = \frac{v^2}{1.0}$ (1 MARK)

$v = 2.50 \times 10^{5}$ m s^{-1}

$a = \frac{F_B}{m} = \frac{qvB}{m}$

$6.25 \times 10^{10} = \frac{1.6 \times 10^{-19} \times 2.50 \times 10^{5} \times 1.42 \times 10^{-6}}{m}$

(1 MARK)

$m = 9.09 \times 10^{-31} = 9.1 \times 10^{-31}$ kg (1 MARK)

The charge must be an electron. (1 MARK)

b. [The radius of the alpha particle's path will be larger than the radius of the electrons.[1]] [Even though the alpha particle has twice the charge of an electron, it has a much larger mass. From $r = \frac{mv}{qB}$, the radius of the alpha particles path will be larger than the electron.[2]] [The alpha particle will travel in the opposite direction to the electron.[3]] [This is because the alpha particle is positively charged as opposed to negatively charged, and so will experience a magnetic force in the opposite direction to the electron.[4]]

- I have identified the alpha particle's path will be larger.[1]
- I have justified my answer.[2]
- I have identified the alpha particle will travel in the opposite direction.[3]
- I have justified my answer.[4]

Previous lessons

21. $KE = \frac{1}{2}mv^2 = \frac{1}{2} \times 2.5 \times \left(\frac{13}{3.6}\right)^2$

$KE = 16.3 = 16$ J

FROM LESSON 2A

22. The change in gravitational potential energy is calculated using the area under the field-distance graph, multiplied by the mass of the asteroid.

Approximately 11 squares under the graph (between 10 and 12 is acceptable) (1 MARK)

Area of each square $= (2 \times 10^{8}\ \text{m}) \times (20\ \text{N kg}^{-1})$
$= 40 \times 10^{8}\ \text{J kg}^{-1}$

$\Delta GPE = 11 \times 40 \times 10^{8} \times 200$ (1 MARK)

$\Delta GPE = 8.80 \times 10^{12} = 8.8 \times 10^{12}$ J (between 8.0×10^{12} and 9.6×10^{12} is acceptable) (1 MARK)

FROM LESSON 3B

4D DC motors

Progress questions

1. A. By the right-hand palm rule, the direction of the magnetic force on side AB is upwards for the first quarter rotation.

2. C. The magnitude of the magnetic force, $F = nBIL$, remains constant on side AB.

3. D. The force on the side BC does not contribute to the torque, as the force does not act to rotate the loop around the axis of rotation.

4. A. The direction of the magnetic force on side AB is up, and on side CD is down. This creates a clockwise turning effect on the loop.

5. B. $F = nBIL = 10 \times (40 \times 10^{-3}) \times 3.0 \times \left(\frac{10}{100}\right) = 1.2 \times 10^{-2}$ $= 0.12$ N.

6. B. More turns increase the magnetic force acting on the perpendicular sides of the wire.

7. A. The split ring commutator reverses the direction of the current when the loop is in the vertical position, every half rotation.

8. C. The direction of the turning effect will alternate when the coil reaches the vertical position if slip rings are used, which will cause the coil to oscillate about the vertical position before coming to rest.

Deconstructed exam-style

9. [Current on side WX runs from W to X.[1]]

I have identified that the current runs from W to X.[1]

10. [By the right-hand palm rule, the direction of the magnetic force on side WX is downwards.[1]]

I have determined the direction of the magnetic force on side WX is downwards.[1]

11. [By the right-hand palm rule, the direction of the magnetic force on side WX is downwards.[1]][As a result, the DC motor rotates anticlockwise when viewed from the battery.[2]]

I have identified the direction of the magnetic force on side WX is downwards.[1]

I have determined the DC motor rotates anticlockwise when viewed from the battery.[2]

36% of students answered this VCAA exam question correctly.

Exam-style

12. a. $F = nBIL = 10 \times 0.50 \times 1.5 \times \left(\frac{12}{100}\right)$ (1 MARK)

$F = 0.900 = 0.90$ N (1 MARK)

48% of students answered this VCAA exam question correctly.

b. [The size of the magnetic force on side KL in the orientation shown is 0 N,[1]][as the current in the side runs parallel to the direction of the magnetic field.[2]]

I have determined the size of magnetic force on side KL is 0 N.[1]

I have justified my answer.[2]

69% of students answered this VCAA exam question correctly.

13. a. [By the right-hand palm rule, the direction of the magnetic force on side UV is downwards, in the direction D.[1]]

I have determined the direction of the magnetic force on side UV is downwards, in the direction D.[1]

b. [By the right-hand palm rule, the direction of the magnetic force on side UV is upwards, in the direction A.[1]]

I have determined the direction of the magnetic force on side UV is upwards, in the direction A.[1]

c. [A split ring commutator in a DC motor reverses the direction of current in the coil every half rotation so that the force on each side reverses direction every half turn.[1]][As a result, the coil keeps rotating in a constant direction.[2]]

I have explained the operation of a split ring commutator in a DC motor.[1]

I have explained the purpose of a split ring commutator in a DC motor.[2]

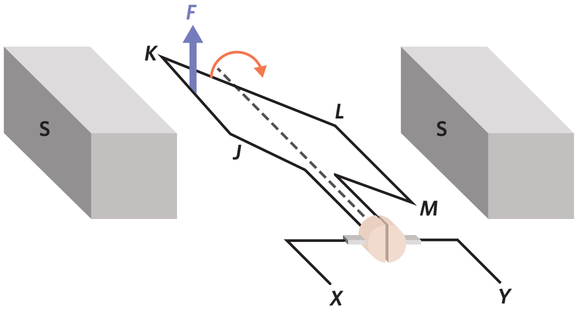
14. D. When the loop is horizontal, the current runs parallel to the magnetic field, so no magnetic force is present. When the loop is vertical, the loop is detached from the split-ring commutator, so no magnetic force is present.

40% of students answered this VCAA exam question correctly.

15. A, C. The speed of rotation is dependent upon the magnetic force on sides WX and YZ, $F = nBIL$. Increasing the battery voltage, which increases the current in the loop, and the number of turns increases the magnitude of the magnetic force on those sides.

34% of students answered this VCAA exam question correctly.

16. a.



I have drawn an arrow upwards on side JK.

55% of students answered this VCAA exam question correctly.

b. [In order for the loop to rotate clockwise, the direction of the magnetic force on side JK must be upwards.[1]][Using the right-hand palm rule, the direction of the current must be from K to J.[2]][As a result, terminal Y must be connected to the positive terminal of the power supply.[3]]

I have identified the direction of the magnetic force on side JK must be upwards.[1]

I have identified current must run from K to J.[2]

I have determined terminal Y must be connected to the positive terminal of the power supply.[3]

78% of students answered this VCAA exam question correctly.

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17. a. [The motor will rotate anticlockwise.[1]][By the right hand-palm rule, the direction of the magnetic force on side *MN* is downwards, and the direction of magnetic force on side *OP* is upwards.[2]][This creates a turning effect (torque) in the anticlockwise direction.[3]]

- I have identified the motor will rotate anticlockwise.[1]
- I have determined the magnetic force on side *MN* is downwards and on side *OP* is upwards.[2]
- I have explained this creates a turning effect (torque) in the anticlockwise direction.[3]

47% of students answered this VCAA exam question correctly.

b. [The motor would no longer function correctly.[1]][The coil will oscillate around the vertical position and eventually come to rest.[2]]

- I have determined the motor will no longer function correctly.[1]
- I have explained the coil will oscillate around the vertical position and eventually come to rest.[2]

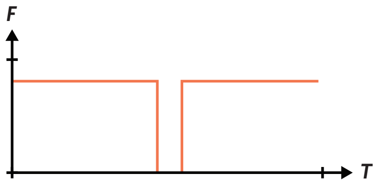
23% of students answered this VCAA exam question correctly.

c. [The best position to start the motor from rest is the horizontal position.[1]][In this position, the force exerted on the sides of the coil acts to create the maximum turning effect (or torque).[2]]

- I have identified the best position to start the motor from is the horizontal position.[1]
- I have explained at this orientation the turning effect (torque) on the coil is a maximum.[2]

18% of students answered this VCAA exam question correctly.

18. a.



- I have drawn a constant force for the majority of the coil's rotation.
- I have drawn a short region of no force in the middle of the coil's rotation.

FROM LESSON 12D

b. [When the coil is not in the vertical position, the current through the coil will remain at the same value.[1]][When the coil is in the vertical position, there will be no current reading as there is no current running through the coil.[2]]

- I have predicted that the current will have the same value when the coil is not in the vertical position.[1]
- I have predicted that there will be no current when the coil is in the vertical position.[2]

FROM LESSON 12C

Previous lessons

19. [As the person is not moving in the direction of the gravitational force,[1]][there is no work done by the gravitational force on the person across this distance.[2]]

- I have identified the person is not moving in the direction of the gravitational force.[1]
- I have determined there is no work done by the gravitational force on the person.[2]

FROM LESSON 2A

20. [As an object moves a significant distance away from the Earth, the strength of gravitational field changes.[1]][The formula $\Delta GPE = mg\Delta h$ assumes the gravitational field strength is always a constant value.[2]]

- I have identified the gravitational field strength changes at large distances away from the Earth.[1]
- I have explained that $\Delta GPE = mg\Delta h$ cannot be used when the gravitational field strength is not constant.[2]

FROM LESSON 3B

Chapter 4 review

Section A

1. A. As the bar magnet is stationary, the magnetic field around it is static. As the field lines around the bar magnet are not parallel, the field is non-uniform.

2. C. By the right-hand palm rule, the direction of the force on side JK is down and on side *LM* is up. This causes an anticlockwise rotation, in direction *B* as shown in the diagram.

51% of students answered this VCAA exam question correctly.

3. D. Gravitational fields are only monopoles, whereas electric fields may be monopoles or dipoles.

56% of students answered this VCAA exam question correctly.

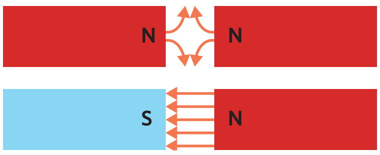
4. B. $E_1 = E_2\left(\frac{d_1}{d_2}\right)^2 \Rightarrow 6.8 \times 10^{-6}\left(\frac{d}{3d}\right)^2 = 7.6 \times 10^{-7}\ \text{N C}^{-1}$.

5. C. An electron travelling to point Y has an electric and magnetic force of equal magnitude. The force due to the electric field will remain unchanged when the electron travels faster than v_0 and the force due to the magnetic field will increase. This will result in an unbalanced force downwards, causing the electron to hit the aperture plate at point Z.

42% of students answered this VCAA exam question correctly.

Section B

6.

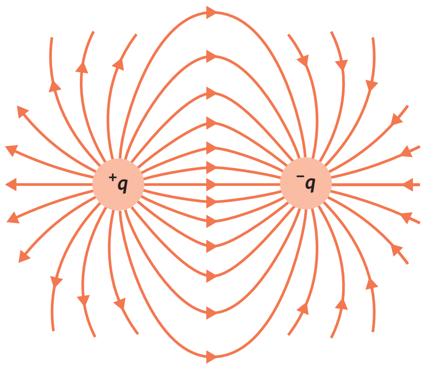


I have drawn at least four field lines for each pair of magnets.

I have drawn the correct magnetic field patterns and included arrowheads to show direction.

48% of students answered this VCAA exam question correctly.

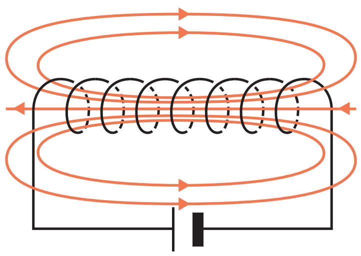
7.



I have drawn at least five field lines.

I have drawn the correct electric field pattern and included arrowheads to show direction.

8.



I have drawn five magnetic field lines.

I have drawn the correct magnetic field pattern and included arrowheads to show direction.

45% of students answered this VCAA exam question correctly.

9. a. $E = k\frac{Q}{r^2} = 8.99 \times 10^9 \times \frac{4.0 \times 10^{-7}}{2.25^2}$ (1 MARK)

$E = 7.10 \times 10^2 = 7.1 \times 10^2$ N C^{-1} (or V m^{-1}) (1 MARK)

b. $F = k\frac{q_1 q_2}{r^2} = 8.99 \times 10^9 \times \frac{4.0 \times 10^{-7} \times 1.6 \times 10^{-19}}{2.25^2}$ (1 MARK)

$F = 1.14 \times 10^{-16} = 1.1 \times 10^{-16}$ N (1 MARK)

OR

$F = qE = 1.6 \times 10^{-19} \times 7.10 \times 10^2$ (1 MARK)

$F = 1.14 \times 10^{-16} = 1.1 \times 10^{-16}$ N (1 MARK)

10. $F = nBIL = 1 \times 6.6 \times 3.2 \times 3.1 \times 10^{-5}$ (1 MARK)

$F = 6.547 \times 10^{-4} = 6.5 \times 10^{-4}$ N (1 MARK)

By the right-hand palm rule, the direction of the magnetic force is east. (1 MARK)

11. a. [By the right-hand grip rule, the two ends of the solenoids closest to point Z can both be modelled as north poles.[1]] [As a result, the magnetic field at point Z is directed downwards.[2]] [The north pole of the compass needle will align with the magnetic field, and so also points downwards.[3]]

I have determined the two ends of the solenoids closest to Z can be modelled as north poles, using the right-hand grip rule.[1]

I have explained the magnetic field at point Z is directed downwards.[2]

I have identified the north pole of a compass will point downwards.[3]

b. [The direction of the magnetic field at the position of the wire is vertical, due to the solenoids.[1]] [As the direction of current in the wire is parallel to the direction of the magnetic field,[2]] [there is no magnetic force on the wire.[3]]

I have determined the direction of the magnetic field at wire is vertical, due to the solenoids.[1]

I have explained the direction of the current in the wire is parallel to the magnetic field.[2]

I have concluded there is no magnetic force acting on the wire.[3]

12. a. $F = nBIL \Rightarrow 4.0 = 100 \times 1.75 \times L \times 750 \times 10^{-3}$ (1 MARK)

$L = 3.047 \times 10^{-2} = 3.0 \times 10^{-2}$ m (1 MARK)

b. [Slip rings would cause the current to flow around the coil in a constant direction rather than changing direction every half turn.[1]] [This means the direction of the force on each side of the wire is always in the same direction.[2]] [As a result, the motor would oscillate about and eventually come to rest in the vertical position.[3]]

I have explained slip rings cause the current in the loop to flow in a constant direction.[1]

I have identified the force on each side of the wire would always act in the same direction.[2]

I have concluded the motor will oscillate about and eventually come to rest in the vertical position.[3]

23% of students answered this VCAA exam question correctly.

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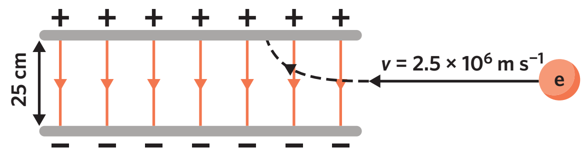
13. a. $E = \frac{V}{d} \Rightarrow 7.0 \times 10^3 = \frac{V}{25 \times 10^{-2}}$ (1 MARK)

$V = 1.75 \times 10^3 = 1.8 \times 10^3$ V (1 MARK)

b.



I have drawn the path of the electron moving towards the positive plate.

I have drawn a curved path of the electron.

c. By the conservation of energy:

$KE_f = KE_i + W$ (1 MARK)

$\frac{1}{2}mv^2 = \frac{1}{2}mu^2 + qED$ (1 MARK)

$\frac{1}{2} \times 9.1 \times 10^{-31} \times v^2 = \frac{1}{2} \times 9.1 \times 10^{-31} \times (2.5 \times 10^6)^2$
$+ 1.6 \times 10^{-19} \times 7.0 \times 10^3 \times \left(\frac{25}{100} \times \frac{1}{2}\right)$ (1 MARK)

$v = 1.77 \times 10^6 = 1.8 \times 10^6$ m s^{-1} (1 MARK)

14. a. [The function of a split ring commutator is to reverse the direction of the current in the loop every half rotation,[1]] [so that the direction of the magnetic force on sides *AB* and *CD* flip every half rotation.[2]] [This results in the turning effect on the loop acting in a constant direction and allows continuous rotation of the motor.[3]]

I have identified the split ring commutator reverses the direction of current in the loop every half rotation.[1]

I have explained that the direction of the magnetic force on sides *AB* and *CD* flips every half rotation.[2]

I have identified this allows the motor to continuously rotate.[3]

59% of students answered this VCAA exam question correctly.

b. [Increasing the number of turns of wire,[1]] [increasing the strength of the magnetic field between the magnets,[2]] [and decreasing the resistance of the wire.[3]]

I have identified one change to increase the rate of rotation of the DC motor.[1]

I have identified a second change to increase the rate of rotation of the DC motor.[1]

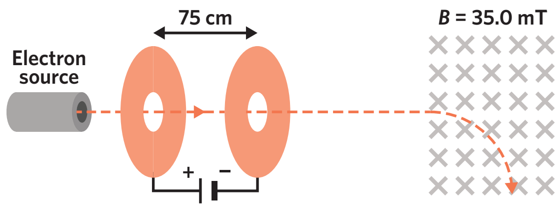
I have identified a third change to increase the rate of rotation of the DC motor.[1]

Other answers include:

- increasing the side length of *AB* and *CD*, increasing the voltage supplied to the DC motor.

34% of students answered this VCAA exam question correctly.

15. a.



I have drawn a straight path of the electron from the source to the edge of the magnetic field.

I have drawn a circular path for the electron inside the magnetic field.

I have drawn the electron moving anticlockwise in the magnetic field.

b. By the conservation of energy:

$KE_f = KE_i - W$ (1 MARK)

$\frac{1}{2}mv^2 = \frac{1}{2}mu^2 - qV$

$\frac{1}{2} \times 9.1 \times 10^{-31} \times v^2 = \frac{1}{2} \times 9.1 \times 10^{-31} \times (2.9 \times 10^6)^2$
$- 1.6 \times 10^{-19} \times 0.45$ (1 MARK)

$v = 2.61 \times 10^6$ m s^{-1}

$r = \frac{mv}{qB} = \frac{9.1 \times 10^{-31} \times 2.61 \times 10^6}{1.6 \times 10^{-19} \times 35.0 \times 10^{-3}}$ (1 MARK)

$r = 4.246 \times 10^{-4} = 4.2 \times 10^{-4}$ m (1 MARK)

Unit 3 AOS 2 review

Section A

1. C. Diagram 1 cannot be a gravitational field as the field lines are directed away from the source. Diagram 2 may be either an electric or gravitational field, as field lines are directed towards the source.

2. C. $E = k\frac{Q}{r^2} = 9.0 \times 10^9 \times \frac{2.0 \times 10^{-7}}{0.030^2} = 2.0 \times 10^6$ V m^{-1}

3. B. As the Van de Graaff generator is negatively charged, it will repel the electron.

4. A. $F_g = G\frac{m_1 m_2}{r^2} = 6.67 \times 10^{-11} \times \frac{65 \times 2.59 \times 10^{20}}{(2.63 \times 10^5)^2} = 16$ N

5. B. The orbital period can be found from $4\pi^2 R^3 = GMT^2$. This does not depend on the mass of the spacecraft, as *M* represents the mass of the object being orbited, in this case Earth.

Section B

6. a.

I have drawn an arrow pointing to the left.

63% of students answered this VCAA exam question correctly.

b. [The field between the three charges is non-uniform.[1]]

I have identified the field is non-uniform between the three charges.

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7. a. $E = k\frac{Q}{r^2} = 9.0 \times 10^9 \times \frac{2.4 \times 10^{-6}}{(5.3 \times 10^{-2})^2}$ (1 MARK)

$E = 7.69 \times 10^6 = 7.7 \times 10^6 \text{ N C}^{-1}$ (1 MARK)

b. As the smaller sphere is travelling in a circular path around the larger sphere, $F = \frac{mv^2}{r}$ (1 MARK)

$18.5 = \frac{25 \times 10^{-3} \times v^2}{5.3 \times 10^{-2}}$ (1 MARK)

$v = 6.26 = 6.3 \text{ m s}^{-1}$ (1 MARK)

8. a. $r = 3.4 \times 10^6 + 8.39 \times 10^5 = 4.239 \times 10^6 \text{ m}$ (1 MARK)

$4\pi^2 R^3 = GMT^2$

$4\pi^2 \times (4.239 \times 10^6)^3 = 6.67 \times 10^{-11} \times 6.4 \times 10^{23} \times T^2$ (1 MARK)

$T = 8.39 \times 10^3 = 8.4 \times 10^3 \text{ s}$ (1 MARK)

b. [When radius decreases, the speed of the spacecraft will need to increase.[1]][As $v = \sqrt{\frac{GM}{r}}$, for the satellite to remain in a stable order, the speed needs to increase if the orbital radius decreases.[2]]

- I have identified the speed of the spacecraft will need to increase.[1]
- I have explained my answer using $v = \sqrt{\frac{GM}{r}}$.[2]

c. [The astronaut will keep the same orbit as the spacecraft.[1]][Orbital velocity is dependent on the orbital radius.[2]][This means, unless acted on by an external force, the astronaut will have the same orbital radius and velocity as the spacecraft.[3]]

- I have compared the astronaut's motion with the spacecraft's.[1]
- I have explained the relationship between orbital velocity and radius.[2]
- I have explained the astronaut's motion.[3]

9. a. The change in gravitational potential energy per kilogram of a mass is calculated using the area under the field-distance graph. (1 MARK)

There are approximately 10 squares under the graph. (between 9 and 11 is acceptable)

Area of each square $= (1.0 \text{ N kg}^{-1}) \times (0.5 \times 10^8 \text{ m}) = 5.0 \times 10^7 \text{ J kg}^{-1}$ (1 MARK)

The *GPE* per kilogram would be $5.0 \times 10^8 \text{ J kg}^{-1}$. (between $4.5 \times 10^8 \text{ J kg}^{-1}$ and $5.5 \times 10^8 \text{ J kg}^{-1}$ is acceptable) (1 MARK)

b. [Using the trapezium method would significantly overestimate the area under the graph and leads to a less accurate area being calculated compared to counting squares.[1]][As a result, this would lead to a less accurate estimation being obtained.[2]]

- I have identified that using the trapezium method is less accurate than using the counting squares method for finding the area under the graph.[1]
- I have explained this would lead to a less accurate estimation being obtained.[2]

FROM LESSON 12C

10. a. [Out of the page.[1]]

- I have identified the direction of the force on wire *XY* is out of the page.[1]

b. $F = nILB = 1 \times 958 \times (2.6 \times 10^{-2}) \times 8.0 \times 10^{-5}$ (1 MARK)

$F = 1.99 \times 10^{-3} = 2.0 \times 10^{-3} \text{ N}$ (1 MARK)

c. [The force on side *YZ* is 0 N.[1]][This is because the current running through side *YZ* is parallel to the direction of Earth's magnetic field.[2]]

- I have identified the force on the side *YZ* is 0 N.[1]
- I have explained that the current through the side *YZ* is parallel to the direction of Earth's magnetic field.[2]

11. a. [The motor will rotate anticlockwise.[1]][By the right-hand palm rule, the force on side *HG* is upwards and the force on side *FE* is downwards.[2]][This creates a torque (turning effect) in the anticlockwise direction on the coil.[3]]

- I have identified the motor will rotate anticlockwise.[1]
- I have explained that the force on side *HG* is upwards and on side *FE* is downwards.[2]
- I have explained that this creates an anticlockwise torque (turning effect) on the coil.[3]

50% of students answered this VCAA exam question correctly.

b. $F = nILB = 30 \times 1.5 \times (20 \times 10^{-2}) \times 4.0 \times 10^{-3}$ (1 MARK)

$F = 3.60 \times 10^{-2} = 3.6 \times 10^{-2} \text{ N}$ (1 MARK)

66% of students answered this VCAA exam question correctly.

c. [The net force on the motor is zero.[1]]

- I have identified the net force acting on the motor is zero.[1]

d. [A split ring commutator in a DC motor reverses the direction of the current every half turn.[1]][This ensures that the force produced on each side is reversed in direction every half turn.[2]][As a result, the loop maintains a constant direction of rotation.[3]]

- I have identified the split ring commutator reverses the direction of the current every half turn.[1]
- I have identified the force produced on each side of the coil reverse every half turn.[2]
- I have explained this allows the motor to maintain a constant direction of rotation.[3]

e. [The motor would no longer function as intended.[1]][The loop would rotate to the vertical position and oscillate about the vertical position, before coming to rest.[2]]

- I have explained the motor will no longer function as intended.[1]
- I have explained the loop would rotate to and oscillate about the vertical position before coming to rest.[2]

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12. a.

- I have drawn an arrow labelled F_E pointing upwards and F_g pointing downwards.
- I have drawn the arrows for F_E and F_g the same length.

b. As $F_{net} = ma$, if the oil drop is suspended then the net force acting on the drop is 0. (1 MARK)

$F_{net} = 0 \Rightarrow mg = qE = q\frac{V}{d}$ (1 MARK)

$m \times 9.8 = 1.59 \times 10^{-19} \times \frac{10}{3.0 \times 10^{-3}}$ (1 MARK)

$m = 5.41 \times 10^{-14} = 5.4 \times 10^{-14}$ kg (1 MARK)

c. [The gravitational field strength on the surface of Mars is $g = G\frac{M}{r^2} = 6.67 \times 10^{-11} \times \frac{6.4 \times 10^{23}}{(3396 \times 10^3)^2} = 3.7$ m s^{-2} or N kg^{-1}.[1]] [As the gravitational field strength on the surface of Mars is less than that on Earth, the gravitational force on the oil drop will be reduced, but the electric force on the oil drop will remain the same.[2]] [As a result, the oil drop will accelerate upwards when it enters the region between the two charged parallel plates.[3]]

- I have calculated the gravitational field strength on the surface of Mars to be 3.7 m s^{-2} or N kg^{-1}.[1]
- I have identified that the gravitational force on the oil drop will be less on Mars than on Earth, but the electric force will not change.[2]
- I have predicted the oil drop will accelerate upwards as it enters the region between the two charged plates.[3]

FROM LESSON 12A

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5A EMF and Faraday's law

Progress questions

1. B. $\Phi_B = BA = 0.30 \times \left(\frac{10}{100^2}\right) = 3.0 \times 10^{-5}$ Wb

53% of students answered this VCAA exam question correctly.

2. B. The area of the wire perpendicular to the loop is greater than zero but less than the total area of the loop.

3. D. An EMF will not be induced as neither the magnetic field or the area perpendicular to the magnetic field changes.

4. A, B, C, D. $\varepsilon = -N\frac{\Delta\Phi_B}{\Delta t}$ therefore all of the options increase the magnetic flux through the coil.

5. D. The gradient of the Φ_B vs. time graph increase with a constant gradient, then decreases with a constant gradient.

60% of students answered this VCAA exam question correctly.

Deconstructed exam-style

6. A. $\frac{10^2}{100^2} = 1.0 \times 10^{-2}$ m^2

7. $\Phi_B = 0$ as the loop is entirely outside the magnetic field.

8. $\Phi_B = BA$

$\Phi_B = 0.15 \times 1.0 \times 10^{-2}$

$\Phi_B = 1.5 \times 10^{-3}$ Wb

9. $\Phi_{Bf} = BA$

$\Phi_{Bf} = 0.15 \times \frac{10^2}{100^2}$ (1 MARK)

$\Phi_{Bf} = 1.5 \times 10^{-3}$

$\varepsilon = -N\frac{\Delta\Phi_B}{\Delta t}$

$\varepsilon = -20 \times \frac{1.5 \times 10^{-3} - 0}{0.25}$ (1 MARK)

$\varepsilon = -0.120 = -0.12$ V

Magnitude of average EMF is 0.12 V (1 MARK)

Exam-style

10. Q: zero (1 MARK)

R: negative (1 MARK)

S: positive (1 MARK)

11. C. The gradient of the graph in section R is greater than in section P.

12. A. The flux is 0 at 0 s, rises to a maximum at 2 s and remains constant until 4 s, then falls to 0 at 6s.

13. B. The gradient of the flux time graph is constant from $t = 0$ to $t = 2$ s, is zero from $t = 2$ to $t = 4$ s, and constant from $t = 4$ to $t = 6$ s.

14. At $t = 0$ s:

$\Phi_B = B_\perp A = 0.040 \times 0 = 0$ Wb

At t = 2 s:

$\Phi_B = B_\perp A = 0.040 \times \frac{2.5 \times 10^3}{100^2} = 1.0 \times 10^{-2}$ Wb (1 MARK)

$\varepsilon = -N\frac{\Delta\Phi_B}{\Delta t}$

$\varepsilon = -15 \times \frac{1.0 \times 10^{-2} - 0}{2 - 0}$ (1 MARK)

$\varepsilon = -7.50 \times 10^{-2}$ V

Magnitude of average EMF is 7.5×10^{-2} V. (1 MARK)

15. [Moving a portion of the loop outside the magnetic field.[1]] [Rotating the loop inside the magnetic field will induce an EMF in it.[2]]

I have identified one action that induces an EMF in the loop.[1]

I have identified a second action that induces and EMF in the loop.[2]

33% of students answered this VCAA exam question correctly.

16. **a.** When the rate of change of magnetic flux is zero the EMF will also be zero.

$t = 0, 1.0, 2.0, 3.0, 4.0, 5.0$ s

41% of students answered this VCAA exam question correctly.

b. $\varepsilon = -N\frac{\Delta\Phi_B}{\Delta t}$

$\varepsilon = -4 \times \frac{0.5 - 2.5}{2.0 - 1.0}$ (1 MARK)

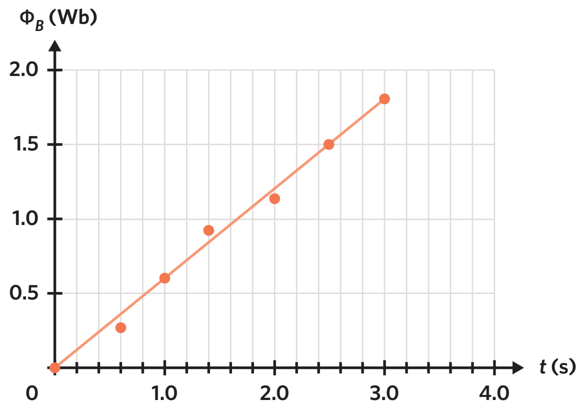
$\varepsilon = 8.0$ V

The magnitude of the average EMF through the loop is 8.0 V. (1 MARK)

c. When the magnetic flux is a maximum the magnet is in the middle of the loop.

$t = 1.0, 3.0, 5.0$ s

17. **a.**



I have correctly labelled both axes, including units.

I have included appropriate and consistent scales.

I have correctly plotted each point of data.

I have drawn a line of best fit.

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b. $Gradient = \frac{1.8 - 0}{3 - 0} = 0.6 \text{ Wb s}^{-1}$ (1 MARK)

$\varepsilon = N\frac{\Delta\Phi_B}{\Delta t}$

$6.0 = N \times gradient$ (1 MARK)

$N = \frac{6.0}{0.6} = 10 \text{ turns}$ (1 MARK)

Note we are investigating the effects of the change in magnitude flux on the magnitude of the induced EMF, so the negative sign can be ignored.

FROM LESSONS 12D & 12E

18. D. Halving the frequency of rotations doubles the time it takes for a cycle of the EMF to occur and halves the magnitude of the EMF produced.

60% of students answered this VCAA exam question correctly.

19. a. When loop entirely within the magnetic field:

$\Phi_B = B_\perp A$

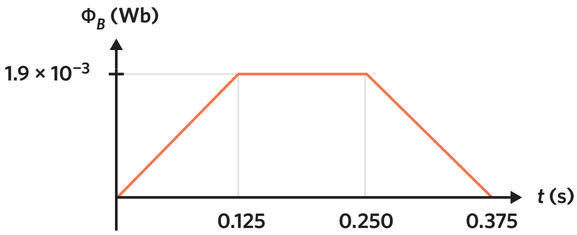
$\Phi_B = 3.0 \times 10^{-2} \times (0.25 \times 0.25)$

$\Phi_B = 1.875 \times 10^{-3} = 1.9 \times 10^{-3} \text{ Wb}$

Coil must move 25 cm to be entirely within magnetic field, another 25 cm to begin leaving the field, and another 25 cm to be entirely outside the field again.

Time for each stage:

$\Delta t = \frac{\Delta s}{v} = \frac{0.25}{2} = 0.125 \text{ s}$



I have drawn the magnetic flux increasing at a constant rate when the loop enters the field.

I have drawn a constant magnetic flux when the loop is entirely within the field.

I have drawn the magnetic flux decreasing at a constant rate when the loop exits the field.

I have included the value of the maximum magnetic flux and the time for each stage of the motion.

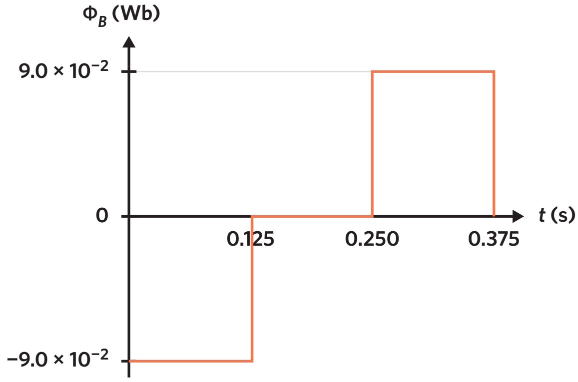
Note that the reciprocal graph (all flux values negative) is also acceptable.

11% of students answered this VCAA exam question correctly.

b. $\varepsilon = -N\frac{\Delta\Phi_B}{\Delta t}$

$\varepsilon = -6 \times \frac{1.875 \times 10^{-3}}{0.125}$

$\varepsilon = -9.0 \times 10^{-2} \text{ V}$



I have drawn a constant EMF when the rate of change of magnetic flux is constant and zero EMF when the rate of change of magnetic flux is zero.

I have drawn the EMF with the opposite sign to the change in flux.

I have included values for the maximum EMF induced and times when EMF changes.

Note that the reciprocal graph is also acceptable.

34% of students answered this VCAA exam question correctly.

20. [During movement A, as the change in flux through the loop is constantly changing[1]][the EMF induced in the loop is constantly changing in magnitude.[2]][For movement B, as the flux through the loop is not changing[3]][there is no EMF induced in the loop.[4]]

I have described the change in flux during movement A as constantly changing.[1]

I have described how the constantly changing flux relates to a constantly changing EMF.[2]

I have described there is no change in flux during movement B.[3]

I have described how no change in flux through the loop relates to no induced EMF in the loop.[4]

7% of students answered this VCAA exam question correctly.

Previous lessons

21. [The collision is inelastic,[1]][as some kinetic energy has been converted into sound energy due to the loud sound being produced.[2]]

I have stated the collision is inelastic.[1]

I have identified kinetic energy was converted to sound energy.[2]

FROM LESSON 2B

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22. [As the gravitational force is constant in magnitude and perpendicular to the direction of the satellite's motion,[1]] [it is providing the centripetal force for a satellite to remain in stable orbit around Earth without the use of a propulsion engine.[2]]

- I have identified the magnitude and direction of the gravitational force is acting on the satellite.[1]
- I have stated the gravitational force is providing the centripetal force.[2]

FROM LESSON 3C

5B Direction of induced current and Lenz's law

Progress questions

1. C. An induced current will flow in a direction such that the magnetic field created by the current will oppose the change in flux that induced the current

2. C. The magnetic flux is increasing to the right, so the induced magnetic field will oppose this change in flux, causing the induced current to flow clockwise.

Deconstructed exam-style

3. [Decreasing.[1]]

- I have identified the magnetic flux as decreasing.[1]

4. A. The north pole of the magnet is facing the loop so the flux is to the left.

5. A. The induced current will flow in a direction such that its magnetic field opposes the change in flux.

6. [As the magnet moves away from the loop, the magnetic flux through the loop to the left decreases.[1]] [Lenz's law states the induced current will oppose the decrease in flux by creating a magnetic field to the left.[2]] [And hence, the induced current will flow anticlockwise when viewed from the left.[3]]

- I have identified if the flux increasing or decreasing, and in which direction it points.[1]
- I have used Lenz's law to determine the direction of the induced magnetic field.[2]
- I have explained why the current flows anticlockwise.[3]

16% of students answered this VCAA exam question correctly.

Exam-style

7. [Increasing.[1]]

- I have identified the magnetic flux is increasing.[1]

8. B. The induced magnetic field will oppose the change in flux.

9. [Anticlockwise.[1]]

- I have identified the direction of the induced current.[1]

10. B. To induce a current, the magnetic flux needs to be increasing to the left.

11. [The strength of the magnet.[1]]

- I have identified a controlled variable.[1]

Other possible answers:

- The area of the conducting loop
- The strength of the magnetic field

FROM LESSON 12A

12. B. The other options keep the loop fully in the magnetic field, so the magnetic flux doesn't change and a current is not induced.

33% of students answered this VCAA exam question correctly.

13. [The magnetic flux through the loop is decreasing and is directed downwards.[1]] [Lenz's law states the induced EMF will produce a current that will have a magnetic field which will oppose this decrease in flux, so it will be directed downwards.[2]] [Using the right-hand coil rule, the induced current will flow clockwise.[3]]

- I have identified if the flux is increasing or decreasing, and which direction it points.[1]
- I have used Lenz's law to determine the direction of the induced magnetic field.[2]
- I have stated the direction the induced current will flow.[3]

21% of students answered this VCAA exam question correctly.

14. a. [Decrease. The area of the loop decreases, resulting in a decrease in flux.[1]]

- I have identified that the magnetic flux through the coil will decrease.[1]

61% of students answer this VCAA exam question correctly.

b. [The magnetic flux through the loop is decreasing into the page.[1]] [Lenz's law states the induced EMF will produce a current that will have a magnetic field which will oppose this decrease in flux, so it will be directed into the page.[2]] [Using the right-hand coil rule, the induced current will flow clockwise.[3]]

- I have identified if the flux is increasing or decreasing, and which direction it points.[1]
- I have used Lenz's law to determine the direction of the induced magnetic field.[2]
- I have determined the direction the induced current will flow.[3]

22% of students answered this VCAA exam question correctly.

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c. [From X to Y, the magnetic flux through the loop is increasing into the page. Using the right-hand coil rule, the induced current will flow anticlockwise.[1]] [From Y to Z, the magnetic flux is decreasing into the page. Using the right-hand coil rule, the induced current will flow clockwise.[2]]

- I have identified the direction of the current as the loop changes from X to Y.[1]
- I have identified the direction of the current as the loop changes from Y to Z.[2]

23% of students answered this VCAA exam question correctly.

15. a. [Qualitative. The direction of the current will most likely be recording using words like 'clockwise' or 'anticlockwise'.[1]]

- I have identified that the type of data recorded is likely to be qualitative.[1]

FROM LESSON 12A

b. [Using the right-hand coil rule, the solenoid produces a magnetic field which acts to the left along its long axis.[1]] [The magnetic flux through the loop of wire as it moves away from the solenoid is decreasing and points to the left.[2]] [By Lenz's law, the induced EMF will produce a current that will have a magnetic field which will oppose this decrease in flux, so it will be directed to the left.[3]] [Using the right-hand coil rule, the induced current will flow in an anticlockwise direction when viewed from the solenoid.[4]]

- I have identified the direction of the magnetic field produced by the solenoid.[1]
- I have identified if the flux is increasing or decreasing, and in which direction it points.[2]
- I have used Lenz's law to determine the direction of the induced magnetic field.[3]
- I have stated the direction the induced current will flow.[4]

c. [By Lenz's law, the anticlockwise induced current must create a magnetic field to oppose the initial change in flux.[1]] [The initial flux must have been increasing and directed to the right.[2]] [For this to occur when the loop approaches the solenoid, the right side of the pole must be acting as a north pole.[3]] [The current is flowing out of the right side of the cell and into the left side of the cell, so the cell must be connected in orientation B.[4]]

- I have explained the direction of the initial change in flux.[1]
- I have stated the direction of the initial change in flux.[2]
- I have interpreted which end of the solenoid is acting as the north pole.[3]
- I have determined the correct orientation of the cell.[4]

19% of students answered this VCAA exam question correctly.

Previous lessons

16. C. In elastic collisions, all momentum and kinetic energy are conserved.

FROM LESSON 2B

17. $E = \dfrac{kq}{r^2}$

$E = \dfrac{8.99 \times 10^9 \times 1.6 \times 10^{-19}}{1.4^2}$

$E = 7.34 \times 10^{-10} = 7.3 \times 10^{-10}\ \text{N C}^{-1}$ (1 MARK)

FROM LESSON 4A

5C Generators and alternators

Progress questions

1. B. An alternator is a type of generator, and all generators convert kinetic energy into electrical energy.
2. D. Slip rings account for the rotation of the coil and allow it to connect to the external coil even as the direction of the current changes.
3. D. When the coil is perpendicular to the field, the amount of flux through the coil is maximum as the entire area of the coil has field lines running through it.
4. C. When the coil is parallel to the field, no field lines can pass through the coil therefore there is no flux.
5. C. When the coil is parallel to the field, the EMF induced is a maximum as the gradient of the change in flux is a maximum.
6. D. When the coil is perpendicular to the field, the induced EMF is a minimum as the gradient of the change in flux is zero.
7. C. Period is the time it takes for one wave to pass and amplitude is the height of the wave.
8. A. The amplitude is halved because the rate of rotation, or period, is halved.
9. A. Increasing the rotation speed increases the number of rotations per second, thereby increasing the frequency and reducing the period. This increases the rate of change in magnetic flux which increases the amplitude (induced EMF).
10. A, B, C. The apparatus in the diagram is an alternator that produces AC and uses slip rings to function.
11. D, E, F. The apparatus in the diagram is a DC generator that produces DC and uses a split ring commutator to function.

Deconstructed exam-style

12. $\Delta\Phi_{BA} = BA_f - BA_i = 0 - 4.5 \times 10^{-2} \times 0.020$

$\Delta\Phi_{BA} = -9.0 \times 10^{-4}\ \text{Wb}$

13. $\Delta t = \dfrac{T}{4} = \dfrac{0.20}{4} = 0.050\ \text{s}$

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14. $\Delta\Phi_{BA} = BA_f - BA_i = 0 - 4.5 \times 10^{-2} \times 0.020$

$\Delta\Phi_{BA} = -9.0 \times 10^{-4}$ Wb (1 MARK)

$\Delta t = \frac{T}{4} = \frac{0.20}{4} = 0.050$ s (1 MARK)

$\varepsilon = -N\frac{\Delta\Phi_B}{\Delta t} = -30 \times \frac{-9.0 \times 10^{-4}}{0.050} = 0.54$ V (1 MARK)

Exam-style

15. A. The split ring commutator works to connect the generator to the external circuit, and therefore the resistor, and ensures that the current provided is DC.

51% of students answered this VCAA exam question correctly.

16. a. $T = \frac{1}{f} \Rightarrow f = \frac{1}{T}$ (1 MARK)

$f = \frac{1}{20 \times 10^{-3}} = 50$ Hz (1 MARK)

68% of students answered this VCAA exam question correctly.

b. [The maximum magnitude of EMF will occur when the coil is parallel to the magnetic field (horizontal).[1]] [At this position the rate of change of flux is a maximum.[2]]

- I have described the orientation as parallel to the magnetic field or horizontal.[1]
- I have justified my answer using the relevant theory: electromagnetic induction.[2]

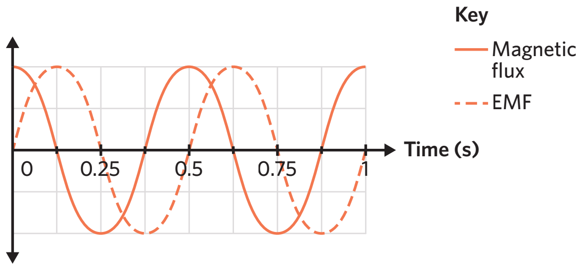
83% of students answered this VCAA exam question correctly.

c.

Suggested change	Effect on EMF amplitude (increase, decrease, no effect)
Decrease the period of rotation of the coil.	Increase
Decrease the strength of the permanent magnets.	Decrease
Increase the number of turns in the coil.	Increase
Increase the area of the coil.	Increase

15% of students answered this VCAA exam question correctly.

17. a.



- I have drawn the magnetic flux graph starting at a maximum and varying sinusoidally with a period of 0.5 s.
- I have drawn the EMF graph starting at zero and varying sinusoidally with a period of 0.5 s.
- I have drawn two full cycles for both graphs.

b. $\Phi_B = B_{\perp}A = 0.090 \times (0.30 \times 0.50)$ (1 MARK)

$\Phi_B = 1.35 \times 10^{-2} = 1.4 \times 10^{-2}$ Wb (1 MARK)

c. $f = \frac{1}{T} = \frac{1}{0.50} = 2.0$ Hz

d. $\varepsilon = -N\frac{\Delta\Phi_B}{\Delta t} = -20 \times \frac{1.35 \times 10^{-2}}{\frac{0.50}{4}}$ (1 MARK)

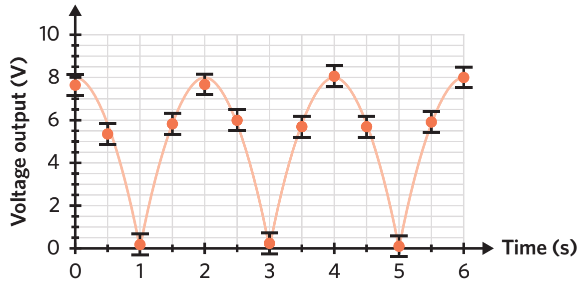
$\varepsilon = -2.2 = 2.2$ V (1 MARK)

e. [Slip rings allow the coil in an alternator to rotate while maintaining contact with an external circuit.[1]] [This results in the alternating EMF induced in the coil producing AC electricity.[2]]

- I have explained the function of slip rings.[1]
- I have explained how slip rings are required for AC electricity.[2]

18. C. Doubling the rate doubles the frequency as well as the amplitude of the voltage produced.

19. a.



- I have labelled the horizontal axis and included units.
- I have labelled the vertical axis and included units.
- I have included an appropriate and consistent scale on the axes.
- I have correctly plotted each data point.
- I have drawn correctly sized uncertainty bars.
- I have drawn a curve of best fit which passes through all uncertainty bars.

FROM LESSON 12D

b. The time from zero voltage to peak voltage occurs over a one-quarter rotation.

Taking the amount of time it takes to complete four quarter turns: $T = 4.0$ s (1 MARK)

$f = \frac{1}{T} = \frac{1}{4.0} = 0.25$ Hz (1 MARK)

c. [The coil is connected via a split ring commutator[1]] [because the output voltage has a constant direction (all voltage values are positive).[2]]

- I have identified that the coil uses a split ring commutator.[1]
- I have explained how split ring commutators produce voltage in one direction.[2]

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20. a. $f = \frac{1}{T} \Rightarrow T = \frac{1}{10} = 0.10$ s (1 MARK)

$\Delta t = \frac{T}{4} = \frac{0.10}{4} = 0.025$ s

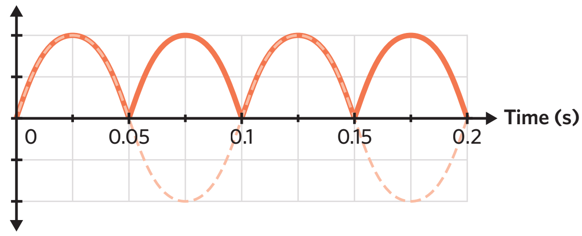
$\varepsilon = N\frac{\Delta\Phi_B}{\Delta t} \Rightarrow 1.6 = 5 \times \frac{\Phi_B}{0.025}$ (1 MARK)

$\Phi_B = 8.0 \times 10^{-3}$ Wb (1 MARK)

$\Phi_B = B_{\perp}A \Rightarrow 8.0 \times 10^{-3} = 8.0 \times 10^{-3} \times L^2$

$L = 1.0$ m $= 1.0 \times 10^2$ cm (1 MARK)

b. EMF (V)



I have drawn a solid line that inverts either the positive or the negative EMF values of the original graph.

Previous lessons

21. a. There are approximately 22 squares (between 20 and 24 is acceptable) beneath the graph between the surface of the Earth and 20×10^6 m.

Area of each square $(1.0\ \text{N kg}^{-1}) \times (2.0 \times 10^6\ \text{m})$
$= 2.0 \times 10^6\ \text{J kg}^{-1}$ (1 MARK)

$\Delta GPE = 22 \times 2.0 \times 10^6 \times 1300$ (1 MARK)

$\Delta GPE = 5.7 \times 10^{10}$ J (1 MARK)

b. The area under the graph between the centre and the surface of the Earth is a triangle.

$\Delta GPE = \frac{1}{2} \times 6.37 \times 10^6 \times 9.8 \times 1300$ (1 MARK)

$\Delta GPE = 4.1 \times 10^{10}$ J (1 MARK)

25% of students answered this VCAA exam question correctly.

FROM LESSON 2C

22. a. $F = qvB = 1.6 \times 10^{-19} \times 2.5 \times 10^7 \times 8.0 \times 10^{-2}$ (1 MARK)

$F = 3.2 \times 10^{-13}$ N (1 MARK)

b. [The electrons follow a circular path[1]][since the force acting on them is always at right angles to their direction of motion (as is the case for a centripetal force).[2]]

I have described the path of the electrons.[1]

I have justified my answer using the direction of the centripetal force.[2]

FROM LESSON 4B

5D Photovoltaic cells

Progress questions

1. B. PV cells don't emit light, they absorb it.

2. B. The front and back electrical contacts complete the circuit allowing electricity to flow.

3. Ejected electrons are **attracted to** the **p-type** semiconductor and flow from the **front** electrical contact to the **back** electrical contact.

4. D. PV cells are similar to batteries when connected in series.

5. A. Modules are a larger structure made from PV cells.

6. B. PV cells absorb sunlight and produce DC.

7. A. An inverter is needed to convert DC to AC so solar generated electricity can be used in the home.

Deconstructed exam-style

8. D. n-type semiconductors are specially treated to eject electrons when sunlight falls on them.

9. [The electric field causes electrons to only flow in one direction.[1]]

I have described the purpose of the electric field.[1]

10. B. Electricity is the flow of charge.

11. [Light passes through the antireflection layer and is absorbed by atoms in the n-type semiconductor, causing them to eject electrons.[1]][An electric field forces electrons to travel in only one direction.[2]][The electrons are attracted to p-type semiconductor and flow from the front electrical contact to the back electrical contact,[3]][creating an electric current.[4]]

I have described how light is absorbed and electrons are ejected.[1]

I have described how electrons travel in only one direction.[2]

I have described how electrons flow from front to back electrical contacts.[3]

I have identified that this creates an electric current.[4]

Exam-style

12. D. The antireflection layer is designed to maximise the amount of sunlight reaching the semiconductors.

13. [Solar installations produce DC while households runs on AC.[1]] [An inverter is required to convert DC to AC allowing solar power to be used in the home.[2]]

I have identified that solar installations produce DC and homes run on AC.[1]

I have explained why an inverter is needed.[2]

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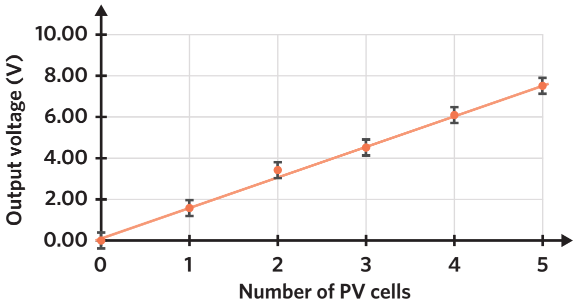
14. a. [The number of PV cells.[1]]

I have identified the independent variable.[1]

b. **Output voltage (V) vs. Number of PV cells**



I have plotted a graph of Output voltage vs. Number of PV cells.

I have included appropriate scales.

I have included axis titles.

I have included units for both axes.

I have drawn a line of best fit.

I have included appropriate error bars.

c. [The output current did not increase as more PV cells were added because connecting cells in series only increases the output voltage not the output current.[1]]

I have explained why the output current did not increase.[1]

15. [Elie is correct.[1]][Solar panels are composed of many PV cells connected together and consequently they can be built in different sizes; this makes counting them an inaccurate way of judging how much power they are generating.[2]][Looking at the power reading on your inverter is a more accurate way to measure how much power solar panels generate.[3]]

I have identified who is correct.[1]

I have explained that counting solar panels is a poor measure of the amount of electricity generated.[2]

I identified reading the inverter as a better measure and used this to justify my answer.[3]

16. [The ISS would not need an inverter.[1]][This is because it is designed to travel into space and does not need to be connected to the electrical grid.[2]]

I have identified that the ISS does not need an inverter.[1]

I have justified my response.[2]

Other possible answers:

- The equipment can be designed to run on DC.

Previous lessons

17. D. The centripetal force always acts towards the centre of the circular path.

FROM LESSON 1E

18. $KE = \frac{1}{2}mv^2$

$KE = \frac{1}{2} \times 1200 \times \left(\frac{30}{3.6}\right)^2$

$KE = 4.17 \times 10^4 = 4.2 \times 10^4$ J

FROM LESSON 2A

Chapter 5 review

Section A

1. B. The value of the EMF induced is equal to the gradient of a flux-time graph.

60% of students answered this VCAA exam question correctly.

2. A. Stronger magnets would increase the flux therefore the potential EMF induced.

3. C. The experimenters are changing the strength of the field, measuring the peak EMF, and keeping the period constant.

82% of students answered this VCAA exam question correctly.

FROM LESSON 12A

4. B. When light enters the cell through the antireflection layer it is absorbed by the n-type semiconductor, which causes the emission of electrons.

5. D. We can identify this generator as an alternator due to the presence of slip rings, therefore the output is AC.

80% of students answered this VCAA exam question correctly.

Section B

6. $T = 1.5$ s (1 MARK)

amplitude = 4.0 V (1 MARK)

$f = \frac{1}{T} = \frac{1}{1.5} = 0.67$ Hz (1 MARK)

7. a. [Light passes through the antireflection layer and is absorbed by atoms in the n-type semiconductor, causing them to eject electrons.[1]][An electric field forces electrons to travel in only one direction.[2]][The electrons are attracted to p-type semiconductor and flow from the front electrical contact to the back electrical contact creating a current.[3]]

I have described how light is absorbed and electrons are ejected.[1]

I have described how electrons travel in only one direction.[2]

I have described how electrons flow from front to back electrical contacts.[3]

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b. [The apartments require an inverter to convert direct current (DC) to alternating current (AC).[1]] [This is because solar panels produce DC while most household appliances require AC to function.[2]]

- I have identified the need for an inverter.[1]
- I have provided the reason that households require AC.[2]

8. a. $\varepsilon = -N\frac{\Delta\Phi_B}{\Delta t} = -4 \times \frac{(1.6 - 0.4)}{2.5 - 0.5} = -9.6\ \text{V}$ (1 MARK)

The magnitude of the induced EMF is 9.6 V.

$V = IR \Rightarrow 9.6 = 0.80 \times I$ (1 MARK)

$I = 12\ \text{A}$ (1 MARK)

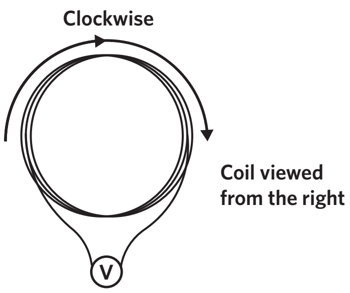
49% of students answered this VCAA exam question correctly.

b. The gradient has a maximum positive value at 0.25 s, 1.25 s, and 2.25 s (1 MARK)

The gradient has a maximum negative value at 0.75 s, 1.75 s, and 2.75 s (1 MARK)

41% of students answered this VCAA exam question correctly.

c. [As the magnet approaches the coil, the magnetic flux through the coil increases[1]] [to the right.[2]] [According to Lenz's law, the induced current opposes this change in flux by creating a magnetic field to the left.[3]] [Using the right-hand coil rule, the induced current when observed from the right is clockwise.[4]]



- I have identified if the flux is increasing or decreasing.[1]
- I have identified the direction of the change in flux.[2]
- I have used Lenz's law to determine the direction of the induced magnetic field.[3]
- I have described the direction of the induced current and explained how I found it.[4]

13% of students answered this VCAA exam question correctly.

d. Position 1: 0, 2.0 s (1 MARK)

Position 2: 0.5, 1.5, 2.5 s (1 MARK)

Position 3: 1.0, 3.0 s (1 MARK)

21% of students answered this VCAA exam question correctly.

9. [The flux through the square coil is zero[1]] [because the magnetic field produced by the solenoid is parallel to the plane of the loop.[2]]

- I have identified the value of the flux through the loop.[1]
- I have explained my answer using the angle of the loop with respect to the solenoid.[2]

10. a. $\Phi_B = BA \Rightarrow 0.15 = B \times 0.20 \times 0.30$ (1 MARK)

$B = 2.5\ \text{T}$ (1 MARK)

b. $T = \frac{1}{f} = \frac{1}{8.0} = 0.125\ \text{s}$

For a quarter rotation, $\Delta t = \frac{0.125}{4} = 3.13 \times 10^{-2}\ \text{s}$ (1 MARK)

$\varepsilon = -N\frac{\Delta\Phi_B}{\Delta t} = -5 \times \frac{0.15}{3.13 \times 10^{-2}}$ (1 MARK)

$\varepsilon = -24 = 24\ \text{V}$ (1 MARK)

c. [The magnetic flux through the coil in the horizontal position begins at zero and increases to a maximum of 0.15 Wb in the vertical position.[1]] [It then returns to zero as the coil rotates through to being horizontal again.[2]] [The flux increases again to the 0.15 Wb maximum through the other side of the coil in the vertical position.[3]] [Finally, after one full revolution it will return to having zero magnetic flux through the coil in the horizontal position.[4]]

- I have described the motion of the coil and the magnetic flux through it from the initial to vertical position.[1]
- I have described the motion of the coil and the magnetic flux through it from the vertical to horizontal again.[2]
- I have described the motion of the coil and the magnetic flux through it as turns from horizontal to vertical.[3]
- I have described the endpoint of the revolution.[4]

d. [The maximum EMF occurs when the coil is in the horizontal position.[1]] [In this orientation the rate of change of magnetic flux is greatest which creates the greatest EMF according to Faraday's law ($\varepsilon = -N\frac{\Delta\Phi_B}{\Delta t}$).[2]]

- I have identified which orientation corresponds to the maximum EMF.[1]
- I have explained the relationship between orientation, change in flux, and induced EMF using Faraday's law.[2]

e. [The split ring commutator should be replaced with slip rings.[1]] [The slip rings maintain a constant connection between the external circuit and the rotating coil which produces an alternating current as it is rotated.[2]]

- I have explained which change needs to be made to convert the DC generator into an alternator.[1]
- I have explained why this change will achieve an AC output.[2]

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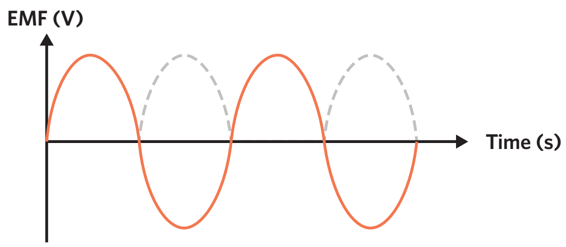
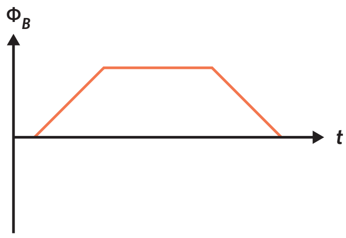
f. 

I have drawn a sinusoidal graph that has the same amplitude as the DC graph.

I have drawn a sinusoidal graph that has the same period as the DC graph.

11. a. 

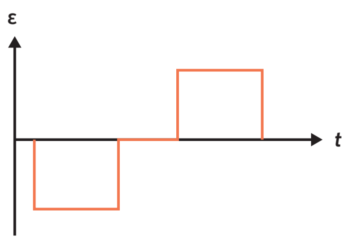
A negative version of this graph (flipped upside down) is also correct.

I have drawn a positively sloped straight line.

I have drawn a straight horizontal line.

I have drawn a negatively sloped straight line.

11% of students answered this VCAA exam question correctly.

b. 

A negative version of this graph (flipped upside down) is also correct.

I have drawn a period of negative EMF with a constant value.

I have included a period of zero EMF.

I have drawn a period of positive EMF with a constant value and duration equal to the negative section.

34% of students answered this VCAA exam question correctly.

c. [As the loop enters the magnetic field, the flux through the coil is increasing[1]] [upwards.[2]] [By Lenz's law the induced current would oppose this change in flux by creating a magnetic field directed downwards.[3]] [Using the right-hand coil rule, the induced current flows from *Y* to *X* through the voltmeter.[4]]

I have identified the direction of the changing flux through the coil.[1]

I have identified the the sign of the changing flux through the coil.[2]

I have used Lenz's law to determine the direction of the induced magnetic field.[3]

I have explained the direction of the induced current as *Y* to *X* through the voltmeter and how I found it.[4]

15% of students answered this VCAA exam question correctly.

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6A Electricity recap

Progress questions

1. C. Current is a measure of charge through a circuit.

2. D. Voltage is a measure of the difference in energy stored by a charge between two points.

3. C. Ohm's law is $V = IR$.

4. B. $V = IR \Rightarrow 2.0 = 3.0 \times R \Rightarrow R = 0.67\ \Omega$

5. B and C. In a series circuit the current is the same through all components, and the power supplied by the power source is equivalent to the sum of power dissipated by the resistors.

6. C. $P = I^2R \Rightarrow 3.5 = I^2 \times 5.0 \Rightarrow I = 0.84$ A

Deconstructed exam-style

7. $R_T = R_{eq} = R_1 + R_2 + R_3 = 1.5 + 1.5 + 9.0 = 12.0\ \Omega$

8. C. We can find the current through the globe by finding the total current in the series circuit, $V_T = IR_T$.

9. B. We can find the power dissipated by the globe by considering the current through the globe and the resistance of the globe, $P = I^2R_{Globe}$.

10. $R_T = R_{eq} = R_1 + R_2 + R_3 = 1.5 + 1.5 + 9.0 = 12.0\ \Omega$ (1 MARK)

$V_T = IR_T \Rightarrow 18 = I \times 12.0$

$I = 1.50$ A

$P_{Globe} = I^2R_{Globe} = 1.50^2 \times 9.0$ (1 MARK)

$P_{Globe} = 20.3 = 20$ W (1 MARK)

31% of students answered this VCAA exam question correctly.

Exam-style

11. **a.** $V_T = IR_T \Rightarrow 10 = I \times 200$

$I = 0.0500 = 0.050$ A

b. The current through the power supply is 0.050 A.

c. $P_{200\ \Omega} = V_{200\ \Omega}I = 10 \times 0.050$

$P_{200\ \Omega} = 0.500 = 0.50$ W

12. B. $R_T = R_{eq} = R_1 + R_2 + R_3 + R_4$

$= 300 + 2.00 \times 10^3 + 500 + 1.00 \times 10^3 = 3.80$ kΩ

13. **a.** $V_T = IR_T = 10.0 = 5.0 \times R_T$

$R_T = 2.00 = 2.0\ \Omega$, as required.

b. $R_T = R_{eq} = R_1 + R_2$

$2.0 = 1.5 + R_2$ (1 MARK)

$R_2 = 0.5\ \Omega$ (1 MARK)

14. B. $V_R = V_{supply} - V_{light} = 7 - 5 = 2.0$ V

$V_R = IR_R \Rightarrow 2.0 = I \times 2 \Rightarrow I = 1.0$ A

$P_{light} = V_{light}I = 5 \times 1 = 5$ W

15. **a.** $R_T = R_{eq} = R_1 + R_2 + R_3 = 2.0 + 2.0 + 12.0 = 16.0\ \Omega$

$P_T = \frac{V_{supply}^{\ 2}}{R_T} = \frac{50.0^2}{16.0}$ (1 MARK)

$P = 1.56 \times 10^2 = 1.6 \times 10^2$ W (1 MARK)

b. $V_{sup} = IR_T \Rightarrow 50.0 = I \times 16.0$ (1 MARK)

$I = 3.13$ A

$V_{12\ \Omega} = IR_{12\ \Omega} = 3.13 \times 12.0$

$V_{12\ \Omega} = 37.5 = 38$ V (1 MARK)

c. $R_{combined} = R_{eq} = R_1 + R_2 = 2.0 + 2.0 = 4.0\ \Omega$

$P_{combined} = I^2R_{combined} = 3.125^2 \times 4.0$ (1 MARK)

$P_{combined} = 39.1 = 39$ W (1 MARK)

16. $P_G = V_GI \Rightarrow 4.0 = 2.0 \times I$ (1 MARK)

$I = 2.0$ A

$P_{line} = I^2R_{line}$

$P_{line} = 2.0^2 \times (2.0 + 2.0)$ (1 MARK)

$P_{line} = 16.0 = 16$ W (1 MARK)

62% of students answered this VCAA exam question correctly.

17. **a.** [There is no current running through the 10 Ω resistor when the switch is in the position shown,[1]] [as the 10 Ω resistor is in an open circuit.[2]]

- I have identified there is no current through the 10 Ω resistor in the position shown.[1]
- I have explained the 10 Ω resistor is an open circuit.[2]

b. $P_G = I^2R_G \Rightarrow 6.0 = I^2 \times 10$ (1 MARK)

$I = 0.775$ A

$V_{supply} = IR_T = 0.775 \times (10 + 5.0)$ (1 MARK)

$V_{supply} = 11.6 = 12$ V (1 MARK)

c. [When the switches are flicked, the total equivalent resistance of the circuit increases, as the closed circuit now consists of the globe and a 10 Ω resistor in series.[1]] [As $V_{supply} = IR_T$, increasing the total equivalent resistance of the circuit will decrease the current in the circuit.[2]] [As a result, the power dissipated by the globe, $P_G = I^2R_G$, will also decrease.[3]]

- I have identified that changing the position of the switches increase the total equivalent resistance of the circuit.[1]
- I have explained that the current in the circuit decreases as a result.[2]
- I have explained that the power dissipated by the light globe will decrease.[3]

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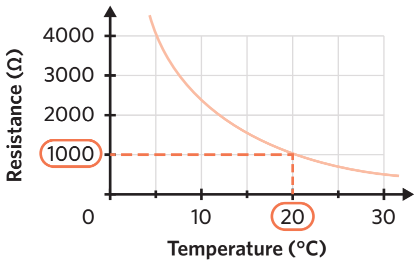
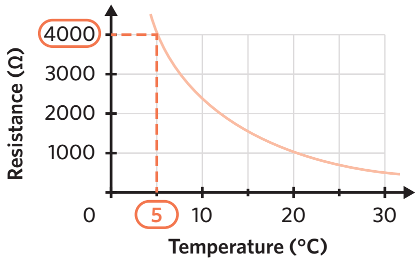
18. a. 1000 Ω



97% of students answered this VCAA exam question correctly.

FROM LESSON 12D

b.



At 5°C, $R_{thermistor} = 4000\ \Omega$ (1 MARK)

$V_{thermistor} = IR_{thermistor}$

$4.0 = I \times 4000$ (1 MARK)

$I = 1.00 \times 10^{-3}$ A

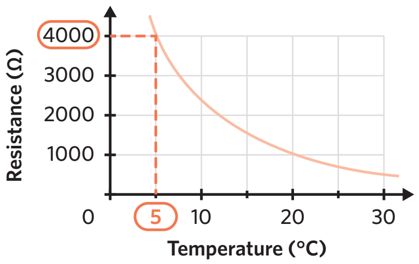
$V_R = IR_R$

$(12 - 4.0) = 1.00 \times 10^{-3} \times R_R$ (1 MARK)

$R_R = 8.00 \times 10^3 = 8.0 \times 10^3\ \Omega$ (1 MARK)

52% of students answered this VCAA exam question correctly.

OR



At 5°C, $R_{thermistor} = 4000\ \Omega$ (1 MARK)

$V_R = V_{supply} - V_{thermistor} = 12 - 4.0 = 8.0$ V

As the resistor and thermistor are in series with one another:

$I = \frac{V_R}{R_R} = \frac{V_{thermistor}}{R_{thermistor}}$ (1 MARK)

$\frac{8.0}{R_R} = \frac{4.0}{4000}$ (1 MARK)

$R_R = 8.00 \times 10^3 = 8.0 \times 10^3\ \Omega$ (1 MARK)

52% of students answered this VCAA exam question correctly.

c. [If the temperature in the coolroom was lower, the resistance of the thermistor would increase (this can be seen from the graph).[1]][Since the variable resistor still requires 4.0 V to control the relay, its resistance must be increased,[2]][so that the voltage across the variable resistor is not decreased as a result of the increase in the thermistor's resistance.[3]]

- I have identified that the resistance of the thermistor will increase is the temperature in the coolroom lowers.[1]
- I have identified that the resistance of the variable resistor must also increase.[2]
- I have explained that the voltage across the variable resistor must not decrease as a result of the increase in the thermistor's resistance in order for the relay to operate correctly.[3]

19% of students answered this VCAA exam question correctly.

Previous lessons

19. $SPE = \frac{1}{2}k(\Delta x)^2 \Rightarrow 140 = \frac{1}{2} \times k \times \left(\frac{16}{100}\right)^2$ (1 MARK)

$k = 1.09 \times 10^4 = 1.1 \times 10^4$ N m^{-1} (1 MARK)

FROM LESSON 2D

20. $F_g = F_B$

$mg = qvB$

$\Rightarrow 1.67 \times 10^{-27} \times 9.8 = 1.6 \times 10^{-19} \times 1.4 \times 10^5 \times B$ (1 MARK)

$B = 7.31 \times 10^{-13} = 7.3 \times 10^{-13}$ T (1 MARK)

FROM LESSON 4C

6B Transformers and comparing AC and DC power

Progress questions

1. B. The peak voltage is the amplitude of the voltage vs. time graph, 3.0 V.

2. B. $V_{RMS} = \frac{1}{\sqrt{2}}V_{peak} = \frac{1}{\sqrt{2}} \times 3.0 = 2.1$ V

3. C. The RMS voltage represents a DC equivalent for an AC power supply.

4. B. $I_{peak} = \frac{I_{p-p}}{2} = \frac{4.0}{2} = 2.0$ A

$P = I_{RMS}{}^2R = \left(\frac{1}{\sqrt{2}} \times 2.0\right)^2 \times 15 = 30$ W

5. B. As the transformer is ideal, $P_1 = P_2$. As the resistor is the only component connected to the secondary coil, all of the power delivered to the secondary coil is dissipated by the resistor.

6. D. $\frac{N_1}{N_2} = \frac{V_1}{V_2} \Rightarrow \frac{50}{100} = \frac{50}{V_2} \Rightarrow V_2 = 100\ V_{RMS}$. As the resistor is the only component connected to the secondary coil, all of the voltage delivered to the secondary coil is dropped across the resistor.

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Deconstructed exam-style

7. C. As we know information about the primary and secondary voltage, the correct ratio involving voltage and current should be used.

8. $I_{RMS} = \frac{1}{\sqrt{2}} I_{peak}$

9. $\frac{V_1}{V_2} = \frac{I_2}{I_1} \Rightarrow \frac{240}{8.0} = \frac{I_2}{0.35}$ (1 MARK)

$I_2 = 10.5\ A_{RMS}$

$I_{2,\,RMS} = \frac{1}{\sqrt{2}} I_{2,\,peak} \Rightarrow 10.5 = \frac{1}{\sqrt{2}} I_{2,\,peak}$ (1 MARK)

$I_{2,\,peak} = 14.8 = 15\ A$ (1 MARK)

Exam-style

10. D. $\frac{N_1}{N_2} = \frac{345}{15} = 23 \Rightarrow N_1{:}N_2 = 23{:}1$

11. B. The DC voltage required to operate the speaker correctly is the same as the AC RMS voltage required.

12. a. $I_{RMS} = \frac{1}{\sqrt{2}} I_{peak} \Rightarrow 13.5 = \frac{1}{\sqrt{2}} I_{peak}$

$I_{peak} = 19.09\ A$

$I_{p-p} = 2I_{peak} = 2 \times 19.09$

$I_{p-p} = 38.18 = 38.2\ A$

b. $\frac{N_1}{N_2} = \frac{I_2}{I_1} \Rightarrow \frac{200}{1200} = \frac{13.5}{I_1}$

$I_1 = 81.00 = 81.0\ A_{RMS}$

13. B. $V_{peak} = 3.5 \times 3.0 = 10.5\ V$

$V_{RMS} = \frac{1}{\sqrt{2}} V_{peak} = \frac{1}{2} \times 10.5 = 7.4\ V$

84% of students answered this VCAA exam question correctly.

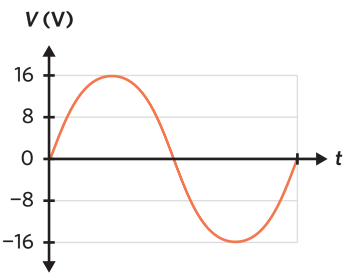
14. a. $\frac{N_1}{N_2} = \frac{V_1}{V_2} \Rightarrow \frac{500}{4000} = \frac{2.0}{V_2}$ (1 MARK)

$V_2 = 16\ V_{peak}$

$P_2 = \frac{V_{drop}{}^2}{R_2} = \frac{\left(\frac{1}{\sqrt{2}} \times 16\right)^2}{1000}$ (1 MARK)

$P_2 = 0.128 = 0.13\ W$ (1 MARK)

b.



I have drawn a sinusoidal graph.

I have drawn a peak voltage of 16 V.

Note that a range of starting points for the sinusoidal graph is acceptable.

FROM LESSON 12D

c. [By Faraday's law, there will be an induced voltage in the secondary coil, and hence a current in the resistor, only when there is a change in magnetic flux through the secondary coil.[1]] [When the switch is closed, there is an increase in the current in the primary coil, from zero, which results in a change in the flux in the secondary coil and a voltage induced.[2]] [When the switch remains closed there is no change in the current in the primary coil and so no change in the flux and no voltage is induced.[3]]

I have explained that a change in flux is required through the secondary coil for a voltage to be induced.[1]

I have explained that as the switch closes, there is a change in flux in the secondary coil.[2]

I have explained that when the switch remains close, there is no change in flux in the secondary coil.[3]

16% of students answered this VCAA exam question correctly.

15. On the secondary side:

$V_2 = R_2 I_2 \Rightarrow 20.0 = 10 \times I_2$ (1 MARK)

$I_2 = 2.00\ A_{RMS}$

$\frac{N_1}{N_2} = \frac{I_2}{I_1} \Rightarrow \frac{15}{1} = \frac{2.00}{I_1}$ (1 MARK)

$I_1 = 0.133\ A_{RMS}$

$I_{RMS} = \frac{1}{\sqrt{2}} I_{peak} \Rightarrow 0.133 = \frac{1}{\sqrt{2}} I_{peak}$

$I_{peak} = 0.189\ A$ (1 MARK)

$I_{p-p} = 2I_{peak} = 2 \times 0.189\ A$

$I_{p-p} = 0.377 = 0.38\ A$ (1 MARK)

16. A. When a DC voltage is connected to a transformer, there is no output voltage.

16% of students answered this VCAA exam question correctly.

17. $P = \frac{V_2{}^2}{R} \Rightarrow 144 = \frac{V_2{}^2}{36}$ (1 MARK)

$V_2 = 72.0\ V_{RMS}$

$\frac{N_1}{N_2} = \frac{V_1}{V_2} \Rightarrow \frac{500}{N_2} = \frac{\left(\frac{1}{\sqrt{2}} \times 18.5\right)}{72.0}$ (1 MARK)

$N_2 = 2752$ turns (1 MARK)

18. a. $\frac{N_1}{N_2} = \frac{V_1}{V_2} \Rightarrow \frac{1}{10} = \frac{200}{V_2}$ (1 MARK)

$V_2 = 2000\ V_{RMS}$

$P_1 = P_2 = V_2 I_2 \Rightarrow 400 = 2000 \times I_2$ (1 MARK)

$I_2 = 0.200\ A$

$P_{15.0\,\Omega} = I_{15.0\,\Omega}{}^2 R_{15.0\,\Omega} = 0.200^2 \times 15.0$ (1 MARK)

$P_{15.0\,\Omega} = 0.600\ W$ (1 MARK)

b. $\frac{N_1}{N_2} = \frac{I_2}{I_1} \Rightarrow \frac{5}{1} = \frac{I_R}{0.200}$ (1 MARK)

$I_R = 1.00\ A$

$P_R = I_R{}^2 R \Rightarrow 400 - 0.600 = 1.00^2 \times R$ (1 MARK)

$R = 399.4 = 399\ \Omega$ (1 MARK)

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c. [To increase the amount of power supplied to R, the amount of power dissipated by the 15.0 Ω resistor must be reduced.[1]] [This can be done by reducing the current through 15.0 Ω resistor, as $P = I^2R$.[2]] [By increasing the turns ratio of the first transformer, the current through 15.0 Ω resistor is reduced.[3]]

- I have identified that the amount of power dissipated by the 15.0 Ω resistor must be reduced to increase the power supplied to R.[1]
- I have explained reducing the current through 15.0 Ω resistor will reduce the power dissipated by it.[2]
- I have explained by increasing the turns ratio of the first transformer will reduce the current through the 15.0 Ω resistor.[3]

Previous lessons

19. $SPE = \frac{1}{2}k(\Delta x)^2 = \frac{1}{2} \times 15 \times \left(\frac{20-15}{100}\right)^2$ (1 MARK)

$SPE = 1.88 \times 10^{-2} = 1.9 \times 10^{-2}$ J (1 MARK)

FROM LESSON 2D

20. [By the right hand palm rule, the force on side WX is directed downwards and the force on side YZ is directed upwards.[1]] [The coil begins to rotate because the forces that act on the current-carrying wires WX and YZ are in opposite directions, which creates a torque (turning effect).[2]]

- I have identified the direction of the magnetic force on sides WX and YZ by the right hand palm rule.[1]
- I have explained that the forces on sides WX and YZ creates a torque (turning effect) on the coil.[2]

36% of students answered this VCAA exam question correctly.

FROM LESSON 4D

6C Transmission of power

Progress questions

1. A. $P_{supply} = V_{supply}I \Rightarrow 300 = 30 \times I \Rightarrow I = 10$ A

2. B. $V_{drop} = I_{line}R_{line} = 10 \times 2.00 = 20$ V

$P_{loss} = I_{line}^2R_{line} = 10^2 \times 2.00 = 200$ W

3. D. By reducing the current in transmission lines, the power loss in transmission lines is reduced. This means AC power can be transmitted more efficiently.

4. B, D. The power loss can either be calculated using the voltage drop in the line or the current and resistance of the lines.

5. B. As $V_{drop} = I_{line}R_{line}$, decreasing I_{line} by a factor 4 will decrease the V_{drop} by a factor 4.

6. D. As $P_{loss} = I_{line}^2R_{line}$, decreasing I_{line} by a factor 4 will decrease the P_{loss} by a factor 16.

Deconstructed exam-style

7. B. The power supplied by the clubhouse is dissipated by the transmission lines and the light tower.

8. $\frac{N_1}{N_2} = \frac{I_2}{I_1} \Rightarrow \frac{10}{1} = \frac{3.0}{I_{line}}$

$I_{line} = 0.30$ A

9. C. Power loss in transmission lines depends on the current through the transmission lines and their resistance.

10. $\frac{N_1}{N_2} = \frac{I_2}{I_1} \Rightarrow \frac{10}{1} = \frac{3.0}{I_{line}}$ (1 MARK)

$I_{line} = 0.30$ A

$P_{loss} = I_{line}^2 R_{line} = 0.30^2 \times 100$ (1 MARK)

$P_{loss} = 9.00$ W

$P_{supply} = P_{loss} + P_{light\ tower} = 9.00 + 720$ (1 MARK)

$P_{supply} = 729.0 = 729$ W (1 MARK)

Exam-style

11. B. By transmitting electricity at a high voltage, the current is reduced. As a result, the power loss in the transmission lines, $P_{loss} = I_{line}^2 R_{line}$, is also reduced.

12. a. [The input power is the same as the output power in an ideal transformer.[1]]

- I have described the input power is the same as the output power in an ideal transformer.[1]

b. $\frac{N_1}{N_2} = \frac{V_1}{V_2} = \frac{240}{12} = 20$

$N_1 : N_2 = 20:1$

c. $R_{line} = R_{line\ per\ m}L = 0.050 \times (12 \times 2)$

$R_{line} = 1.20$ Ω

$V_{drop} = I_{line}R_{line} = 3.0 \times 1.20$ (1 MARK)

$V_{drop} = 3.6$ V

$V_{supply} = V_{drop} + V_{light} \Rightarrow 12 = 3.6 + V_{light}$ (1 MARK)

$V_{light} = 8.4 = 8$ V (1 MARK)

13. a. [When the resistor is added, it will dissipate some of the power provided by the power supply.[1]] [As a result, less power will dissipated by the light globe, so it will be dimmer.[2]]

- I have identified that the resistor will dissipate power provided by the power supplied.[1]
- I have predicted that the light globe will be dimmer.[2]

FROM LESSON 12A

Back to contents

b. [When the resistor is moved to the secondary circuit, the current through the resistor will be reduced due to the step up transformer.[1]][The power dissipated by the resistor, $P = I^2R$, will also be reduced.[2]][As a result, more power will be dissipated by the light globe, so it will be brighter than when the resistor is on the primary side.[3]]

- I have identified that moving the resistor to the secondary circuit will reduce the current through the resistor.[1]
- I have identified that the power dissipated by the resistor will be reduced.[2]
- I have predicted that the light globe will be brighter than when the resistor is on the primary side.[3]

FROM LESSON 12A

c. [Replacing the AC power supply with a DC battery will mean there is no power in the secondary coil, as the transformer does not operate with DC electricity.[1]][As a result, the light globe will not glow.[2]]

- I have identified that there will be no power in the secondary coil, as the transformer does not operate with DC electricity.[1]
- I have predicted that the light globe will not glow.[2]

FROM LESSON 12A

14. **a.** $P_{W.G} = V_{W.G.}I_{W.G.} = 415 \times 100$

$P_{W.G.} = 41500\text{ W} = 41.5\text{ kW}$, as required.

83% of students answered this VCAA exam question correctly.

b. $P_{loss} = I_{line}{}^2 R_{line} = 100^2 \times 2.0$ (1 MARK)

$P_{loss} = 20\,000\text{ W} = 20\text{ kW}$

$P_{W.G.} = P_{loss} + P_{factory} \Rightarrow 41.5 = 20 + P_{factory}$ (1 MARK)

$P_{factory} = 21.5 = 20\text{ kW}$

The energy system will not be able to supply power to the factory as shown as $P_{factory} < 40\text{ kW}$. (1 MARK)

65% of students answered this VCAA exam question correctly.

c. At the step-up transformer:

$\frac{N_1}{N_2} = \frac{I_2}{I_1} \Rightarrow \frac{1}{10} = \frac{I_{line}}{100}$ (1 MARK)

$I_{line} = 10\text{ A}$

$P_{loss} = I_{line}{}^2 R_{line} = 10^2 \times 2.0$ (1 MARK)

$P_{loss} = 200\text{ W} = 0.200\text{ kW}$

$P_{W.G.} = P_{loss} + P_{factory} \Rightarrow 41.5 = 0.200 + P_{factory}$ (1 MARK)

$P_{factory} = 41.3 = 41\text{ kW}$ (1 MARK)

55% of students answered this VCAA exam question correctly.

15. A. From $\frac{N_1}{N_2} = \frac{I_2}{I_1}$, doubling the number of secondary coils will halve the current in the transmission lines. As $P_{loss} = I_{line}{}^2 R_{line}$, the new power loss will be a quarter of the old power loss.

16. **a.** $P_1 = P_2 \Rightarrow P_1 = V_2 I_2$

$500 \times 10^6 = 500 \times 10^3 \times I_2$ (1 MARK)

$I_2 = 1.00 \times 10^3 = 1.0 \times 10^3\text{ A}$ (1 MARK)

OR

$P_{plant} = V_{plant} I_{plant} \Rightarrow 500 \times 10^6 = 25 \times 10^3 \times I_{plant}$

$I_{plant} = 2.00 \times 10^4\text{ A}$

$\frac{V_1}{V_2} = \frac{I_2}{I_1} \Rightarrow \frac{5 \times 10^3}{500 \times 10^3} = \frac{I_{line}}{2.00 \times 10^4}$ (1 MARK)

$I_{line} = 1.00 \times 10^3 = 1.0 \times 10^3\text{ A}$ (1 MARK)

42% of students answered this VCAA exam question correctly.

b. $P_{loss} = I_{line}{}^2 R_{line} = (1.00 \times 10^3)^2 \times 30.0$ (1 MARK)

$P_{loss} = 3.00 \times 10^7\text{ W}$

$P_{gen} = P_{loss} + P_{domestic}$

$\Rightarrow 500 \times 10^6 = 3.00 \times 10^7 + P_{domestic}$ (1 MARK)

$P_{domestic} = 4.70 \times 10^8 = 4.7 \times 10^8\text{ W}$ (1 MARK)

32% of students answered this VCAA exam question correctly.

c. [Voltage is stepped up for transmission so that current can be reduced, while maintaining constant power.[1]][This reduces power loss in transmission, $P_{loss} = I_{lines}{}^2 R_{line}$, as I_{line} is reduced.[2]]

- I have explained that stepping up voltage for transmission allows the same amount of power to be transmitted at lower currents.[1]
- I have explained that lower current leads to lower power loss in transmission.[2]

12% of students answered this VCAA exam question correctly.

Previous lessons

17. **a.** $F_A = k_A \Delta x = 3.00 \times \left(\frac{5.88}{100}\right)$ (1 MARK)

$F_A = 0.1764 = 0.176\text{ N}$ (1 MARK)

35% of students answered this VCAA exam question correctly.

b. The sum of the two spring forces balances the force due to gravity.

$F_A + F_B = F_g \Rightarrow 0.1764 + F_B = mg$

$0.1764 + F_B = 60.0 \times 10^{-3} \times 9.8$ (1 MARK)

$F_B = 0.412 = 0.41\text{ N}$ (1 MARK)

FROM LESSON 2E

18. $\varepsilon = N\frac{\Delta\Phi_B}{\Delta t} = 15 \times \frac{(2.4 \times 10^{-2} \times 4.0 \times 10^{-3}) - 0}{0.25 - 0}$ (1 MARK)

$\varepsilon = 5.76 \times 10^{-3} = 5.8 \times 10^{-3}\text{ V}$ (1 MARK)

72% of students answered this VCAA exam question correctly.

FROM LESSON 5A

Chapter 6 review

Section A

1. B. $\frac{N_1}{N_2} = \frac{V_1}{V_2} = \frac{240}{16} = 15 \Rightarrow N_1{:}N_2 = 15{:}1$

84% of students answered this VCAA exam question correctly.

2. C. $P = VI \Rightarrow 80 = 240 \times I \Rightarrow I = 0.333\ \text{A}_{\text{RMS}}$

$\frac{V_1}{V_2} = \frac{I_2}{I_1} \Rightarrow \frac{240}{16} = \frac{I_2}{0.333} \Rightarrow I_2 = 5.00\ \text{A}_{\text{RMS}}$

$I_{2,\,RMS} = \frac{1}{\sqrt{2}} I_{2,\,peak} \Rightarrow 5.00 = \frac{1}{\sqrt{2}} I_{2,\,peak} \Rightarrow I_{2,\,peak} = 7.07 = 7.1\ \text{A}$

51% answered this VCAA exam question correctly.

3. C. $P_{loss} = I_{lines}{}^2 R_{lines} \Rightarrow 2450 = I_{lines}{}^2 \times 2.0$

$I_{lines} = 35\ \text{A}$

4. B. The output from the transformer will have the same frequency as the input. $\frac{N_1}{N_2} = \frac{V_1}{V_2} \Rightarrow \frac{180}{2880} = \frac{60.0}{V_2} \Rightarrow V_2 = 960\ \text{V}_{\text{RMS}}$

$960 = \frac{1}{\sqrt{2}} V_{peak} \Rightarrow V_{peak} = 1.36 \times 10^3\ \text{V}$

5. D. To reduce power loss in transmission lines, $P_{loss} = I_{lines}{}^2 R_{lines}$, the current in the transmission lines or resistance of the lines must be decreased. Decreasing the number of primary turns in the step-up transformer, N_1, will decrease the current in the transmission lines, I_2, as $\frac{N_1}{N_2} = \frac{I_2}{I_1}$.

Section B

6. a. $R_T = R_{eq} = R_1 + R_2$

$R_T = 2.0 + 3.0 = 5.0\ \Omega$

b. $V_T = IR_T \Rightarrow 9.0 = I \times 5.0$ (1 MARK)

$I = 1.80 = 1.8\ \text{A}$ (1 MARK)

c. $V_{2.0\,\Omega} = IR_{2.0\,\Omega} = 1.80 \times 2.0$

$V_{2.0\,\Omega} = 3.60 = 3.6\ \text{V}$

d. $P_{3.0\,\Omega} = I^2 R_{3.0\,\Omega} = 1.80^2 \times 3.0$

$P_{3.0\,\Omega} = 9.72 = 9.7\ \text{W}$

7. a. From the graph, $V_{peak} = 9.0\ \text{V}$.

FROM LESSON 12D

b. From the graph, $V_{p-p} = 18.0\ \text{V}$.

FROM LESSON 12D

c. $V_{RMS} = \frac{1}{\sqrt{2}} V_{peak} = \frac{1}{\sqrt{2}} \times 9.0$

$V_{RMS} = 6.36 = 6.4\ \text{V}$

8. a. $V_{RMS} = \frac{1}{\sqrt{2}} V_{peak} \Rightarrow 200 = \frac{1}{\sqrt{2}} V_{peak}$

$V_{peak} = 282.8 = 283\ \text{V}$

b. [A DC voltage of 200 V would provide the same average power,[1]] [as the RMS voltage of the AC power supply is equivalent to the DC voltage that supplies the same average power.[2]]

- I have identified that a DC voltage of 200 V would deliver the same average power.[1]
- I have justified that the RMS AC voltage delivers the same average power as the same value DC voltage.[2]

9. a. $P_{loss} = I_{lines}{}^2 R_{lines} = 2.5^2 \times (2.0 + 2.0)$ (1 MARK)

$P_{loss} = 25.0 = 25\ \text{W}$ (1 MARK)

75% of students answered this VCAA exam question correctly.

b. $\frac{N_1}{N_2} = \frac{I_2}{I_1} \Rightarrow \frac{3}{1} = \frac{I_2}{2.5}$ (1 MARK)

$I_2 = 7.50\ \text{A}$

$P_{P.C.} = V_{P.C.} I_{P.C.} = 5.0 \times 7.50$ (1 MARK)

$P_{P.C.} = 37.5 = 38\ \text{W}$ (1 MARK)

44% of students answered this VCAA exam question correctly.

c. $P_{supply} = P_{loss} + P_{P.C.} = 25.0 + 37.5$ (1 MARK)

$P_{supply} = 62.5 = 63\ \text{W}$ (1 MARK)

d. A current of 7.5 A (calculated in part **b**) must still flow through the charger for it to operate correctly.

$\frac{N_1}{N_2} = \frac{I_2}{I_1} \Rightarrow \frac{6}{1} = \frac{7.5}{I_1}$ (1 MARK)

$I_1 = 1.25\ \text{A}$

$P_{loss} = I_{line}{}^2 R_{line} = 1.25^2 \times 4.0$ (1 MARK)

$P_{loss} = 6.25 = 6.3\ \text{W}$ (1 MARK)

e. [Unlike DC power, AC power can utilise transformers to reduce power loss.[1]] [Transformers allow for transmission at a higher voltage and a reduced current.[2]] [As $P_{loss} = I_{line}{}^2 R_{line}$, this results in reduced power loss during long distance transmission for AC power compared to DC power.[3]]

- I have identified that AC power can utilise transformers to reduce power loss.[1]
- I have identified that AC power can be transmitted at a reduced current.[2]
- I have explained a reduced current means less power is lost in transmission.[3]

10. a. $\frac{N_1}{N_2} = \frac{V_1}{V_2} \Rightarrow \frac{N_1}{50} = \frac{12000}{300}$ (1 MARK)

$N_1 = 2000$ turns (1 MARK)

b. $P_{loss,\,old} = I_{lines}{}^2 R_{lines}$

$P_{loss,\,new} = \left(\frac{1}{2} I_{lines}\right)^2 R_{lines} = \frac{1}{4} I_{lines}{}^2 R_{lines} = \frac{1}{4} P_{loss,\,old}$ (1 MARK)

The new power loss is $\frac{1}{4}$ of the old power loss. (1 MARK)

45% of students answered this VCAA exam question correctly.

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c. [A battery produces DC power which cannot be transmitted through a transformer.[1]] [A transformer relies on a changing magnetic field produced by the primary coil to induce a current in the secondary coil.[2]] [The constant current from a battery produces a constant magnetic field so there is no induced current in the secondary coil.[3]]

- I identified that a battery's DC power cannot be transmitted through a transformed.[1]
- I have explained a transformer requires a changing magnetic field in the primary coil to induce a current in the secondary coil.[2]
- I have explained a battery does not produce a changing magnetic field.[3]

11. a. $P_{supply} = V_{supply} I_{supply} = 40\,000 \times 10.0$ (1 MARK)

$P_{supply} = 4.000 \times 10^5 = 4.00 \times 10^5$ W (1 MARK)

85% of students answered this VCAA exam question correctly.

b. $P_{loss} = 0.15 \times P_{supply} = 0.15 \times 4.000 \times 10^5$ (1 MARK)

$P_{loss} = 6.00 \times 10^4$ W

$P_{loss} = I_{lines}{}^2 R_{lines} \Rightarrow 6.00 \times 10^4 = (10.0)^2 \times R_{lines}$ (1 MARK)

$R_{lines} = 6.00 \times 10^2\ \Omega$

$R_{lines\ per\ km} = \dfrac{R_{lines,\ total}}{L} = \dfrac{6.00 \times 10^2}{2 \times 25}$ (1 MARK)

$R_{lines\ per\ km} = 12.0 = 12\ \Omega\ \text{km}^{-1}$ (1 MARK)

c. [The AC current in the primary coil creates a changing magnetic flux.[1]] [This changing magnetic flux is directed through the secondary coil via the iron core.[2]] [The changing magnetic flux through the secondary coil induces an EMF in the secondary coil.[3]]

- I have described how the AC current produces a changing magnetic flux.[1]
- I have described how the iron core directs the changing flux to the secondary coil.[2]
- I have explained that this change in flux induces an EMF in the secondary coil.[3]

12. $P_{supply} = P_{loss} + P_{load} \Rightarrow 10\,000 = P_{loss} + 9980$

$P_{loss} = 20$ W

$P_{loss} = I_{lines}{}^2 R_{lines} \Rightarrow 20 = I_{lines}{}^2 \times 5.00$

$I_{lines} = 2.00$ A

$P_{supply} = V_{supply} I_{supply} \Rightarrow 10\,000 = 500 \times I_{supply}$

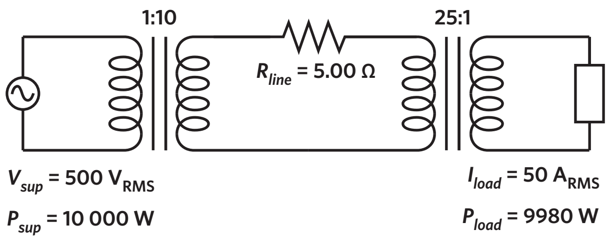
$I_{supply} = 20.0$ A

For the step-up transformer:

$\dfrac{N_1}{N_2} = \dfrac{I_2}{I_1} = \dfrac{2.00}{20.0} = \dfrac{1}{10} \Rightarrow N_1{:}N_2 = 1{:}10$

For the step down transformer:

$\dfrac{N_1}{N_2} = \dfrac{I_2}{I_1} = \dfrac{50}{2.00} = 25 \Rightarrow N_1{:}N_2 = 25{:}1$



- I have drawn an AC power supply of 10 000 W at 500 V_{RMS}
- I have drawn a step-up transformer with turns ratio 1:10
- I have drawn the transmission lines as a 4.00 Ω resistor
- I have drawn a step-down transformer with turns ratio 25:1
- I have drawn a load dissipating 9980 W at 50 A_{RMS}

Unit 3 AOS 3 review

Section A

1. C. The induced EMF depends on the change in the magnetic flux, rather than the value of the magnetic flux.

60% of students answered this VCAA exam question correctly.

2. B. $\dfrac{N_1}{N_2} = \dfrac{V_1}{V_2} = \dfrac{240}{6000} = \dfrac{1}{25} \Rightarrow 1{:}25$

84% of students answered this VCAA exam question correctly.

3. B. $P_{RMS} = V_{RMS} I_{RMS} \Rightarrow 75.0 = 6000 \times I_{RMS} \Rightarrow I_{RMS} = 0.0125$ A

$I_{RMS} = \dfrac{1}{\sqrt{2}} I_{peak} \Rightarrow 0.0125 = \dfrac{1}{\sqrt{2}} \times I_{peak} \Rightarrow I_{peak} = 1.77 \times 10^{-2}$ A

51% of students answered this VCAA exam question correctly.

4. A. $\varepsilon = N\dfrac{\Delta\Phi}{\Delta t} \Rightarrow 7.5 = 80 \times \dfrac{2.2 \times 10^{-3}}{\Delta t} \Rightarrow \Delta t = 2.34 \times 10^{-2}$ $= 2.3 \times 10^{-2}$ s

5. D. Decreasing the period of rotation increases the voltage (peak and RMS) since the changes in magnetic flux happen faster.

Section B

6. a. $P = VI \Rightarrow 18 = 4.5 \times I$ (1 MARK)

$I = 4.0$ A

$\dfrac{I_2}{I_1} = \dfrac{N_1}{N_2} \Rightarrow \dfrac{4.0}{I_{line}} = \dfrac{20}{1}$ (1 MARK)

$I_{line} = 0.20$ A (1 MARK)

75% of students answered this VCAA exam question correctly.

b. $P_{loss} = I_{line}^2 R_{line} = 0.20^2 \times (3.0 + 3.0)$ (1 MARK)

$P_{loss} = 0.24$ W (1 MARK)

67% of students answered this VCAA exam question correctly.

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c. $\frac{V_1}{V_2} = \frac{N_1}{N_2} \Rightarrow \frac{V_1}{4.5} = \frac{20}{1}$ (1 MARK)

$V_1 = 90$ V (input to T_2)

$V_{drop} = I_{line} R_{line} = 0.20 \times 6.0 = 1.2$ V (1 MARK)

$V_{output} = V_1 + V_{drop} = 90 + 1.2 = 91.2$ V (1 MARK)

$\frac{V_1}{V_2} = \frac{N_1}{N_2} \Rightarrow \frac{V_{input}}{91.2} = \frac{1}{20}$

$V_{input} = 4.56 = 4.6$ V (1 MARK)

d. [Unlike DC, AC power is able to utilise ideal transformers.[1]] [Transformers allow for the transmission of power at a higher (stepped up) voltage and a reduced current.[2]] [As power loss is proportional to the square of current by $P_{loss} = I_{line}^2 R_{line}$, this results in reduced power loss compared to when using DC, which is why AC favourable for long distance power transmission.[3]]

- I have stated that AC power is able to utilise transformers.[1]
- I have described the function of transformers.[2]
- I have explained how reducing current reduces power loss.[3]

50% of students answered this VCAA exam question correctly.

e. [An inverter is used to convert DC electricity produced by solar panels into AC electricity used in the electricity grid.[1]]

- I have described the purpose of an inverter.[1]

7. a. [Slip rings act as a constant connection between the generator's coil and the external circuit.[1]] [This causes the alternating current produced in the coil during rotation to be transferred to the external circuit as AC power.[2]]

- I have described what slip rings do.[1]
- I have explained slip rings allow AC power to be transferred to the external circuit.[2]

b. $\frac{I_2}{I_1} = \frac{N_1}{N_2} \Rightarrow \frac{I_2}{3.5} = \frac{1}{10}$ (1 MARK)

$I_2 = 0.35$ A

$P_{loss} = I_{line}^2 R_{line} = 0.35^2 \times 3.5 = 0.429 = 0.43$ W (1 MARK)

c. [The farmer could replace the slip ring with a split ring commutator.[1]] [The split rings would contact alternate sides of the generator's coil every half rotation, acting to rectify the AC output to DC.[2]]

- I have identified how to convert an AC generator to DC.[1]
- I have described how split ring commutators produce DC power.[2]

8. a. $P_{loss} = I_{line}^2 R_{line} = 16.0^2 \times 35.0$ (1 MARK)

$P_{loss} = 8.96 \times 10^3$ W (1 MARK)

76% of students answered this VCAA exam question correctly.

b. Output of step-up: $\frac{V_{1,\,step\text{-}up}}{V_{2,\,step\text{-}up}} = \frac{N_1}{N_2} \Rightarrow \frac{900}{V_{2,\,step\text{-}up}} = \frac{1}{15}$ (1 MARK)

$V_{2,\,step-up} = 1.35 \times 10^4$ V

$V_{drop} = I_{line} R_{line} = 16.0 \times 35.0 = 560$ V (1 MARK)

Input of step-down: $V_{1,\,step\text{-}down} = V_{2,\,step\text{-}up} - V_{drop}$
$= 1.35 \times 10^4 - 560 = 1.294 \times 10^4$ V (1 MARK)

Output of step-down is the voltage across the lamp:
$\frac{V_{1,\,step\text{-}down}}{V_{2,\,step\text{-}down}} = \frac{N_1}{N_2} \Rightarrow \frac{1.294 \times 10^4}{V_{lamp}} = \frac{15}{1}$

$V_{lamp} = 8.63 \times 10^2 = 8.6 \times 10^2$ V (1 MARK)

c. [One change that could be made to ensure the lamp operates correctly is increasing the output voltage of the power plant.[1]]

- I have stated one change that could be made to ensure the lamp operates correctly.[1]

Other possible answers

- Increasing the ratio of secondary to primary coils on the step-up transformer
- Decreasing the ratio of primary to secondary coils on the step-down transformer
- Using a thicker cable with less resistance

9. a. $\Phi_B = B_\perp A \Rightarrow 7.5 \times 10^{-3} = B_\perp \times 7.5 \times 10^{-2} \times 12.5 \times 10^{-2}$

$B_\perp = 0.80$ T or Wb m^{-2}

b. $T = \frac{1}{f} = \frac{1}{12} = 8.33 \times 10^{-2}$ s

For a quarter rotation: $\Delta t = \frac{8.33 \times 10^{-2}}{4} = 2.08 \times 10^{-2}$ s (1 MARK)

$\varepsilon = -N\frac{\Delta\Phi_B}{\Delta t} = 10 \times \frac{7.5 \times 10^{-3}}{2.08 \times 10^{-2}}$ (1 MARK)

$\varepsilon = -3.6$ V

The average EMF induced in the coil over one quarter rotation is 3.6 V. (1 MARK)

c. [As the coil rotates in the magnetic field, the magnetic flux through the coil was to the right and increasing when viewed from the handle.[1]] [Hence the induced current would oppose this change in magnetic flux and increase magnetic flux to the left by Lenz's law.[2]] [Using the right-hand grip rule, the induced current would be from Y to X.[3]]

- I have described the initial change in magnetic flux.[1]
- I have determined the direction of the induced magnetic flux using Lenz's law.[2]
- I have stated the direction of the induced current using the right-hand grip rule.[3]

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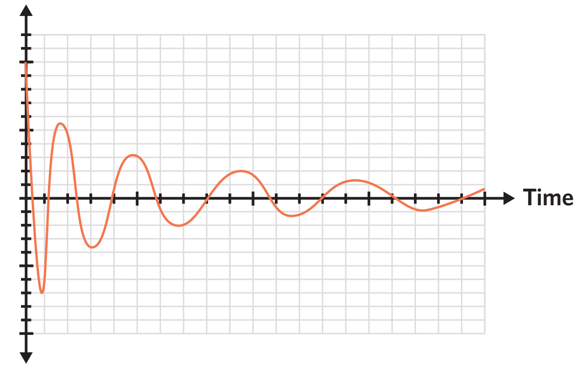
d. EMF

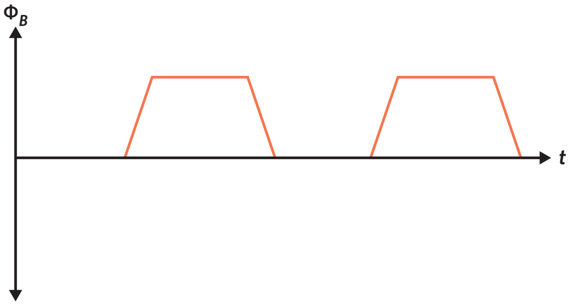


I have correctly labelled my axes.[1]

I have drawn an oscillating voltage.[2]

I have drawn a graph with decreasing amplitude and increasing period.[3]

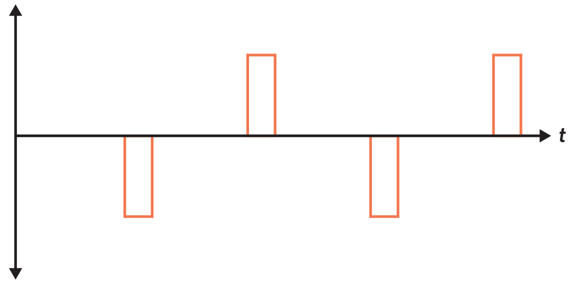
10. a.



I have correctly labelled the axes.[1]

I have drawn two trapeziums with zero magnetic flux before, after, and in between them.[2]

b. EMF



I have correctly labelled the axes.[1]

I have drawn four equal rectangles alternating above and below the horizontal axis with zero EMF before, after, and in between them.[2]

c. At $t = 0$ s:

$\Phi_B = B_\perp A = 0.500 \times 0 = 0$

At $t = 0.10$ s:

$\Phi_B = B_\perp A = 0.500 \times (15 \times 10^{-2} \times 25 \times 10^{-2})$

$= 1.875 \times 10^{-2}$ Wb

$\varepsilon = -N\frac{\Delta\Phi_B}{\Delta t} = 25 \times \frac{1.875 \times 10^{-2} - 0}{0.10}$ (1 MARK)

$\varepsilon = -4.69 = 4.7$ V

The magnitude of the EMF induced in the coil is 4.7 V. (1 MARK)

d. [When viewed from the north pole, the magnetic flux through the loop is increasing away from the pole (into the page).[1]] [By Lenz's law, the induced magnetic field will oppose this change in magnetic flux, so it will be directed towards the pole (out of the page).[2]] [Using the right-hand coil rule, the induced current will flow anticlockwise when viewed from the north pole.[3]]

I have identified whether the magnetic flux is increasing or decreasing, and in which direction.[1]

I have determined the direction of the induced magnetic field using Lenz's law.[2]

I have determined the direction of the induced current using the right-hand coil rule.[3]

UNIT 3 AOS 3 REVIEW

7A Waves recap

Progress questions

1. D. Direction of oscillation is the most important distinction between longitudinal and transverse waves.

2. A. $f = \frac{1}{T} \Rightarrow 3.0 = \frac{1}{T} \Rightarrow T = 0.33$ s

3. C. Measuring compression to compression or rarefaction to refraction is the longitudinal equivalent of measuring crest to crest or trough to trough in transverse waves.

4. C, D. Features to do with time can not be read off a displacement-distance graph.

5. A, C. Period can be read using the horizontal axis and amplitude can be read using the vertical axis.

6. D. The wave speed is determined only by the medium the wave is travelling in.

7. C. The frequency is determined by the source of the wave.

8. C. $v = f\lambda \Rightarrow 330 = 60 \times \lambda \Rightarrow \lambda = 5.5$ m

9. B, C. As the speed of a wave is constant in the same medium, if the wave's wavelength is doubled the frequency will halve, and period will double, to satisfy the wave equation.

10. A. $v_A = f\lambda = 10 \times 20 = 200$ m s^{-1} $< v_D = 80 \times 5$ $= 400$ m s^{-1} $< v_B = 25 \times 20 = 500$ m s^{-1} $< v_C = 60 \times 30$ $= 1800$ m s^{-1}

Deconstructed exam-style

11. $\lambda = 2 \times 1.2 = 2.4$ m

12. C. The wave equation, $v = f\lambda$, relates the speed, frequency, and wavelength of a wave.

13. $\lambda = 2 \times 1.2 = 2.4$ m

$v = f\lambda = 300 \times 2.4$ (1 MARK)

$v = 720 = 7.2 \times 10^2$ m s^{-1} (1 MARK)

66% of students answered this VCAA exam question correctly.

Exam-style

14. $v = f\lambda \Rightarrow 340 = 880 \times \lambda$

$\lambda = 3.9 \times 10^{-1}$ m

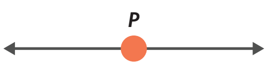
92% of students answered this VCAA exam question correctly.

15. B. Waves transfer energy without the net transfer of matter.

16. **a.** $v = \frac{\lambda}{T} \Rightarrow 0.40 = \frac{\lambda}{8.0}$

$\lambda = 3.2$ m

b. Since the wave is longitudinal, Point P moves back and forth in the direction of the wave.



I have drawn two arrows parallel to the direction the wave travels.

17. C. The amplitude is the height of the wave while the frequency is $v = f\lambda \Rightarrow 20 = f \times 4.0 \times 10^{-2} \Rightarrow f = 500$ Hz.

55% of students answered this VCAA exam question correctly.

18. Based on wave equation, longest wavelength occurs at the lowest frequency 85 Hz. (1 MARK)

$\lambda = \frac{v}{f} = \frac{340}{85} = 4.0$ m (1 MARK)

19. [The particle oscillates left and right fifty times per second[1]] [about its neutral position 3.00 cm from the speaker.[2]]

I have described the motion of his particle.[1]

I have described the motion in relation to its neutral position.[2]

20. $\lambda = \frac{1}{4}$ length of tube $= \frac{1}{4} \times 2.00 = 0.500$ m

$v = f\lambda = 534 \times 0.500 = 267$ m s^{-1} (1 MARK)

The unknown gas is carbon dioxide. (1 MARK)

21. [Considering that wave speed is constant for a given medium, wavelength and frequency are the only variables that change in the equation $v = f\lambda$.[1]] [Therefore increasing the frequency of a wave decreases the wavelength allowing the wave speed to remain constant.[2]]

I have described the variables of the wave equation.[1]

I have explained the impact of changing the frequency of wave.[2]

22. [Dominique should make the period shorter[1]] [as period and frequency are inversely proportional ($f = \frac{1}{T}$), and so a smaller period, T, will result in a higher frequency, f.[2]]

I have identified whether the period should be shorter or longer.[1]

I have explained the relationship between period and frequency.[2]

23. $T = 4 \times 0.340 = 1.36$ s (1 MARK)

$f = \frac{1}{T} = \frac{1}{1.36} = 0.735$ Hz (1 MARK)

$v = f\lambda = 0.735 \times 1.80 = 1.32$ m s^{-1} (1 MARK)

OR

$T = 4 \times 0.340 = 1.36$ s (1 MARK)

$v = \frac{\lambda}{T} = \frac{1.80}{1.36}$ (1 MARK)

$v = 1.32$ m s^{-1} (1 MARK)

OR

$v = \frac{d}{t}$ (1 MARK)

$v = \frac{\left(\frac{1.80}{4}\right)}{0.340}$ (1 MARK)

$v = 1.32$ m s^{-1} (1 MARK)

41% of students answered this VCAA exam question correctly.

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24. a. W: not moving (1 MARK)

X: up (1 MARK)

Y: up (1 MARK)

Z: down (1 MARK)

b. [The graph is non-linear.[1]]

I have identified the type of graph.[1]

c. [Displacement-distance graphs display information about amplitude and wavelength[1]][however, does not display information about frequency and period.[2]][Transverse waves are better represented by displacement-distance graphs as they displace particles in the same direction as the graph.[3]][Longitudinal waves are poorly represented by displacement-distance graphs as they displace particles in a different direction to the graph.[4]]

I have identified a strength of displacement-distance graphs.[1]

I have identified a weakness of displacement-distance graphs.[2]

I have evaluated representing a transverse wave with displacement-distance graphs.[3]

I have evaluated representing a longitudinal wave with displacement-distance graphs.[4]

Previous lessons

25. a. $SPE_{bot} = \frac{1}{2}k(\Delta x)^2 = \frac{1}{2} \times 29.4 \times 1.00^2$ (1 MARK)

$SPE_{bot} = 14.7$ J (1 MARK)

OR

$SPE_{bot} = GPE_{top} = mgh_{top} = 1.50 \times 9.8 \times 1.00$ (1 MARK)

$SPE_{bot} = 14.7 = 15$ J (1 MARK)

87% of students answered this VCAA exam question correctly.

b. The speed will be at a maximum when its acceleration is zero, which is at the midpoint.

$KE_{bot} + GPE_{bot} + SPE_{bot} = KE_{mid} + GPE_{mid} + SPE_{mid}$

$SPE_{bot} = KE_{mid} + GPE_{mid} + SPE_{mid}$

$\Rightarrow 14.7 = \frac{1}{2}mv^2 + mgh + \frac{1}{2}k(\Delta x)^2$ (1 MARK)

$14.7 = \frac{1}{2} \times 1.50 \times v^2 + 1.50 \times 9.8 \times 0.50 + \frac{1}{2} \times 29.4 \times 0.50^2$ (1 MARK)

$v = 2.2 \text{ m s}^{-1}$ (1 MARK)

55% of students answered this VCAA exam question correctly.

c. [B is the correct graph.[1]][At the top, the acceleration is downwards because the only force is the force due to gravity.[2]][The spring force on the mass is directed upwards and it increases directly with the extension so that the net force and acceleration is zero at the midpoint[3]][and it is upwards at the lowest point.[4]]

I have identified the correct graph.[1]

I have explained the acceleration at the top.[2]

I have explained the acceleration at the midpoint.[3]

I have explained the acceleration at the lowest point.[4]

25% of students answered this VCAA exam question correctly.

FROM LESSON 2E

26. AC supply: $P = \frac{V_{RMS}^2}{R} = \frac{\left(\frac{325}{\sqrt{2}}\right)^2}{8.0} = 6.6 \times 10^3$ W (1 MARK)

DC supply: $P = \frac{V^2}{R} = \frac{250^2}{9.0} = 6.9 \times 10^3$ W

The DC supply provides more power. (1 MARK)

50% of students answered this VCAA exam question correctly.

FROM LESSON 5C

7B Wave interference and path difference

Progress questions

1. C. The amplitude of the two waves will sum as constructive interference is occurring: $A + A = 2A$
2. B. The amplitude of the waves have opposite signs (out of phase by 180°) so destructive interference will occur.
3. C. Points Y and Z both lie on points of consistent constructive interference, Z lies on a point of consistent destructive interference, and X lies equidistant to the speakers so will also experience consistent constructive interference.
4. D. Non-coherent sources still interact with constructive and destructive interference but consistent points of interference will not occur, they will change position.
5. A. $p.d. = |S_1X - S_2X| = |3.0 - 5.0| = 2.0$ m.
6. C. $\frac{3.0}{2.0} = 1.5\lambda$. A node requires the path difference to be an odd multiple of $\frac{\lambda}{2}$.
7. B. We count bands from zero so the second bright band has $n = 1$.

Deconstructed exam-style

8. $n = 2$
9. $p.d. = \left(n + \frac{1}{2}\right)\lambda \Rightarrow p.d. = \left(2 + \frac{1}{2}\right) \times 5.00 \times 10^{-2}$

$p.d. = 0.125 = 1.3 \times 10^{-2}$ m

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10. $p.d. = |PT - QT| = \left(n + \frac{1}{2}\right)\lambda$ (1 MARK)

$\left|PT - \left(\frac{15}{100}\right)\right| = \left(2 + \frac{1}{2}\right) \times 5.00 \times 10^{-2}$ (1 MARK)

$PT = 27.5 \times 10^{-2} = 2.75 \times 10^{-1}$ m (1 MARK)

Exam-style

11. B. $p.d. = n\lambda \Rightarrow 45 = 3\lambda \Rightarrow \lambda = 15$ m

12. **a.** From the diagram $PM = 2\lambda$ and $QM = 3\lambda$

$p.d. = |PM - QM|$

$4.0 = |2\lambda - 3\lambda| \Rightarrow 4.0 = |-\lambda|$ (1 MARK)

$\lambda = 4.0$ cm (1 MARK)

b. From the diagram $PN = 2\lambda$ and $QN = 1.5\lambda$ (1 MARK)

$p.d. = |PN - QN| = |2 \times 4.0 - 1.5 \times 4.0| = 2.0$ cm (1 MARK)

13. **a.** Y is the third loud point.

$p.d. = |S_1Y - S_2Y| = n\lambda$ (1 MARK)

$|1.0 - S_2Y| = 2 \times 0.60$ (1 MARK)

$S_2Y = 2.2$ m (1 MARK)

b. **i.** $p.d. = 0$ so constructive interference (high intensity) occurs.

ii. $\frac{p.d.}{\lambda} = \frac{1.2}{0.80} = 1.5$ (1 MARK)

$p.d. = \left(n + \frac{1}{2}\right)\lambda$ where $n = 1$ so destructive interference (low intensity) occurs. (1 MARK)

14. [At point C, the beacon will be in large waves.[1]][This is because the path difference is zero at this point, $p.d. = 0 = 0 \times \lambda$, resulting in constructive interference.[2]]

- I have identified the beacon is in large waves at point C.[1]
- I have explained constructive interference occurs at this point, as the $p.d. = 0$.[2]

15. **a.** $p.d. = |4.50 - 7.00| = 2.50$ m

$p.d. = \left(n + \frac{1}{2}\right)\lambda \Rightarrow 2.50 = \left(2 + \frac{1}{2}\right)\lambda$ (1 MARK)

$\lambda = 1.00$ m (1 MARK)

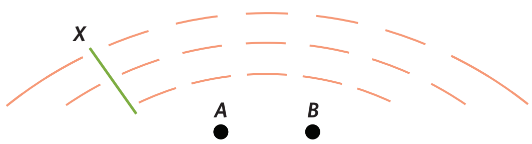
b. $f = \frac{v}{\lambda} = \frac{340}{1.00} = 340$ Hz

16. **a.** $p.d. = |7.0 - 12.0| = 5.0$ cm

$\frac{p.d.}{\lambda} = \frac{5.0}{2.0} = 2.5$ (1 MARK)

$p.d. = \left(n + \frac{1}{2}\right)\lambda$, where $n = 2$ so destructive interference occurs at X. (1 MARK)

b.



Any point along the green line (the third nodal line) is an acceptable location for X.

17. **a.** [Loud regions are caused by constructive interference and quiet regions are caused by destructive interference.[1]] [These regions alternate as Mark walks towards speaker A because the type of interference depends on the path difference, which is constantly changing as Mark walks towards speaker A.[2]][Constructive interference occurs where $p.d. = n\lambda$ and destructive interference occurs where $p.d. = \left(n + \frac{1}{2}\right)\lambda$.[3]]

- I have identified the impact of constructive and destructive interference.[1]
- I have explained the alternation between loud and quiet regions.[2]
- I have explained the relationship between path difference and interference.[3]

b. $\lambda = \frac{v}{f} = \frac{340}{680} = 0.500$ m (1 MARK)

$p.d. = \left(n + \frac{1}{2}\right)\lambda = \left(2 + \frac{1}{2}\right) \times 0.500 = 1.25$ m (1 MARK)

The $p.d.$ is twice the distance the Mark moves, as the distance travelled towards one speaker is also travelled from the other speaker, resulting in double the change in the path difference.

Distance from centre is $\frac{p.d.}{2} = 0.625$ m (1 MARK)

5% of students answered this VCAA question correctly.

18. **a.** $v = f\lambda = 4.0 \times 0.015 = 0.060$ m s^{-1}

b. $p.d. = n\lambda \Rightarrow |5.0 - 2.0| = 1.5 \times n$ (1 MARK)

$n = 2$ (1 MARK)

P is the third antinode. (1 MARK)

19. **a.** Let the speed of sound be 340 m s^{-1} (note that speed does not affect the result).

For 1st experiment $\lambda = \frac{v}{f} = \frac{340}{400} = 0.850$ m

$p.d. = n\lambda = 1 \times 0.850 = 0.850$ m (1 MARK)

For 2nd experiment $p.d. = \left(n + \frac{1}{2}\right)\lambda$

$0.850 = \left(1 + \frac{1}{2}\right)\lambda$ (1 MARK)

$\lambda = 0.567$ m

$f = \frac{v}{\lambda} = \frac{340}{0.567} = 600$ Hz (1 MARK)

b. [Yes. The measurements taken and the formula used will allow Beyoncé to determine the wavelength.[1]]

- I have identified that the experiment measures what it intends to measure and is therefore valid.[1]

FROM LESSON 12A

c. [Measure the path difference at multiple nodal points and repeat the calculation.[1]][This provides multiple valid measurements for wavelength which can be averaged to reduce the effect of random errors.[2]]

- I have explicitly addressed a way to improve accuracy.[1]
- I have used the relevant theory: the relationship between random error and accuracy.[2]

FROM LESSON 12C

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Previous lessons

20. a. When the mass is stationary, it is in equilibrium. Any data set with non-zero mass can be used. Our answer uses 3 masses.

$mg = k\Delta x \Rightarrow 3 \times 30 \times 10^{-3} \times 9.8 = k \times 0.15$ (1 MARK)

$k = 5.88 = 5.9 \text{ N m}^{-1}$ (1 MARK)

61% of students answered this VCAA exam question correctly.

b. Take the gravitational potential energy to be zero at the lowest point of oscillation.

$GPE_{top} = SPE_{bot}$

$mgh = \frac{1}{2}k(\Delta x)^2 \Rightarrow 5 \times 0.030 \times 9.8 \times h$
$= \frac{1}{2} \times 5.88 \times (\Delta x)^2$ (1 MARK)

$h = \Delta x$ since the top of the oscillation is the unstretched position.

$\Delta x = 0.50 \text{ m}$ (1 MARK)

$L = 0.60 + 0.50 = 1.10 \text{ m}$ (1 MARK)

14% of students answered this VCAA exam question correctly.

FROM LESSON 2E

21. [The ammeter is registering the changing current in the coil due to the change in magnetic flux in the coil that induces an EMF, and hence a current in the loop, according to Faraday's Law[1]] [From time 1 to time 2 the loop is experiencing an increasing flux into the page. So by the right hand grip rule the induced current will flow anticlockwise around the loop.[2]] [From time 2 to time 3, the loop is experiencing a decreasing flux into the page. So by the right hand grip rule the induced current will flow clockwise around the loop.[3]]

- I have explained why the ammeter is registering a changing current.[1]
- I have identified the direction of current in the loop between time 1 and time 2.[2]
- I have identified the direction of current in the loop between time 2 and time 3.[3]

23% of students answered this VCAA exam question correctly.

FROM LESSON 5B

7C Standing waves

Progress questions

1. D. The resultant standing wave is formed by travelling waves.

2. B. Point S is the only antinode.

3. C. The harmonic number is 3, as the standing wave is comprised of three half-wavelengths.

4. C. $\lambda = \frac{2L}{n} = \frac{2 \times 16.0}{2} = 16.0 \text{ m}$

Deconstructed exam-style

5. $v = f\lambda \Rightarrow 50 = 8.0 \times \lambda$

$\lambda = 6.25 = 6.3 \text{ m}$

81% of students answered this VCAA exam question correctly.

6. $\frac{2L}{\lambda} = \frac{2 \times 7.0}{6.25} = 2.24 = 2.2$

7. $v = f\lambda \Rightarrow 50 = 8.0 \times \lambda$ (1 MARK)

$\lambda = 6.25 = 6.3 \text{ m}$

$\frac{2L}{\lambda} = \frac{2 \times 7.0}{6.25} = 2.24 = 2.2$ (1 MARK)

As $\frac{2L}{\lambda}$ is not an integer, a standing wave will not form. (1 MARK)

17% of students answered this VCAA exam question correctly.

Exam-style

8. a. $f = \frac{nv}{2L} = \frac{1 \times 200}{2 \times 5.0} = 20 \text{ Hz}$, as required.

b. $v = f\lambda \Rightarrow 200 = 20 \times \lambda$

$\lambda = \frac{200}{20} = 10 \text{ m}$

OR

$\lambda = \frac{2L}{n} = \frac{2 \times 5.0}{1} = 10 \text{ m}$

c. [Yes a standing wave will form[1]] [as the new frequency is an integer multiple of the fundamental frequency, $60 = 3 \times 20$.[2]]

- I have identified that a standing will form.[1]
- I have explained that the frequency is an integer multiple of the fundamental frequency.[2]

9. a. [There are three antinodes, so the harmonic number is 3.[1]]

- I have determined the harmonic number.[1]

b. The standing wave is composed of three half wavelengths, therefore the length of the string is $L = 3 \times 1.5 = 4.5 \text{ m}$

10. a. $\lambda = \frac{2L}{n} = \frac{2 \times 0.690}{3} = 0.460 \text{ m}$

b. $f = \frac{nv}{2L} = \frac{3 \times 330}{2 \times 0.690} = 717.4 = 717 \text{ Hz}$

OR

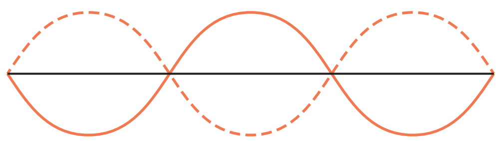
$f = \frac{v}{\lambda} = \frac{330}{0.460} = 717.4 = 717 \text{ Hz}$

11. a. $v = f\lambda = 82 \times (2 \times 1.20)$ (1 MARK)

$v = 1.97 \times 10^2 = 2.0 \times 10^2 \text{ m s}^{-1}$ (1 MARK)

66% of students answered this VCAA exam question correctly.

b.



- I have drawn a standing wave with three antinodes.
- I have drawn a standing wave with four nodes, including one at either end.

64% of students answered this VCAA exam question correctly.

12. A. There are two wavelengths on the rope so $\lambda = \frac{3.6}{2} = 1.8 \Rightarrow v = \frac{\lambda}{T} = \frac{1.8}{2.4} = 0.75 \text{ m s}^{-1}$.

63% of students answered this VCAA exam question correctly.

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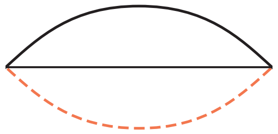
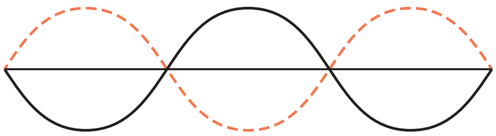
13. a. *n* = 1



I have drawn a standing wave with one antinode.

I have drawn a standing wave with two nodes, including one at either end.

b. *n* = 3



I have drawn a standing wave with three antinodes.

I have drawn a standing wave with four nodes, including one at either end.

14. [A standing wave is formed on a string when waves travelling in opposite directions reflect at the end of the strings.[1]] [The waves superimpose to produce an interference pattern.[2]]

I have identified that standing waves form from travelling waves reflecting at the ends of the string.[1]

I have explained that these travelling waves form an interference pattern.[2]

21% of students answered this VCAA exam question correctly.

15. a. The length of string has halved: $L = \frac{0.325}{2} = 0.1625$ m (1 MARK)

$\lambda = \frac{2L}{n} = \frac{2 \times 0.1625}{1} = 0.325$ m (1 MARK)

b. Frequency has doubled since the wavelength of the wave has halved, according to $v = f\lambda$. (1 MARK)

$f = 2 \times 440 = 880$ Hz (1 MARK)

16. a. [The independent variable is the effective length of the string.[1]]

I have identified the independent variable.[1]

b. [Peter collects qualitative data.[1]]

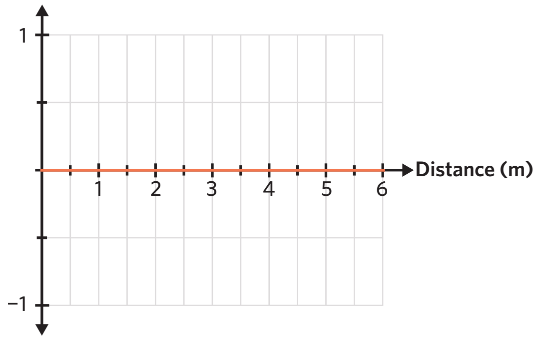
I have identified the type of data Peter collects.[1]

c. $f = \frac{nv}{2L} \Rightarrow 520 = \frac{5 \times v}{2 \times 0.275}$ (1 MARK)

$v = 57.20 = 57.2$ m s^{-1} (1 MARK)

FROM LESSONS 12A & 12C

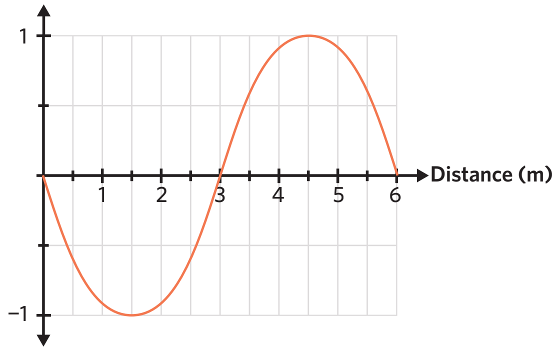
17. a. 1.0 second later is one quarter of a period later.



I have drawn a flat line at 0 m displacement.

FROM LESSON 12D

b. 2.0 seconds later is half a period later.



I have drawn a graph with the same wavelength and amplitude.

I have drawn a graph that is inverted.

FROM LESSON 12D

c. From the graph, $\lambda = 6.0$ m.

$v = \frac{\lambda}{T} = \frac{6.0}{4.0} = 1.50$ m s^{-1} (1 MARK)

$f = \frac{nv}{2L} = \frac{5 \times 1.50}{2 \times 6}$ (1 MARK)

$f = 0.625 = 0.63$ Hz (1 MARK)

Previous lessons

18. The area under a force-distance graph is the work done by the force on the object. Therefore, due to conservation of energy, the kinetic energy is equal to the area under the graph. Each square is 2×10^6 J. The area under the graph required is $\frac{2.4 \times 10^7}{2 \times 10^6} = 12$ squares. (1 MARK)

Counting 12 squares from the surface of the Earth gives a distance of 10×10^6 m from the centre of the Earth. (1 MARK)

FROM LESSON 3B

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19. [The laptop could not be charging as the solar panel requires an inverter to make it function with household devices.[1]] [Without an inverter, the solar panel produces DC and will not work with household devices required to work with AC.[2]] [An inverter will turn the DC provided into AC to work with the laptop.[3]]

- I have identified why the laptop is not charging.[1]
- I have explained what inverters do.[2]
- I have explained why an inverter is necessary.[3]

FROM LESSON 5D

7D Diffraction

Progress questions

1. C. Diffraction describes the phenomenon of a wave bending around an obstacle or an aperture.

2. C. The gap width is the size of the space that the wave must pass through.

3. A. The lowest frequency will have the longest wavelength and therefore the greatest extent of diffraction.

4. B. The greatest extent of diffraction will occur when $\frac{\lambda}{w}$ is the largest.

Deconstructed exam-style

5. $v = f\lambda \Rightarrow 343 = 100 \times \lambda$

   $\lambda = 3.43$ m

6. $v = f\lambda \Rightarrow 343 = 400 \times \lambda$

   $\lambda = 0.283$ m

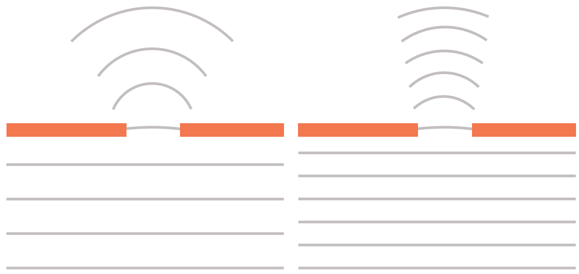
7. [The scientist is more likely to hear the 100 Hz note.[1]] [The notes diffract as they pass through the door, according to the ratio $\frac{\lambda}{w}$.[2]] [For the 100 Hz sound, $\frac{\lambda}{w} = \frac{\frac{v}{f}}{w} = \frac{\left(\frac{343}{100}\right)}{3.00} = 1.14$, while for the 400 Hz sound, $\frac{\lambda}{w} = \frac{\left(\frac{343}{400}\right)}{3.00} = 0.283$.[2]] [As the ratio $\frac{\lambda}{w}$ is greater for the 100 Hz sound, the scientist is more likely to hear this sound, as it has a greater extent of diffraction[3]]

- I have identified the scientist is more likely to hear the 100 Hz note.[1]
- I have calculated the ratio $\frac{\lambda}{w}$ for each note.[2]
- I have justified the 100 Hz sound has a greater extent of diffraction, according to the ratio $\frac{\lambda}{w}$.[3]

Exam-style

8. D. Diffraction will cause low pitch sounds to be heard more clearly around a street corner than a high pitched sound.

9. a.



Original frequency — New frequency

- I have drawn a pattern for the new frequency with shorter wavelengths.
- I have drawn a pattern for the new frequency with less diffraction.

   b. [Increasing frequency decreases wavelength, as $v = f\lambda$, which reduces the ratio $\frac{\lambda}{w}$.[1]] [As a result, there is a lower extent of diffraction, and so the diffraction pattern will be less spread out.[2]]

- I have described the relationship between frequency and wavelength.[1]
- I have explained the change in the diffraction pattern.[2]

10. a. [Wave intensity has no effect on the width of the diffraction pattern as[1]] [diffraction depends only on the width of the aperture and the wavelength of the wave, $\frac{\lambda}{w}$.[2]]

- I have identified the effect that increasing the intensity has on the diffraction pattern.[1]
- I have explained my answer.[2]

   b. [The independent variable is the gap size,[1]] [the dependent variable is the width of the diffraction pattern,[2]] [and a controlled variable is the wavelength of the wave.[3]]

- I have identified the independent variable.[1]
- I have identified the dependent variable.[2]
- I have identified a controlled variable.[3]

Other possible answers include:

- a controlled variable is the frequency of the wave.
- a controlled variable is the wave medium.

FROM LESSON 12A

   c. [The experiment and its results are reproducible.[1]]

- I have identified that the results are reproducible.[1]

FROM LESSON 12C

7D ANSWERS

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11. [Speaker B can be heard with greater intensity[1]][as the extent of diffraction depends on the ratio $\frac{\lambda}{w}$.[2]][For speaker B, $\frac{\lambda}{w} = \frac{3.0}{2.0} = 1.5$ which is greater than $\frac{\lambda}{w} = \frac{1.0}{2.0} = 0.50$ for speaker A. Therefore the sound from speaker B will diffract more.[3]]

- I have identified which sound will be heard with greater intensity.[1]
- I have explained that the extent of diffraction depends on the ratio $\frac{\lambda}{w}$.[2]
- I have justified my answer with calculations.[3]

12. C. Increasing the frequency decreases the wavelength and results in less diffraction.

71% of students answered this VCAA exam question correctly.

13. [Hannah's suggestion will double the audible distance to $2x$, but the others will not.[1]][To double the size of the audible region the students will need to double the extent of diffraction by doubling the ratio $\frac{\lambda}{w}$.[2]][Halving the frequency doubles the wavelength (and the ratio), halving the distance between the speaker and the barrier will not affect the ratio $\frac{\lambda}{w}$, and doubling the gap width will halve the ratio $\frac{\lambda}{w}$.[3]]

- I have identified which suggestions are correct and incorrect.[1]
- I have explained what is required to impact the extent of diffraction.[2]
- I have evaluated the suggestions according to the relevant physics.[3]

14. [Campbell's bark will have a greater extent of diffract than Dion's bark.[1]][For Campbell's bark, $\frac{\lambda}{w} = \frac{1.8}{0.60} = 3.0$. For Dion's bark, $\lambda = \frac{v}{f} = \frac{340}{850} = 0.400$ m, which gives a ratio of $\frac{\lambda}{w} = \frac{0.400}{0.20} = 2.0$.[2]] [As the diffraction ratio, $\frac{\lambda}{w}$, is greater for Campbell's bark than Dion's bark, so it will have a greater extent of diffraction.[2]]

- I have identified which dog's bark will diffract more.[1]
- I have calculated the diffraction ratio for both Campell and Dion's barks.[2]
- I have used the diffraction ratio to calculate the extent of diffraction.[3]

Previous lessons

15. [As a satellite moves a large distance away from the surface of a planet, the gravitational field gets weaker.[1]][As the formula $GPE = mg\Delta h$ assumes the gravitational field experienced by the satellite is uniform in the region over which they are moving, it cannot be used to calculate its change in gravitational potential energy.[2]]

- I have identified that as the satellite moves away from the planet, the gravitational field decreases.[1]
- I have explained that $GPE = mg\Delta h$ cannot be used when the gravitational field strength changes.[2]

FROM LESSON 3B

16. $V_T = IR_T \Rightarrow 9.0 = 3.0 \times R_T$ (1 MARK)

$R_T = 3.00\ \Omega$

$R_T = R_{eq} = R_1 + R_2$, and as both resistors are identical, $R_1 = R_2$.

$R_T = 2R_1 \Rightarrow 3.00 = 2R_1$ (1 MARK)

$R_1 = 1.50 = 1.5\ \Omega$ (1 MARK)

FROM LESSON 6A

Chapter 7 review

Section A

1. A. Wave X is the addition of both wave Y and wave Z.

2. D. The amplitude of wave Y is 0.3 m and the wavelength can be measured to be 3 m. The frequency of the wave cannot be determined from a displacement-distance graph.

3. B. There are 2.5 wavelengths shown on the rope.

Therefore, $\lambda = \frac{1.6}{2.5} = 0.64$ m.

$v = \frac{\lambda}{T} = \frac{0.64}{2.6} = 0.246 = 0.25 \text{ m s}^{-1}$.

63% of students answered this VCAA exam question correctly.

4. D. $p.d. = \left(n + \frac{1}{2}\right)\lambda = |1.0 - 2.0| = 1.0$ m

The only given value of λ which results in an integer value for n is $\lambda = 40$ cm.

5. D. $T = 0.120 \times 4 = 0.480$ s

$v = \frac{\lambda}{T} = \frac{1.40}{0.480} = 2.916 = 2.92 \text{ m s}^{-1}$

41% of students answered this VCAA exam question correctly.

Section B

6.

- I have drawn a wave which has been reflected and inverted from the original wave
- I have drawn a wave that is travelling in the opposite direction.

7. The fourth node from the left will be after 3 half-wavelengths. (1 MARK)

$d = 3 \times \frac{1}{2} \times \lambda = 3 \times \frac{1}{2} \times 0.40 = 0.60$ m (1 MARK)

8. [This statement is partially correct.[1]][When a mechanical wave moves through a medium, there is a net transfer of energy, but there is no net transfer of mass.[2]]

- I have identified that this statement is partially correct.[1]
- I have explained why the statement is partially correct.[2]

9. $\lambda = \frac{2L}{n} = \frac{2 \times 1.40}{4} = 0.700$ m (1 MARK)

$v = f\lambda = 250 \times 0.700 = 175.0 = 175 \text{ m s}^{-1}$ (1 MARK)

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10. a. Longest wavelength is when $n = 1 \Rightarrow \lambda = \frac{2L}{n} = \frac{2 \times 5.0}{1}$
$= 10.0 = 10$ m

b. $f = \frac{nv}{2L} = \frac{3 \times 28}{2 \times 5.0}$ (1 MARK)

$f = 8.40 = 8.4$ Hz (1 MARK)

11. a. [Destructive interference is creating a node at the position of the receiver.[1]]

I have explained how the receiver does not register any incoming waves.[1]

b. [The diffraction pattern will spread out more.[1]][This is because diffraction is proportional to the ratio of $\frac{\lambda}{w}$ and a lower frequency means a longer wavelength.[2]]

I have identified effect on the diffraction pattern.[1]

I have explained the extent of diffraction using the formula $\frac{\lambda}{w}$.[2]

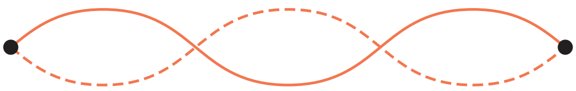
12. a. $v = \frac{\lambda}{T} = \frac{9.00}{1.50} = 6.00 = 6.0 \text{ m s}^{-1}$

b. $p.d. = \left(n + \frac{1}{2}\right)\lambda = \left(1 + \frac{1}{2}\right) \times 9.00 = 13.5$ m (1 MARK)

$p.d. = |PX - PY| \Rightarrow 13.5 = |12.0 - PY|$ (1 MARK)

$PY = 25.50 = 25.5$ m (1 MARK)

13. a.



I have drawn a standing wave with three half-wavelengths.

b. $f = \frac{nv}{2L} \Rightarrow 30 = \frac{3 \times 6.0}{2L}$ (1 MARK)

$L = 0.300 = 0.30$ m (1 MARK)

14. a. [It is possible to hear the instruments as the diffraction of the sound waves causes them to spread out as they travel through the door.[1]]

I have identified why it is possible to hear instruments.[1]

b. [The observer is least likely to hear the trumpet.[1]][Diffraction is proportional to the ratio of $\frac{\lambda}{w}$. Since the trumpet has the highest frequency (shortest wavelength), its diffraction is less significant than the other instruments.[2]]

I have identified which instrument the observer is least likely to hear.[1]

I have explained why it is the most likely to be heard, using the extent of diffraction.[2]

15. a. [Mr Ridley is incorrect and Ms Hawes is correct.[1]][The volume depends on the amplitude of the sound wave. The amplitude at a given point will be large if constructive interference is occurring and smaller if destructive interference is occurring.[2]] [This depends on the path difference to each speaker from that point.[3]]

I have identified who is correct and who is incorrect.[1]

I have explained that the volume will depend on amplitude.[2]

I have explained how the amplitude will change based on the path difference.[3]

b. $\lambda = \frac{v}{f} = \frac{340}{100} = 3.40 = 3.4$ m (1 MARK)

For Toby: $p.d. = |S_1T - S_2T| = |5.05 - 8.45| = 3.40 \text{ m} = n\lambda$, where $n = 1$

Toby sits at an antinode. (1 MARK)

For Reginald: $p.d. = |S_1R - S_2R| = |7.60 - 5.90| = 1.70$ m $= \left(n + \frac{1}{2}\right)\lambda$, where $n = 0$

Reginald sits at a node. (1 MARK)

Toby will hear the sound well since he is at an antinode (constructive interference) whereas Reginald will not hear the sound well/at all since he is at a node (destructive interference). (1 MARK)

16. a. $\Delta x = \frac{\lambda L}{d} \Rightarrow 42 = \frac{\lambda \times 420}{60}$ (1 MARK)

$\lambda = \frac{42 \times 60}{420} = 6.00 = 6.0$ m (1 MARK)

b. [The boat will only experience large waves[1]][as the path the boat travels along is a line of zero path difference, and hence will be constructive interference the entire way.[2]]

I have identified the size of waves experienced by the boat.[1]

I have identified the type of interference that occurs at a path difference of zero.[2]

17. a. From the displacement-distance graph $\lambda = 4$ m and from the displacement-time graph $T = 4$ s (1 MARK)

$v = \frac{\lambda}{T} = \frac{4}{4} = 1 \text{ m s}^{-1}$ (1 MARK)

b. [Particle X is moving upwards.[1]]

I have identified which direction Particle X is moving.[1]

c. [Particle Z is the only particle for which displacement decreases from 0 m just after $t = 0$ s.[1]]

I have identified which particle the displacement-time graph represents.[1]

CHAPTER 7 REVIEW

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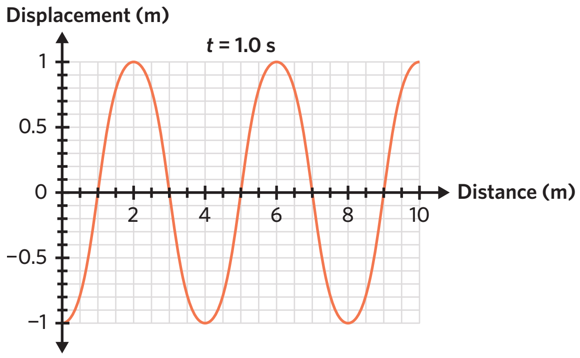
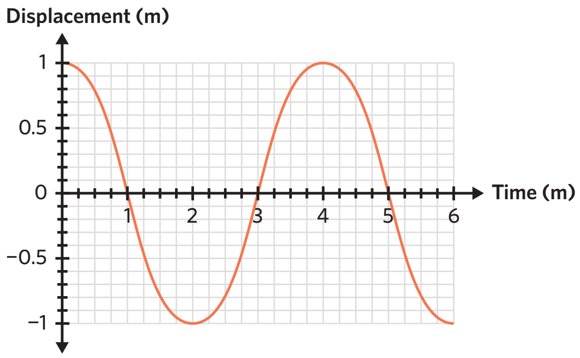
d.



- I have included an appropriate and consistent scale on both axes.
- I have drawn a sinusoidal wave with an amplitude of 1 m and a wavelength of 4 m.
- I have drawn a graph which starts with a minimum at $d = 0$ m and ends with a maximum at $d = 10$ m.

e.



- I have included an appropriate and consistent scale on both axes.
- I have drawn a sinusoidal wave with an amplitude of 1 m and a period of 4 s.
- I have drawn a graph which starts with a maximum at $t = 0$ s and ends with a minimum at $t = 6$ s.

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8A Electromagnetic waves

Progress questions

1. C. Light can be modelled as an electromagnetic wave, which consists of changing electric and magnetic fields perpendicular to each other.

2. B. Unlike mechanical waves, electromagnetic waves do not require a medium to travel through.

3. D. $v = f\lambda \Rightarrow 3.0 \times 10^8 = f \times 710 \times 10^{-9}$

   $f = 4.2 \times 10^{14}$ Hz

4. D. The electromagnetic spectrum is the range of all electromagnetic waves ordered by frequency and wavelength.

5. D. All waves in the electromagnetic spectrum have different frequencies and wavelengths.

Deconstructed exam-style

6. D. Accelerating charged particles produce changing electric fields.

7. C. A changing electric field produces a changing magnetic field and vice versa.

8. [An accelerating charged particle produces a changing electric field.[1]][This changing electric field generates a changing magnetic field perpendicular to it.[2]][The changing magnetic field produces a changing electric field; this process continues with the changing electric and magnetic fields creating a self-propagating electromagnetic wave.[3]]

   - I have stated that an accelerating charged particle generates a changing electric field.[1]
   - I have identified that a changing electric field produces a changing magnetic field.[2]
   - I have explained how these fields create a self-propagating electromagnetic wave.[3]

Exam-style

9. C. All electromagnetic waves travel at the speed of light in a vacuum.

10. $c = f\lambda \Rightarrow 3.0 \times 10^8 = f \times (3 \times 10^{-2})$

    $f = 1.0 \times 10^{10} = 1 \times 10^{10}$ Hz

11. [radio, microwaves, infrared, ultraviolet, X-rays[1]]

    - I have ordered the regions of the electromagnetic spectrum correctly.[1]

12. B. Accelerating charges produce changing electric fields which create a self propagating electromagnetic wave.

13. a. [D represents the green emission[1]][This is because different colours have different wavelengths of light and green has the second longest wavelength of the visible colours that mercury emits.[2]]

    - I have identified which band represents green.[1]
    - I have justified my answer.[2]

    64% of students answered this VCAA exam question correctly.

    b. [One limitation in the student's conclusion is assuming that more electrons means more colours, as a single electron could produce multiple wavelengths of light.[1]][An experiment that could develop the student's idea is to compare the emission spectra of atoms with different numbers of electrons.[2]]

    - I have explained one limitation of the student's conclusion.[1]
    - I have suggested an experiment to develop the student's idea.[2]

    Other possible answers

    - Assuming that the number of electrons corresponds to the number of wavelengths produced.

14. a. $\Delta t = \frac{\Delta s}{v} = \frac{384\,400 \times 10^3}{3.0 \times 10^8} = 1.3$ s

    b. [Electromagnetic waves travel at the speed of light in a vacuum but slower in other mediums.[1]][The calculated time of 1.3 s assumes that the entire journey from Earth to the Moon was in a vacuum.[2]][As Earth has an atmosphere containing air, the signals would have travelled slower while in the atmosphere, giving a longer time delay.[3]]

    - I have identified that electromagnetic waves travel at different speeds in different mediums.[1]
    - I have explained that the calculated time assumed the entire journey was in a vacuum.[2]
    - I have explained that Earth's atmosphere slows the signals down giving a longer time delay than calculated.[3]

15. a. $Average = \frac{532.3 + 532.5 + 532.1 + 531.9 + 532.7}{5}$

    $= 532.3$ nm (1 MARK)

    $Uncertainty = \frac{532.7 - 531.9}{2} = 0.4$ nm (1 MARK)

    b. [Increasing the frequency by one third would result in a decrease in the wavelength of one third[1]][but no change in the speed of the laser.[2]][This is because the speed of light in a medium is constant. Therefore, according to the wave equation, $v = f\lambda$, frequency and wavelength are inversely proportional.[3]]

    - I have identified wavelength of the laser would decrease by one third.[1]
    - I have identified the speed of the laser would not change.[2]
    - I have justified my answer using the wave equation.[3]

Previous lessons

16. D. The acceleration of the satellite is due to the Earth's gravity.

FROM LESSON 3C

17. B. $\frac{N_1}{N_2} = \frac{I_2}{I_1} \Rightarrow \frac{25}{150} = \frac{I_2}{I_1} \Rightarrow \frac{I_1}{I_2} = \frac{150}{25} = \frac{6}{1}$

FROM LESSON 6B

8B Young's double slit experiment

Progress questions

1. A. The particle model predicted two vertical bright bands appearing instead of an interference pattern.

2. D. Interference is a wave property, so Young's double slit experiment shows light has wave-like properties.

3. D. Fringe spacing is the distance between adjacent bright or dark fringes.

4. B. $\Delta x = \frac{\lambda L}{d} = \frac{450 \times 10^{-9} \times 2.00}{3.00 \times 10^{-5}} = 0.030 \text{ m}$

5. A. According to $\Delta x = \frac{\lambda L}{d}$, if L is halved then the fringe spacing will also halve.

Deconstructed exam-style

6. A. P is the fifth bright band from the centre (including the centre), therefore the fringe spacing will be $\frac{1.26 \times 10^{-2}}{4}$.

7. B. L is the distance from the slits to the screen while d is the distance between the slits.

8. $\Delta x = \frac{1.26 \times 10^{-2}}{4} = 3.15 \times 10^{-3} \text{ m}$ (1 MARK)

$\Delta x = \frac{\lambda L}{d} \Rightarrow 3.15 \times 10^{-3} = \frac{\lambda \times 1.50}{3.0 \times 10^{-4}}$ (1 MARK)

$\lambda = 6.30 \times 10^{-7} = 6.3 \times 10^{-7} \text{ m}$ (1 MARK)

28% of students answered this VCAA exam question correctly.

Exam-style

9. C. Young's double slit experiment shows that light exhibits wave-like behaviour, as it creates an interference pattern of alternating dark and bright bands.

10. B. According to $\Delta x = \frac{\lambda L}{d}$, decreasing the slit separation will increase Δx.

55% of students answered this VCAA exam question correctly.

11. a. [This experiment shows that two sources of light create an interference pattern.[1]][Interference is a wave property and so it provides evidence for the wave-like nature of light.[2]]

- I have explained that the experiment shows light interferes with itself.[1]
- I have identified interference as a wave property.[2]

55% of students answered this VCAA exam question correctly.

b. $c = f\lambda \Rightarrow 3 \times 10^8 = 6.50 \times 10^{14} \times \lambda$

$\lambda = 4.615 \times 10^{-7}$ (1 MARK)

$\Delta x = \frac{\lambda L}{d} = \frac{4.615 \times 10^{-7} \times 3.00}{(0.10 \times 10^{-3})}$

$\Delta x = 1.38 \times 10^{-2} = 1.4 \times 10^{-2} \text{ m}$ (1 MARK)

51% of students answered this VCAA exam question correctly.

c. [Point C is a bright spot because the path difference is zero, resulting in constructive interference.[1]][The dark band to the left of C has a path difference of $\frac{\lambda}{2}$, which results in destructive interference.[2]]

- I have explained that point C has a path difference of zero which causes constructive interference.[1]
- I have explained that the dark band has a path difference $\frac{\lambda}{2}$ which causes destructive interference.[2]

20% of students answered this VCAA exam question correctly.

12. a. $\Delta x = \frac{\lambda L}{d} = \frac{650 \times 10^{-9} \times 1.50}{1.0 \times 10^{-3}}$ (1 MARK)

$\Delta x = 9.75 \times 10^{-4} = 9.8 \times 10^{-4} \text{ m}$ (1 MARK)

45% of students answered this VCAA exam question correctly.

b. [The independent variable is the distance from the screen from the slits.[1]][The dependent variable is distance between adjacent dark bands.[2]][One control variable is distance between the two slits.[3]]

- I have identified the independent variable.[1]
- I have identified the dependent variable.[2]
- I have identified one control variable.[3]

Other possible answers:

- The frequency of the laser light
- The wavelength of the laser light
- The intensity of the laser light

FROM LESSON 12A

c. [If the refractive index of the medium increases than the speed of light through medium decreases.[1]][If the speed of light through the medium decreases than the wavelength of light decreases.[2]][If the wavelength of light decreases then the spacing between adjacent dark bands will decrease.[3]]

- I have explained that the speed of light through the medium will decrease.[1]
- I have explained that the wavelength of light will also decrease.[2]
- I have described the change in the spacing.[3]

34% of students answered this VCAA exam question correctly.

FROM LESSON 12A

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13. [Point P is the fifth bright band from the centre (including the centre) so the path difference is four wavelengths.[1]][As the path difference is a whole multiple of the wavelength, constructive interference is occurring, which results in a bright band.[2]]

I have identified the path difference at point P.[1]

I have explained that this path difference results in constructive interference.[2]

10% of students answered this VCAA exam question correctly.

14. a. $p.d. = \frac{81.6}{100} - \frac{73.5}{100} = 0.081$ m. This is the fourth band from the centre (including the centre) so $p.d. = 3\lambda$

$3\lambda = 0.081 \Rightarrow \lambda = 2.70 \times 10^{-2}$ m (1 MARK)

$c = f\lambda \Rightarrow 3.00 \times 10^{8} = f \times 2.70 \times 10^{-2}$

$f = 1.11 \times 10^{10}$ Hz (1 MARK)

26% of students answered this VCAA exam question correctly.

b. [The signal strength is a minimum between P_0 and P_1 because the path difference is $\frac{\lambda}{2}$.[1]][This results in destructive interference, which is why the signal strength is a minimum at this point.[2]]

I have identified the path difference between P_0 and P_1.[1]

I have explained that this path difference results in destructive interference.[2]

17% of students answered this VCAA exam question correctly.

Previous lessons

15. $F = G\frac{M_1M_2}{r^2} \Rightarrow 230 = 6.67 \times 10^{-11} \times \frac{5.98 \times 10^{24} \times M}{(9.00 \times 10^{6})^{2}}$ (1 MARK)

$M = 46.71 = 46.7$ kg (1 MARK)

FROM LESSON 3C

16. C. As power loss is calculated using $P_{loss} = I_{line}{}^{2}R_{line}$, reducing the transmission current reduces power loss.

FROM LESSON 6C

Chapter 8 review

Section A

1. C. As higher energy correlates to shorter wavelength, the waves must be ordered from longest to shortest wavelength.

2. D. Interference is a wave phenomenon.

3. D. Using the path difference formula for constructive interference, $p.d. = n\lambda$, we can see that the value we are missing is n.

4. C. $v = f\lambda \Rightarrow 3.0 \times 10^{8} = 1.2 \times 10^{10} \times \lambda \Rightarrow \lambda = 2.5 \times 10^{-2}$ m

5. A. Using $\Delta x = \frac{\lambda L}{d}$, we can see that substituting in $\frac{1}{2}L$ and 2λ, we would see no change in Δx.

Section B

6. a. [The bright bands are regions of constructive interference.[1]][These are formed when the path difference is an integer multiple of the wavelength, $p.d. = n\lambda$.[2]]

I have identified the bright bands are regions of constructive interference.[1]

I have explained that these form when the path difference is $n\lambda$.[2]

b. [The dark bands are regions of destructive interference.[1]][These are formed when the path difference is a half wavelength more than an integer multiple of the wavelength, $p.d. = \left(n + \frac{1}{2}\right)\lambda$.[2]]

I have identified that the dark bands are regions of destructive interference.[1]

I have explained that these form when the path difference is $\left(n + \frac{1}{2}\right)\lambda$.[2]

7. $c = f\lambda \Rightarrow 3.0 \times 10^{8} = 2.45 \times 10^{9} \times \lambda$ (1 MARK)

$\lambda = 0.1224$ m

$\lambda = 0.1224 \times 10^{2} = 12.24 = 12$ cm, as required. (1 MARK)

8. $p.d. = n\lambda \Rightarrow 1.50 \times 10^{-6} = 2 \times \lambda$ (1 MARK)

$\lambda = 7.50 \times 10^{-7}$ m $= 750$ nm (1 MARK)

26% of students answered this VCAA exam question correctly.

9. [Michael is incorrect.[1]][Light can travel slower than 3.0×10^{8} m s^{-1} in different mediums.[2]]

I have evaluated Michael's statement.[1]

I have explained that light travels different speeds in different mediums.[2]

10. a. [The independent variable is distance from the slits to the screen, L.[1]][The dependent variable is the fringe spacing Δx.[2]]

I have identified the independent variable.[1]

I have identified the dependent variable.[2]

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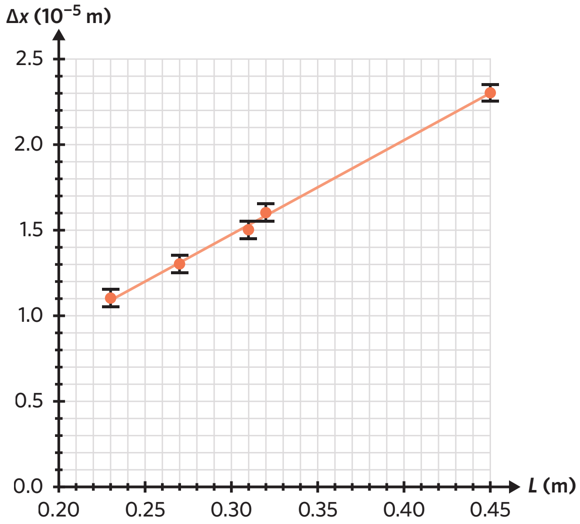
b.



- I have plotted L on the horizontal axis and Δx on the vertical axis.
- I have included axis labels and appropriate units.
- I have included an appropriate and consistent scale on the axes.
- I have correctly plotted all the data points with appropriate error bars.
- I have drawn a straight line of best fit that passes through all of the uncertainty bars

c. [If the uncertainty in Δx doubled to $\pm 0.1 \times 10^{-5}$ then the error bars in the graph from part **b** would also double in length.[1]]

- I have described how the graph in part **b** would change if the uncertainty doubled.[1]

FROM LESSON 12D

11. [As an electron is accelerated, it creates a changing electric field[1]] [which creates an associated changing magnetic field.[2]] [These two fields self-propagate as an electromagnetic wave that we call light.[3]]

- I have identified that an accelerating electron creates a changing electric field.[1]
- I have identified that a changing electric field creates a changing magnetic field.[2]
- I have identified light as an electromagnetic wave.[3]

12. a. $\frac{p.d.}{\lambda} = \frac{1.60 \times 10^{-6}}{640 \times 10^{-9}} = 2.5$ (1 MARK)

Since $p.d. = 2.5\lambda = \left(n + \frac{1}{2}\right)\lambda$, we get $n = 2$, which is the third dark band from the centre (1 MARK)

Therefore the lock will not open. (1 MARK)

OR

$p.d. = \left(n + \frac{1}{2}\right)\lambda = \left(1 + \frac{1}{2}\right) \times 640 \times 10^{-9}$ (1 MARK)

$p.d. = 960 \times 10^{-7}$ m (1 MARK)

The path difference at the second dark band is not 1.60×10^{-6} m so the lock will not open. (1 MARK)

b. [He will not be able to unlock the door this way.[1]] [Changing the distance of the screen would change the fringe spacing, $\Delta x = \frac{\lambda L}{d}$,[2]] [however it would not change the path difference to each dark band.[3]]

- I have stated that superman will not be able to open the room.[1]
- I have identified that changing the distance of the screen would change the fringe spacing.[2]
- I have explained that changing the fringe spacing does not change the path difference.[3]

13. a. $p.d. = n\lambda = 2 \times 480 \times 10^{-9}$ (1 MARK)

$p.d. = 9.60 \times 10^{-7}$ m (1 MARK)

50% of students answered this VCAA exam question correctly.

b. $\Delta x = \frac{\lambda L}{d} = \frac{480 \times 10^{-9} \times 1.50}{3.00 \times 10^{-2}}$ (1 MARK)

$\Delta x = 2.40 \times 10^{-5}$ m (1 MARK)

c. [The interference pattern would be closer together as the fringe spacing would be reduced, according to $\Delta x = \frac{\lambda L}{d}$.[1]]

- I have identified that the fringe spacing would be reduced.[1]

d. [X would be an antinode.[1]] [X is equidistant to both sources and therefore the path difference is zero.[2]] [As $p.d. = n\lambda = 0 \times \lambda$, constructive interference occurs.[3]]

- I have identified X is an antinode.[1]
- I have identified the path difference at X is zero.[2]
- I have explained how path difference affects wave interference.[3]

14. [Young's double slit experiment demonstrated that light creates an interference pattern[1]] [which is a wave phenomenon.[2]] [Therefore it supports a wave model of light.[3]] [A particle model incorrectly predicts two bright spots on a screen rather than the interference pattern.[4]]

- I have identified that an interference pattern is observed in Young's double slit experiment.[1]
- I have identified that interference is a wave property.[2]
- I have explained how the experiment supports a wave model.[3]
- I have explained how the experiment provides evidence against a particle model.[4]

39% of students answered this VCAA exam question correctly.

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15. $n = \frac{c}{v} \Rightarrow 1.80 = \frac{3.0 \times 10^8}{v}$

$v = 1.67 \times 10^8$ m s^{-1} (1 MARK)

$v = f\lambda \Rightarrow 1.67 \times 10^8 = f \times 880 \times 10^{-9}$ (1 MARK)

$f = 1.89 \times 10^{14} = 1.9 \times 10^{14}$ Hz (1 MARK)

16. [Dom's explanation is correct.[1]][The centre of the pattern will appear white with slight coloured fringes.[2]][This is because the combined effect of all colours at the centre results in the white appearance, but as we move further from the centre, the light begins to disperse into its constituent colours.[3]]

- I have identified who is correct.[1]
- I have identified that the band will be predominantly white with coloured fringes.[2]
- I have justified my answer.[3]

9% of students answered this VCAA exam question correctly.

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9A Experimental design of the photoelectric effect

Progress questions

1. B. Electron-volts are an equivalent unit for measuring energy.
2. D. To convert to joules, we must multiply by 1.6×10^{-19}
$\Rightarrow 5.5 \times 1.6 \times 10^{-19} = 8.8 \times 10^{-19}$ J
3. The variable voltage source is used to **positively** charge the collector electrode in order to **attract** any emitted **photoelectrons** from the metal surface.
4. C. The role of an ammeter in a circuit is to measure current, in this case, the photocurrent.
5. C. The work function is the property of a metal which describes the amount of energy required to liberate the most loosely held electrons from its structure.
6. A. $KE_{max} = E_{light} - \phi = 2.4 - 1.7 = 0.70$ eV
7. C. As the voltage is less than the stopping voltage there will still be some photocurrent measured, however it will be less than maximum since the collector electrode is negatively charged.
8. D. The magnitude of the stopping voltage, measured in V, has the same numerical value as the KE_{max} of the electrons when measured in eV.
9. A, B, C. Photocurrent through the ammeter is a dependent variable. This means it is being measured rather than controlled in the experiment.
10. C. An experiment is valid when only one independent variable is changed at a time.

Deconstructed exam-style

11. A. The stopping voltage is the voltage that stops even the most energetic photoelectrons from reaching the collector plate, causing the photocurrent to reach zero.
12. B. The KE_{max} of the electrons, when measured in eV, has the same numerical value as the magnitude of the stopping voltage, measured in V.
13. [As the potential difference across the plates is increased, fewer electrons have enough energy to reach the collector and so photocurrent decreases.[1]][The photocurrent is zero at point X since this is the value of potential difference corresponding to the stopping voltage, repelling even the most energetic electrons from the collector plate.[2]][The kinetic energy of these electrons, measured in eV, has the same numerical value as the stopping voltage.[3]]

- I have explained why the current decreases as the magnitude of the potential difference increases.[1]
- I have explained why photocurrent is zero at X.[2]
- I have identified that the stopping voltage is a way of calculating kinetic energy.[3]

5% of students answered this VCAA exam question correctly.

Exam-style

14. Convert from electron-volts to joules:

$\phi = 3.2 \text{ eV} = 3.2 \times 1.6 \times 10^{-19}$ (1 MARK)

$\phi = 5.12 \times 10^{-19} = 5.1 \times 10^{-19}$ J (1 MARK)

15. A. The cut-off potential has the same numerical value as the KE_{max} $\Rightarrow V_0 = 0.2$ V
16. [The work function of the specific metal used must be controlled throughout the experiment to achieve a valid result.[1]][As the metal used has a direct effect on the maximum kinetic energy of photoelectrons it should remain constant as not to interfere with the investigation.[2]]

- I have identified a controlled variable.[1]
- I have explained why the control variable must be kept constant.[2]

FROM LESSON 12A

17. [Random error is likely to be introduced by reading the ammeter.[1]]

- I have identified that random error is likely to be introduced by reading the ammeter.

70% of students answered this VCAA exam question correctly.

FROM LESSON 12C

18. $KE = \frac{1}{2}mv^2 = \frac{1}{2} \times (9.1 \times 10^{-31}) \times (2.2 \times 10^6)^2 = 2.20 \times 10^{-18}$ J (1 MARK)

$KE = \frac{2.20 \times 10^{-18}}{1.6 \times 10^{-19}} = 13.8 = 14$ eV (1 MARK)

19. $KE_{max} = E_{light} - \phi$

$KE_{max} = 3.70 - 2.90 = 0.80$ eV (1 MARK)

$KE_{max} = 0.80 \times 1.6 \times 10^{-19} = 1.28 \times 10^{-19} = 1.3 \times 10^{-19}$ J (1 MARK)

20. $KE_{max} = 1.1$ eV (1 MARK)

$KE_{max} = 1.1 \times 1.6 \times 10^{-19} = 1.76 \times 10^{-19} = 1.8 \times 10^{-19}$ J (1 MARK)

5% of students answered this VCAA exam question correctly.

21. [Ejected electrons will have a range of kinetic energies, with the maximum value of 0.1 eV.[1]][The maximum kinetic energy is the difference between the energy absorbed (2.9 eV) and the work function (2.8 eV).[2]][Some electrons will be more tightly bound to the metal than others; hence not all electrons will be ejected with the maximum kinetic energy.[3]]

- I have identified the kinetic energy of ejected electrons.[1]
- I have used the data provided in my answer.[2]
- I have explained why not all of the electrons ejected will have the maximum kinetic energy.[3]

22. D. When the current is a minimum (zero), the value of the stopping voltage in volts is equal to the value of the maximum kinetic energy of the photoelectrons in electron-volts.

35% of students answered this VCAA exam question correctly.

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23. $\phi = \frac{4.2 \times 10^{-19}}{1.6 \times 10^{-19}} = 2.63$ eV (1 MARK)

$KE_{max} = E_{light} - \phi$

$KE_{max} = 4.2 - 2.63 = 1.57 = 1.6$ eV (1 MARK)

24. $E_{light} = 4.48 \times 10^{-19}\text{ J} = \frac{4.48 \times 10^{-19}}{1.6 \times 10^{-19}} = 2.8$ eV (1 MARK)

$KE_{max} = 0.60$ eV (1 MARK)

$KE_{max} = E_{light} - \phi$

$0.60 = 2.8 - \phi$ (1 MARK)

$\phi = 2.20 = 2.2$ eV (1 MARK)

25. $KE_{max} = 6.67$ eV

$KE_{max} = 6.67 \times 1.6 \times 10^{-19} = 1.067 \times 10^{-18}$ J (1 MARK)

$KE_{max} = E_{light} - \phi$

$1.067 \times 10^{-18} = E_{light} - 6.93 \times 10^{-19}$ (1 MARK)

$E_{light} = 1.76 \times 10^{-18} = 1.8 \times 10^{-18}$ J (1 MARK)

26. [Ehsan’s method for calculating the KE_{max} of the photoelectrons is more accurate,[1]][as his method was to use a known relationship between the stopping voltage and the maximum kinetic energy of photoelectrons.[2]][Yousef’s method is not accurate [3]][because Yousef is using the average velocity of the electrons and not the velocity of the electrons with the most kinetic energy.[4]]

- I have identified whether Ehsan’s method is accurate for finding the KE_{max} of the photoelectrons.[1]
- I have explained why Ehsan’s method is accurate for finding the KE_{max} of the photoelectrons.[2]
- I have identified whether Yousef’s method is accurate for finding the KE_{max} of the photoelectrons.[3]
- I have explained why Yousef’s method is not accurate for finding the KE_{max} of the photoelectrons.[4]

Previous lessons

27. $F_2 = F_1\left(\frac{r_1}{r_2}\right)^2$

$F_2 = 6.6 \times 10^{-4} \times \left(\frac{d}{3d}\right)^2 = 6.6 \times 10^{-4} \times \left(\frac{1}{3}\right)^2$ (1 MARK)

$F_2 = 7.33 \times 10^{-5} = 7.3 \times 10^{-5}$ N (1 MARK)

FROM LESSON 4A

28. [The students are noticing the power loss due to the transmission lines.[1]][This can be reduced by adding a step up transformer to the system, therefore increasing the voltage across the transmission lines, reducing the current through them, and therefore reducing power loss. [2]]

- I have identified the reason why the students notice a difference in power.[1]
- I have identified an improvement to the system to reduce the power loss in the lines.[2]

FROM LESSON 6C

9B Changing intensity in the photoelectric effect

Progress questions

1. C. When the potential difference applied across the two metal plates reaches the value of the stopping voltage, the photocurrent reduces to zero.

2. C. Only a small positive voltage is needed to attract all of the ejected photoelectrons to the collector electrode.

3. B. The stopping voltage will be equal to the magnitude of the horizontal axis intercept of a photocurrent–electrode potential graph.

4. D. Increasing the voltage beyond that point doesn’t increase the photocurrent as the maximum photocurrent has already been reached for that intensity of light.

5. A, B. A higher intensity of light will have a higher maximum photocurrent. Both Light *X* and Light *Y* produce higher photocurrents than Light *Z*, therefore they are both more intense.

Deconstructed exam-style

6. C. The horizontal axis intercept represents the negative value of the stopping voltage.

7. [The magnitude of the stopping voltage, measured in V, has the same numerical value as the KE_{max} of the electrons when measured in eV.[1]]

- I have described the relationship between the maximum kinetic energy of photoelectrons and the stopping voltage.[1]

8. $V_0 = -(-1.85) = 1.85$ V (1 MARK)

$KE_{max} = V_0 = 1.85$ eV (1 MARK)

$KE_{max} = 1.85 \times 1.6 \times 10^{-19}\text{ J} = 2.96 \times 10^{-19} = 3.0 \times 10^{-19}$ J (1 MARK)

42% of students answered this VCAA exam question correctly.

Exam-style

9. C. By doubling the intensity of the light, the maximum photocurrent will increase, but the stopping voltage will remain the same.

10. A. By changing the intensity of the light, only the maximum photocurrent is affected.

11. a. [Point *P* represents the negative value of the stopping voltage.[1]]

- I have identified that point *P* represents the negative value of the stopping voltage.[1]

73% of students answered this VCAA exam question correctly.

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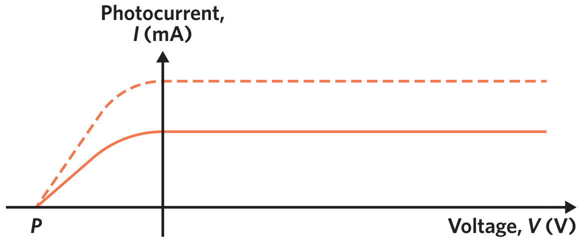
b.



I have drawn a graph that has the same horizontal axis intercept as the original.

I have drawn a graph that has a higher maximum vertical axis value compared to the original.

86% of students answered this VCAA exam question correctly.

12. a. [Voltage is the independent variable because it is deliberately changed by the experimenter.[1]] [Photocurrent is the dependent variable as it is being measured as a result of the change in the voltage.[2]]

I have explained why voltage is the independent variable.[1]

I have explained why photocurrent is the dependent variable.[2]

FROM LESSON 12A

b. [The intensity is a controlled variable.[1]]

I have identified that the intensity is a controlled variable.[1]

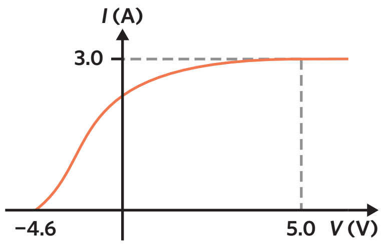
FROM LESSON 12A

c. [The photocurrent will increase.[1]] [This is because photocurrent increases as intensity increases.[2]]

I have identified that the photocurrent will increase.[1]

I have justified my answer.[2]

13.



I have drawn photocurrent on the vertical axis and voltage on the horizontal axis.

I have included units for both axes.

I have drawn the correct shape of a photocurrent-electrode potential graph.

I have drawn a graph that has a horizontal axis intercept at –4.6 V.

I have drawn a graph that begins to flatten out at the point (5.0, 3.0).

14. [Increasing the voltage allows more photoelectrons to be captured at the collector electrode but has an upper limit as once all the ejected photoelectrons are being captured, increasing the voltage will have no effect.[1]] [According to the particle model of light, by increasing the intensity of light we are increasing the number of light particles.[2]] [The more particles of light there are incident on the metal surface, the more photoelectrons are able to be liberated from the metal surface.[3]] [This increases the maximum photocurrent.[4]]

I have explained why there is an upper limit for the photocurrent when increasing voltage.[1]

I have described how the particle model of light models intensity.[2]

I have explained how more photoelectrons are liberated with a greater intensity of light.[3]

I have explained how this increases maximum photocurrent.[4]

Previous lessons

15. $F = k\frac{q_1 q_2}{r^2} = 8.99 \times 10^9 \times \frac{1.6 \times 10^{-19} \times 3.50 \times 10^{-10}}{0.002^2}$ (1 MARK)

The direction is to the right as two positive charges will repel.

$F = 1.26 \times 10^{-13} = 1.3 \times 10^{-13}$ N (1 MARK)

$F = 1.3 \times 10^{-13}$ N to the right (1 MARK)

FROM LESSON 4A

16. $v = \frac{d}{t} = \frac{0.25}{2.0 \times 10^{-4}} = 1250$ m s^{-1} (1 MARK)

$v = f\lambda \Rightarrow 1250 = f \times 9.0$

$f = 139 = 1.4 \times 10^2$ Hz (1 MARK)

FROM LESSON 7A

9C Changing frequency in the photoelectric effect

Progress questions

1. D. The horizontal axis intercept represents the threshold frequency and the negative value of the vertical axis intercept represents the negative work function.

2. A. Only by changing the metal will the kinetic energy-frequency graph change.

3. D. The threshold frequency is the minimum frequency of light required to overcome the work function and liberate electrons.

4. C. $\phi = hf_0 \Rightarrow 2.9 = 4.14 \times 10^{-15} \times f_0$

$f_0 = 7.00 \times 10^{14} = 7.0 \times 10^{14}$ Hz

5. A, B. Both the frequency of light and the work function of the metal plate used affect the horizontal axis intercept of a photocurrent-potential graph.

6. A. Higher frequencies will result in a higher value for the stopping voltage. This is represented by the horizontal axis value of a photocurrent-potential graph.

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Deconstructed exam-style

7. A. Planck's constant is represented by the gradient of a kinetic energy-frequency graph.

8. Any two points are acceptable, as long as they sit on the line. For example: $(5 \times 10^{14}, 0)$ and $(10 \times 10^{14}, 2)$.

9. Planck's constant will be the gradient of the graph. Therefore we can choose any two points on the line, for example $(5 \times 10^{14}, 0)$ and $(10 \times 10^{14}, 2)$. (1 MARK)

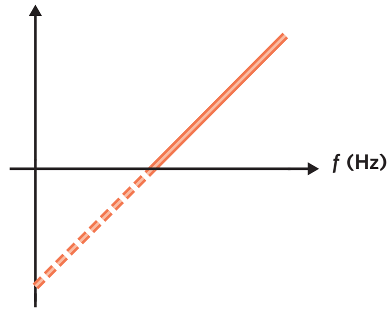
$h = \frac{y_2 - y_1}{x_2 - x_1} = \frac{2 - 0}{10 \times 10^{14} - 5 \times 10^{14}} = 4 \times 10^{-15}$ eV s (1 MARK)

59% of students answered this VCAA exam question correctly.

Exam-style

10. D. $\phi = hf_0 = 4.14 \times 10^{-15} \times 3.6 \times 10^{14} = 1.5$ eV

11. a.



I have drawn a straight line on top of the original line.

b. [The graph is the same as the first experiment[1]][as changing the intensity does not affect the maximum kinetic energy of the photoelectrons.[2]]

I have identified that the graphs are the same.[1]

I have explained that changing the intensity of light doesn't affect the KE_{max}.[2]

55% of students answered this VCAA exam question correctly.

12. a. $KE_{max} = hf - \phi \Rightarrow 0.80 = 9.5 \times 10^{14} \times 4.14 \times 10^{-15} - \phi$

$\phi = 3.13 = 3.1$ eV as required.

b. $\phi = hf_0 \Rightarrow 3.1 = 4.14 \times 10^{-15} \times f_0$ (1 MARK)

$f_0 = 7.48 \times 10^{14} = 7.5 \times 10^{14}$ Hz (1 MARK)

13. $KE_{max} = h(f - f_0)$

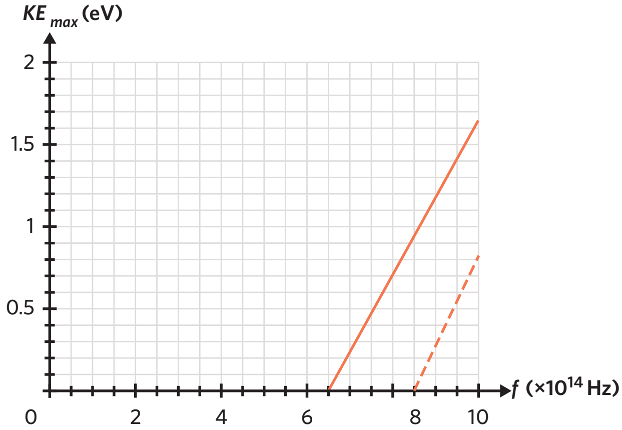
$\Rightarrow 2.6 \times 10^{-19} = 6.63 \times 10^{-34} \times (f - 5.5 \times 10^{14})$ (1 MARK)

$f = 9.42 \times 10^{14} = 9.4 \times 10^{14}$ Hz (1 MARK)

14. D. Lithium has the highest threshold frequency and therefore has the highest work function.

78% of students answered this VCAA exam question correctly.

15. When the work function is increased by a factor of one-third, it shifts the vertical axis intercept down by one-third. This is equivalent to shifting the horizontal axis intercept to the right by one-third (from 6×10^{14} Hz to 8×10^{14} Hz).

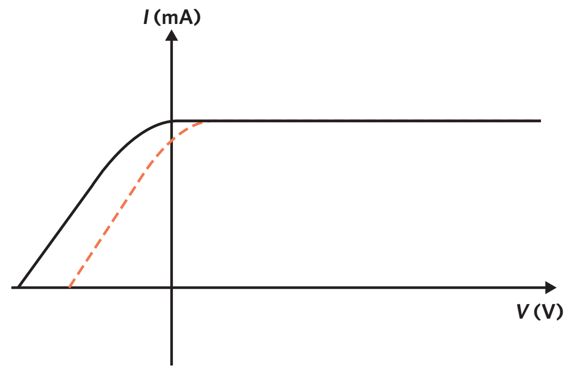


I have drawn the graph parallel to the original.

I have drawn the graph crossing the horizontal axis at 8×10^{14} Hz.

55% of students answered this VCAA exam question correctly.

16. a.



I have drawn a line with the same maximum vertical axis value as the original.

I have drawn a line with a horizontal axis intercept to the left of the original.

50% of students answered this VCAA exam question correctly.

b. The work function of the metal will be the negative value of the vertical axis intercept.

$\phi = -(-2.8) = 2.8$ eV

65% of students answered this VCAA exam question correctly.

17. $\phi = hf_0 \Rightarrow 3.2 \times 10^{-19} = h \times 6.5 \times 10^{14}$ (1 MARK)

$h = 4.92 \times 10^{-34} = 4.9 \times 10^{-34}$ J s (1 MARK)

62% of students answered this VCAA exam question correctly.

18. [Isabella is correct.[1]][No photocurrent is being measured as the light used is below the threshold frequency of the metal used. To produce a photocurrent the incident light must exceed this threshold frequency, as suggested by Isabella.[2]]

I have identified who is correct.[1]

I have explained my answer.[2]

17% of students answered this VCAA exam question correctly.

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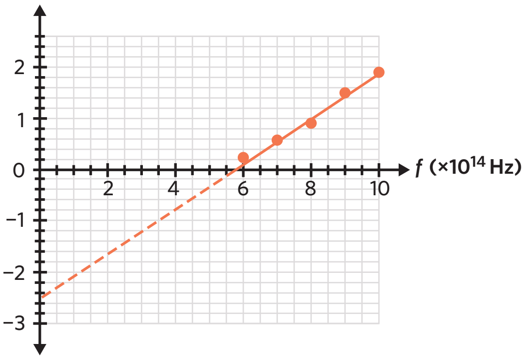
19. a. [The independent variable is the frequency of incident light[1]] [and the dependent variable is the stopping voltage.[2]]

I have identified the independent variable.[1]

I have identified the dependent variable.[2]

FROM LESSON 12A

b.



I have drawn the horizontal axis as the independent variable, and included correct units.

I have drawn the vertical axis as the dependent variable, and included correct units.

I have included an appropriate and consistent scale on the axes.

I have correctly plotted data points

I have drawn an appropriate line of best fit which is dashed below the horizontal axis.

FROM LESSON 12D

c. Use the horizontal axis intercept on the line of best fit: $f_0 = 5.7 \times 10^{14}$ Hz. Any value between 5.45×10^{14} Hz and 5.95×10^{14} Hz is acceptable.

d. Use two points from the line of best fit to calculate the gradient. Using $(7.0 \times 10^{14}, 0.60)$, $(10.0 \times 10^{14}, 1.90)$:

$h = \frac{y_2 - y_1}{x_2 - x_1} = \frac{1.90 - 0.60}{10.0 \times 10^{14} - 7.0 \times 10^{14}}$ (1 MARK)

$h = 4.3 \times 10^{-15}$ eV s. (1 MARK)

Other values close to this answer are acceptable as long as the gradient is calculated using two points on the line of best fit.

FROM LESSON 12D

e. Use the negative value of the vertical axis intercept on the line of best fit to determine the work function.
$\phi = 2.5$ eV (between 2.3 eV and 2.4 eV is acceptable) (1 MARK)

The metal is europium. (1 MARK)

20. a. $c = f\lambda \Rightarrow 3.0 \times 10^8 = f \times 3.75 \times 10^{-7}$ (1 MARK)

$f = 8.0 \times 10^{14}$ Hz

$KE_{max} = 1.25 \text{ eV} = 1.25 \times 1.6 \times 10^{-19}$ J
$= 2.0 \times 10^{-19}$ J (1 MARK)

$KE_{max} = hf - \phi \Rightarrow 2.0 \times 10^{-19}$
$= 6.63 \times 10^{-34} \times 8.0 \times 10^{14} - \phi$ (1 MARK)

$\phi = 3.30 \times 10^{-19} = 3.3 \times 10^{-19}$ J (1 MARK)

b. $\phi = hf_0 \Rightarrow 3.30 \times 10^{-19} = 6.63 \times 10^{-34} \times f_0$ (1 MARK)

$f_0 = 4.98 \times 10^{14} = 5.0 \times 10^{14}$ Hz (1 MARK)

21. Planck's constant is represented by the gradient of a kinetic energy-frequency graph.

Choose two points: $(0, -3.4)$ and $(8.1 \times 10^{14}, 0)$ (1 MARK)

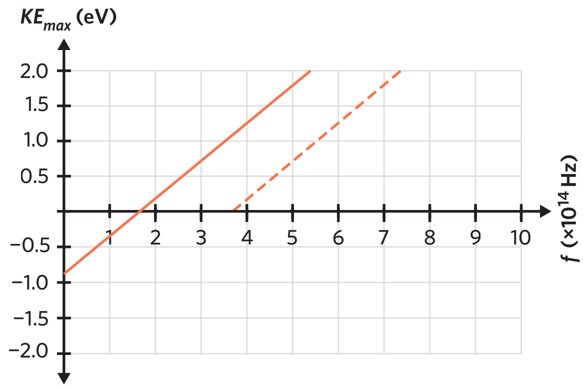
$h = \frac{y_2 - y_1}{x_2 - x_1} = \frac{0 - (-3.4)}{8.1 \times 10^{14} - 0} = 4.198 \times 10^{-15}$ eV s (1 MARK)

Convert eV s to J s:

$4.198 \times 10^{-15} \times 1.6 \times 10^{-19} = 6.72 \times 10^{-34}$
$= 6.7 \times 10^{-34}$ J s (1 MARK)

48% of students answered this VCAA exam question correctly.

22.



I have drawn a solid line with the same gradient as the original line.

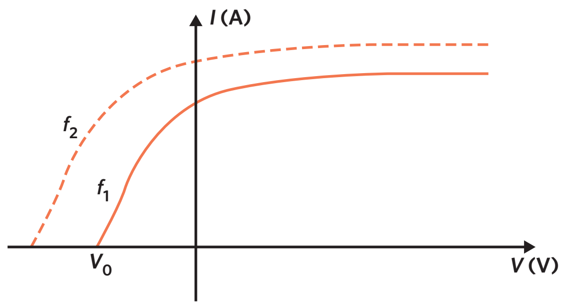
I have drawn a solid line with half of the value of the threshold frequency.

69% of students answered this VCAA exam question correctly.

23. a. $KE_{max} = hf - hf_0 = h(f - f_0)$
$= 4.14 \times 10^{-15} \times (7.3 \times 10^{14} - 5.8 \times 10^{14})$ (1 MARK)

$KE_{max} = 0.621 \text{ eV} \Rightarrow V_0 = 0.621 = 0.62$ V (1 MARK)

b.



I have drawn a dotted line with a higher maximum vertical axis value than the original.

I have drawn a dotted line with a horizontal axis intercept to the left of the original.

Previous lessons

24. D. Using the right hand coil rule, the magnetic field produced by the current will wrap around the coil clockwise as viewed from the left.

90% of students answered this VCAA exam question correctly.

FROM LESSON 4B

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25. The third antinode corresponds to a value of $n = 2$.

$p.d. = n\lambda \Rightarrow 12 = 2\lambda$ (1 MARK)

$\lambda = 6.0$ m (1 MARK)

FROM LESSON 7B

9D Explaining the photoelectric effect

Progress questions

1. A, B. The wave model predicts both a relationship between kinetic energy and intensity, and that any frequency of light should be able to produce a photocurrent.

2. D. The wave model of light does not predict the existence of the threshold frequency.

3. D. Photons are most accurately modelled as 'packets' of energy with properties of both waves and particles.

4. C. By increasing the intensity of light, we are increasing the number of photons incident.

5. C. Photons are modelled as 'packets' of light which are absorbed instantly by the electrons on the metal's surface.

6. C. Light behaves like both a wave and a particle and so has properties of both.

7. B. $E_{ph} = hf = 4.14 \times 10^{-15} \times 3.6 \times 10^{14} = 1.49 = 1.5$ eV

8. A. $E_{ph} = \frac{hc}{\lambda} \Rightarrow 5.8 \times 10 = \frac{4.14 \times 10^{-15} \times 3.0 \times 10^{8}}{\lambda}$
$\Rightarrow \lambda = 3.43 \times 10^{-8} = 3.4 \times 10^{-8}$ m

Deconstructed exam-style

9. [This supports the particle model of light.[1]]

I have identified which model of light is supported.[1]

10. [Less intense light is modelled by a fewer photons according to the particle model of light.[1]]

I have identified how the intensity of light is modelled using the particle model.[1]

11. [The model that is supported is the particle model.[1]][In the particle model, the intensity of light is proportional to the number of photons emitted.[2]][Since one photon is absorbed by one electron, low intensity light still produces a photoelectrons as reducing the intensity of light only affects the number of photons, and not their energy.[3]]

I have identified which model is supported.[1]

I have explained how the intensity of light is modelled using the particle model.[2]

I have explained how the particle model supports the emission of photoelectrons at low light intensities.[3]

14% of students answered this VCAA exam question correctly.

Exam-style

12. B. $E_{ph} = hf \Rightarrow 1.33 \times 10^{6} = 4.14 \times 10^{-15} \times f$

$f = 3.212 \times 10^{20} = 3.21 \times 10^{20}$ Hz

73% of students answered this VCAA exam question correctly.

13. C. Photons are massless particles that exhibit wave and particle characteristics.

14. $c = f\lambda \Rightarrow 3.0 \times 10^{8} = 3.80 \times 10^{15} \times \lambda$ (1 MARK)

$\lambda = 7.89 \times 10^{-8} = 7.9 \times 10^{-8}$ m $= 79$ nm (1 MARK)

74% of students answered this VCAA exam question correctly.

15. [One limitation of the wave model is that it does not explain the existence of a threshold frequency.[1]]

I have identified one limitation of the wave model.[1]

Other possible answers include:

- The absence of a time delay
- The kinetic energy of photoelectrons is independent of the intensity of the light source

63% of students answered this VCAA exam question correctly.

16. [Max Planck is correct.[1]][James Clerk Maxwell is basing his argument on the wave model of light, which predicts that a greater intensity of light should produce photoelectrons with a greater kinetic energy.[2]][Max Planck is basing his argument on the particle model of light, which predicts that the kinetic energy of photoelectrons is independent of the intensity of light.[3]]

I have identified who is correct.[1]

I have explained that James Clerk Maxwell based his argument on the wave model of light.[2]

I have explained that Max Planck based his argument on the particle model of light.[3]

17. $\Delta KE_{electron} = E_{ph} = 15$ eV

$E_{ph} = hf \Rightarrow 15 = 4.14 \times 10^{-15} \times f$ (1 MARK)

$f = 3.62 \times 10^{15} = 3.6 \times 10^{15}$ Hz (1 MARK)

18. [Sam's idea will not produce a greater photocurrent.[1]]
[This is because, even though Sam is increasing the intensity of the light, the frequency of red light is less than that of ultraviolet light, and therefore is below the threshold frequency.[2]]

I have identified that Sam's idea will not produce a greater photocurrent.[1]

I have explained why Sam's idea will not produce a greater photocurrent using the threshold frequency.[2]

19. [Observation 3 is not predicted by the wave model of light.[1]]
[According to the wave model, light is a continuous distribution of energy which must be absorbed over a period of time until an electron in the plate has enough energy to be emitted.[2]]
[This is not consistent with the negligible time delay observed.[3]]

9D ANSWERS

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I have identified which observation the wave model fails to predict.[1]

I have explained the wave model prediction.[2]

I have explained why the wave model prediction is incorrect.[3]

10% of students answered this VCAA exam question correctly.

20. [When the photoelectric experiment is conducted, it is observed that there is negligible time delay before a photocurrent is observed,[1]] [and the maximum kinetic energy of an electron is not affected by the intensity of light.[2]] [A photon has a discrete amount of energy and is absorbed almost instantly by an electron, therefore, there is a negligible time delay between light shining on a metal surface and the emission of photoelectrons. This supports the particle model of light.[3]] [In the particle model of light, intensity is a measure of the number of photons per unit time and does not change the amount of energy carried by individual photons. As an electron's kinetic energy is determined by the absorption of a single photon, it is independent of intensity.[4]]

I have identified an observation that supports the particle model of light.[1]

I have identified a second observation that supports the particle model of light.[2]

I have explained how the first observation supports the particle model of light.[3]

I have explained how the second observation supports the particle model of light.[4]

21. a. [A systematic error has occurred.[1]] [A systematic error is a consistent difference between the measured results and the true values of the intended measurements, looking at the graphs we see that although they are different, they are still parallel, therefore there is a consistent difference between the results of the two experiments.[2]]

I have identified the type of error that has occurred.[1]

I have given reasons for my answer.[2]

FROM LESSON 12C

b. $\phi = hf_0 \Rightarrow 3.6 = 4.14 \times 10^{-15} \times f_0$ (1 MARK)

$f_0 = 8.70 \times 10^{14} = 8.7 \times 10^{14}$ Hz (1 MARK)

From the graph, student 1 records $f_0 = 1.1 \times 10^{15}$ Hz and student 2 records $f_0 = 1.7 \times 10^{15}$ Hz.

As 1.1×10^{15} Hz is closer to f_0 than 1.7×10^{15} Hz, student 1's results were more accurate. (1 MARK)

FROM LESSON 12C

22. [The new frequency of light is less than the threshold frequency of the metal.[1]] [This means each photon does not have enough energy to overcome the work function regardless of how many photons there are.[2]]

I have identified why there is no photocurrent for the new frequency of light.[1]

I have explained why there is no photocurrent for the new frequency of light.[2]

10% of students answered this VCAA exam question correctly.

23. B. $E_{ph} = \frac{hc}{\lambda} = \frac{6.63 \times 10^{-34} \times 3.0 \times 10^{8}}{550 \times 10^{-9}} = 3.62 \times 10^{-19}$ J

$P_{light} = 3.62 \times 10^{-19} \times 2.8 \times 10^{16} = 1.01 \times 10^{-2} = 1.0 \times 10^{-2}$ W

36% of students answered this VCAA exam question correctly.

Previous lessons

24. D. Using the right hand coil rule, the magnetic field will point out of the page.

FROM LESSON 4B

80% of students answered this VCAA exam question correctly.

25. It takes 5.1 s to travel the 1.5 wavelengths between point *Y* and point *Z*.

Therefore the time taken for one wavelength to pass is the period: $T = \frac{5.1}{1.5} = 3.4$ s. (1 MARK)

$f = \frac{1}{T} \Rightarrow f = \frac{1}{3.4} = 0.294 = 0.29$ Hz (1 MARK)

FROM LESSON 7C

Chapter 9 review

Section A

1. C. The frequency of light determines the photon energy and can be changed to measure the effect it has on the maximum kinetic energy of photoelectrons.

2. C. In the photoelectric effect experiment, it is not observed that any frequency of light can produce a photocurrent.

3. D. The higher intensity will not affect the graph of the kinetic energy-frequency graph. Changing to a metal with a lower work function will shift the graph upwards (which moves the x-intercept to the left).

70% of students answered this VCAA exam question correctly.

4. C. The stopping voltage measured in V has the same value as the maximum kinetic energy of photoelectrons measured in eV.

5. B. A lower frequency of light will require a lower magnitude of the stopping voltage. A higher intensity of light will result in a greater maximum vertical axis value.

Section B

6. [This statement is false.[1]] [Photoelectrons are released with a range of kinetic energies because different electrons require different amounts of energy to break free.[2]]

I have identified whether the statement is correct.[1]

I have explained that photoelectrons require different amounts of energy to be ejected.[2]

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7. a. [When the voltage is zero, the photocurrent will be a maximum as the photoelectrons are not repelled by the collector electrode.[1]] [As Aliya increases the voltage, the collector electrode repels photoelectrons with an increasing force. This decreases the number of electrons arriving at the collector electrode which decreases the photocurrent.[2]] [The photocurrent will continue to decrease until even the most energetic photoelectrons are repelled and the photocurrent becomes zero. The voltage for this to happen is called the stopping voltage.[3]]

- I have identified the photocurrent is largest when the voltage is zero.[1]
- I have explained how the photocurrent changes as the voltage increases.[2]
- I have explained what happens when the photocurrent reaches zero.[3]

b. The value of the stopping voltage in V is equivalent to the value of KE_{max} in eV.

$\Rightarrow KE_{max} = 5.0 \text{ eV}$ (1 MARK)

$KE_{max} = 5.0 \times 1.6 \times 10^{-19}$

$KE_{max} = 8.00 \times 10^{-19} = 8.0 \times 10^{-19} \text{ J}$ (1 MARK)

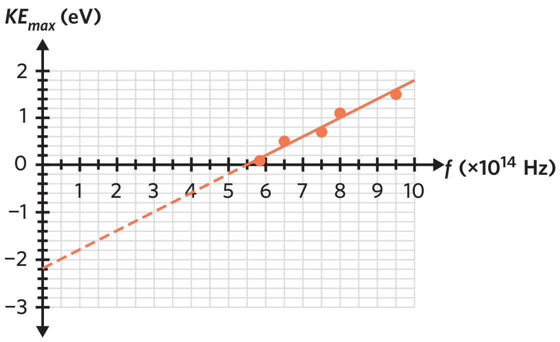
c. $\phi = hf_0 \Rightarrow 3.0 = 4.14 \times 10^{-15} \times f_0$ (1 MARK)

$f_0 = 7.24 \times 10^{14} = 7.2 \times 10^{14} \text{ Hz}$ (1 MARK)

d. $KE_{max} = hf - \phi \Rightarrow 5.0 = 4.14 \times 10^{-15} \times f - 3.0$ (1 MARK)

$f = 1.93 \times 10^{15} = 1.9 \times 10^{15} \text{ Hz}$ (1 MARK)

8. a.



- I have plotted frequency on the horizontal axis and KE_{max} on the vertical axis.
- I have included the correct units, and an appropriate and consistent scale on the axes.
- I have correctly plotted the data points.
- I have drawn an appropriate line of best fit.
- I have used a dashed line for the part of the graph which is below the horizontal axis.

67% of students answered this VCAA exam question correctly.

FROM LESSON 12D

b. Use the vertical axis intercept of the line of best fit: $\phi = 2.2 \text{ eV}$ (between 2.0 eV and 2.4 eV is acceptable).

c. Use two points from the line of best fit to calculate the gradient:

$$h = \frac{y_2 - y_1}{x_2 - x_1} = \frac{1.0 - 0.0}{8.0 \times 10^{14} - 5.5 \times 10^{14}} \text{ (1 MARK)}$$

$h = 4.0 \times 10^{-15} \text{ eV s}$ (1 MARK)

(between 3.8×10^{-15} eV s and 4.2×10^{-15} eV s is acceptable)

FROM LESSON 12D

d. $KE_{electron} = \frac{6.56 \times 10^{-19}}{1.6 \times 10^{-19}} = 4.1 \text{ eV}$ (1 MARK)

$KE_{electron} = E_{photon} - \phi \Rightarrow 4.1 = E_{photon} - 1.8$

$E_{photon} = 5.9 \text{ eV}$ (1 MARK)

9. a. $KE_{max} = 1.4 \text{ eV}$ and $\phi = \frac{7.36 \times 10^{-19}}{1.6 \times 10^{-19}} = 4.6 \text{ eV}$

$KE_{max} = E_{ph} - \phi \Rightarrow 1.4 = E_{ph} - 4.6$ (1 MARK)

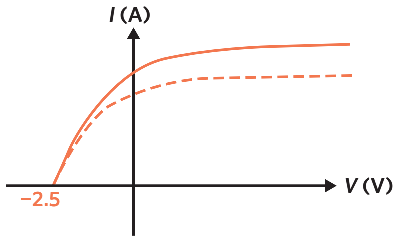
$E_{ph} = 6.0 \text{ eV}$ (1 MARK)

Aragorn is incorrect. (1 MARK)

b. [The wave model predicts that all frequencies of light should produce a photocurrent if given sufficient time.[1]] [The particle model predicts that light of a frequency less than the threshold frequency will not emit photoelectrons, no matter how long the light is incident on the metal.[2]] [Tauriel's observations are consistent with the particle model rather than the wave model because reducing the frequency of light resulted in no photoelectrons being emitted even after shining the light for an extended period of time.[3]]

- I have explained the wave model predictions.[1]
- I have explained the particle model predictions.[2]
- I have explained how Tauriel's observations support the particle model and not the wave model.[3]

10. a.



- I have drawn a curve with the same x-intercept and a lower y value.
- I have drawn a curve with a similar shape.

b. [The fact that both curves share the same horizontal axis intercept (stopping voltage) is evidence for the particle model of light.[1]] [This indicates that the maximum kinetic energy of photoelectrons is the same for both intensities.[2]] [The particle model correctly predicts that increasing the intensity will increase the number of photons released but not the energy of the photons, and so the maximum kinetic energy of photoelectrons will not change.[3]] [The wave model incorrectly predicts that increasing the intensity will deliver more energy and therefore increase the maximum kinetic energy of the photoelectrons.[4]]

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✓ ✗ I have identified a feature of the graph that supports the particle model rather than the wave model.[1]

✓ ✗ I have explained that the KE_{max} is the same for both intensities.[2]

✓ ✗ I have explained the particle model prediction.[3]

✓ ✗ I have explained the wave model prediction.[4]

c. [One photon can be absorbed by one electron. For large positive values of electrode potential all of the available electrons in the metal are being emitted and collected.[1]] [Since there are no more photoelectrons to be collected, increasing the voltage will not result in an increase in photocurrent so the graph is flat.[2]]

✓ ✗ I have explained that for large positive electrode potentials all available electrons are being collected.[1]

✓ ✗ I have explained that this results in the graph remaining flat.[2]

d. $KE_{max} = 2.5 \text{ eV} = 2.5 \times 1.6 \times 10^{-19} = 4.0 \times 10^{-19} \text{ J}$ (1 MARK)

$KE_{max} = \frac{hc}{\lambda} - \phi \Rightarrow 4.0 \times 10^{-19}$

$= \frac{6.63 \times 10^{-34} \times 3.0 \times 10^{8}}{\lambda} - 1.8 \times 10^{-19}$ (1 MARK)

$\lambda = 3.42 \times 10^{-7} = 3.4 \times 10^{-7} \text{ m}$ (1 MARK)

OR

$\phi = 1.8 \times 10^{-19} \text{ J} = \frac{1.8 \times 10^{-19}}{1.6 \times 10^{-19}} = 1.13 \text{ eV}$ (1 MARK)

$KE_{max} = \frac{hc}{\lambda} - \phi \Rightarrow 2.5$

$= \frac{4.14 \times 10^{-15} \times 3.0 \times 10^{8}}{\lambda} - 1.13$ (1 MARK)

$\lambda = 3.42 \times 10^{-7} = 3.4 \times 10^{-7} \text{ m}$ (1 MARK)

11. a. $KE_{max} = \frac{1}{2}mv^2 = \frac{1}{2} \times 9.1 \times 10^{-31} \times (1.22 \times 10^6)^2$

$= 6.77 \times 10^{-19} \text{ J}$ (1 MARK)

$KE_{max} = \frac{6.77 \times 10^{-19}}{1.6 \times 10^{-19}} = 4.23 \text{ eV}$

The maximum kinetic energy of the photoelectrons in eV has the same value as the stopping voltage in V.

$\Rightarrow V_0 = 4.23 = 4.2 \text{ V}$ (1 MARK)

b. $KE_{max} = hf - \phi$

$6.77 \times 10^{-19} = 6.63 \times 10^{-34} \times 1.96 \times 10^{15} - \phi$ (1 MARK)

$\phi = 6.22 \times 10^{-19} = 6.2 \times 10^{-19} \text{ J}$ (1 MARK)

c. $\phi = hf_0 \Rightarrow 4.33 = 4.14 \times 10^{-15} \times f_0$ (1 MARK)

$f_0 = 1.046 \times 10^{15} \text{ Hz}$

$c = f\lambda \Rightarrow 3.0 \times 10^8 = 1.046 \times 10^{15} \times \lambda$ (1 MARK)

$\lambda = 2.868 \times 10^{-7} = 2.9 \times 10^{-7} \text{ m}$ (1 MARK)

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10A Comparing light and matter

Progress questions

1. B. Only very small objects like electrons will demonstrate measurable wave-like behaviour.

2. C. $\lambda = \frac{h}{mv} \Rightarrow \frac{6.63 \times 10^{-34}}{9.1 \times 10^{-31} \times 1.0 \times 10^{7}} = 7.27 \times 10^{-11}$

84% of students answered this VCAA exam question correctly.

3. A. If the wavelength of an electron and a photon are the same then they will have the same momentum.

4. B. They must have the same wavelength and therefore have the same momentum.

5. D. Viruses are often smaller than the wavelength of light and so significant diffraction occurs which limits the clarity of the image.

6. B. Although both electrons and X-rays can image objects smaller than a cell, X-rays can destroy the organic matter they image.

7. D. Light and matter both exhibit wave and particle properties.

8. D. The electrons diffract forming an interference pattern over time.

Deconstructed exam-style

9. [They must have the same wavelength.[1]]

I have identified one requirement for the electrons and X-rays to have the same diffraction pattern.[1]

Other answers include:

- They must have the same momentum.

10. D. The kinetic energy of an electron can be calculated using $KE = \frac{1}{2}mv^2 = \frac{p^2}{2m}$.

11. C. The formula relating photon energy and wavelength is $E_{ph} = \frac{hc}{\lambda}$.

12. For the diffraction patterns to be similarly spaced, the electrons and the X-rays must have the same momentum, $p_e = p_{ph}$.

$KE_e = \frac{p_e{}^2}{2m}$

$5000 \times 1.6 \times 10^{-19} = \frac{p_e{}^2}{2 \times 9.1 \times 10^{-31}}$ (1 MARK)

$p_e = \sqrt{5000 \times 1.6 \times 10^{-19} \times 2 \times 9.1 \times 10^{-31}}$
$= 3.82 \times 10^{-23}$ kg m s^{-1}

$E_{ph} = p_{ph}c = p_e c$

$E_{ph} = 3.82 \times 10^{-23} \times 3.0 \times 10^{8}$ (1 MARK)

$E_{ph} = 1.146 \times 10^{-14}$ J

$E_{ph} = \frac{1.146 \times 10^{-14}}{1.6 \times 10^{-19}} = 7.16 \times 10^{4} = 7.2 \times 10^{4}$ eV (1 MARK)

Ho Man is correct, as the required energy of the X-rays, 7.2×10^4 eV, is different to the electron energy, $5000 = 5 \times 10^3$ eV. (1 MARK)

Exam-style

13. A. The photoelectric effect only demonstrates the particle nature of light.

14. A. $p = mv = 663 \times 10 = 6.63 \times 10^3$ kg m s^{-1}

$\lambda = \frac{h}{p} = \frac{6.63 \times 10^{-34}}{6.63 \times 10^{3}} = 10^{-37}$ m

68% of students answered this VCAA question correctly

15. **a.** For the diffraction patterns produced to be similar, the wavelengths of the X-rays and the electrons must be approximately equal, $\lambda_e = \lambda_{ph} = \lambda$.

$\lambda = \frac{h}{\sqrt{2m \times KE_e}}$

$\Rightarrow 0.20 \times 10^{-9} = \frac{6.63 \times 10^{-34}}{\sqrt{2 \times 9.1 \times 10^{-31} \times KE_e}}$ (1 MARK)

$KE_e = 6.04 \times 10^{-18}$ J $= 37.7 = 38$ eV (1 MARK)

OR

For the diffraction patterns produced to be similar, the momentum of the X-rays and the electrons must be approximately equal, $p_e = p_{ph} = p$.

$\lambda_{ph} = \frac{h}{p}$

$0.20 \times 10^{-9} = \frac{6.63 \times 10^{-34}}{p}$ (1 MARK)

$p_{ph} = 3.32 \times 10^{-24}$ kg m s^{-1}

$E_e = \frac{p^2}{2m_e} = \frac{(3.32 \times 10^{-24})^2}{2 \times 9.1 \times 10^{-31}}$

$E_e = 6.04 \times 10^{-18}$ J $= 37.7 = 38$ eV (1 MARK)

24% of students answered this VCAA question correctly

b. [The diffraction spacing is determined by the wavelength and the gap width the wave is diffracting through, *diffraction* $\propto \frac{\lambda}{w}$.[1]] [In this instance, the X-rays and electrons are diffracting through the same spacing, and have the same wavelength, therefore the diffraction patterns will have the same spacing.[2]]

I have identified the relationship between diffraction, wavelength, and gap width.[1]

I have explained why the X-rays and the electrons produce patterns with the same spacing.[2]

66% of students answered this VCAA question correctly

16. For the electrons and X-ray photons to produce the same diffraction pattern, they must have the same momentum, $p_e = p_{ph} = p$.

$E_{ph} = pc \Rightarrow 1.38 \times 10^{-14} = p \times 3.0 \times 10^{8}$ (1 MARK)

$p = 4.60 \times 10^{-23}$ kg m s^{-1}

$p = m_e v_e$

$4.60 \times 10^{-23} = 9.1 \times 10^{-31} \times v_e$ (1 MARK)

$v_e = 5.05 \times 10^{7} = 5.1 \times 10^{7}$ m s^{-1} (1 MARK)

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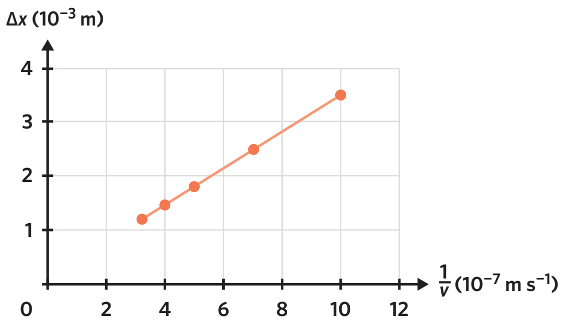
17. C. Both light and matter demonstrate particle and wave properties, and Young's double slit experiment only demonstrates the wave properties of light.

18. [Imaging requires limited diffraction to occur to maintain image quality.[1]][This means if an object is a similar size or smaller than the wavelength of the electromagnetic wave used, $\frac{\lambda}{w} \geq 1$, and significant diffraction will occur limiting the clarity of the image.[2]][Visible light's wavelength limits its ability to image objects bigger than a micrometer and electromagnetic waves with smaller wavelengths that visible light can damage the samples used.[3]]

- I have identified the limiting factor of imaging technology.[1]
- I have referred to diffraction.[2]
- I have explained the limitations of imaging using electromagnetic waves.[3]

19. a.



- I have plotted Δx on the vertical axis against $\frac{1}{v}$ on the horizontal axis.
- I have included titles and units on the axes.
- I have included a consistent and appropriate scale on each axis.
- I have correctly plotted all data values.
- I have drawn a line of best fit.

FROM LESSON 12D

b. $gradient = \frac{rise}{run} = \frac{(3.64 - 1.21) \times 10^{-3}}{(10 - 3.33) \times 10^{-5}}$ (1 MARK)

$gradient = 36.4\ \text{s}^{-1}$ (1 MARK)

Note that as the coordinates lie on the line of best fit, they can be used to calculate the gradient of the line.

FROM LESSON 12D

20. $E_{dust} = \frac{p_{dust}^{\ 2}}{2m_{dust}} \Rightarrow 2.0 \times 10^{-5} = \frac{p_{dust}^{\ 2}}{(2 \times 1.0 \times 10^{-3})}$ (1 MARK)

$p_{dust} = 2.00 \times 10^{-4} = 2.0 \times 10^{-4}\ \text{kg m s}^{-1}$

$E_{ph} = p_{ph}c \Rightarrow 2.0 \times 10^{-5} = p_{ph} \times 3.0 \times 10^{8}$ (1 MARK)

$p_{ph} = 6.67 \times 10^{-14} = 6.7 \times 10^{-14}\ \text{kg m s}^{-1}$

They will not produce the same diffraction pattern, as $diffraction \propto \frac{\lambda}{w}$, and their momentums (and therefore their wavelengths) are different but the gap they pass through is the same. (1 MARK)

21. [Dominik is correct and Alexis is incorrect.[1]][Electrons possess wave properties, such as an associated wavelength given by the de Broglie wavelength, and therefore can produce a diffraction pattern.[2]][Some experiments that demonstrate this include the electron double slit experiment, which shows that electrons diffract,[3]][and the diffraction of electrons through crystals.[4]]

- I have stated Dominik is correct and Alexis is incorrect.[1]
- I have described why Dominik is correct and Alexis is incorrect.[2]
- I have justified my answer using one experiment.[3]
- I have justified my answer using another experiment.[4]

27% of students answered this VCAA question correctly

Previous lessons

22. a. $W = KE \Rightarrow qV = \frac{1}{2}mv^2$

$1.6 \times 10^{-19} \times V = \frac{1}{2} \times 9.1 \times 10^{-31} \times (5.0 \times 10^{7})^2$ (1 MARK)

$V = 7.11 \times 10^{3} = 7.1 \times 10^{3}\ \text{V}$ (1 MARK)

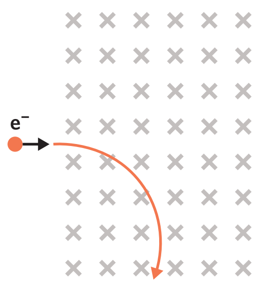
FROM LESSON 4C

b. $r = \frac{mv}{qB} = \frac{9.1 \times 10^{-31} \times 5.0 \times 10^{7}}{1.6 \times 10^{-19} \times 350}$ (1 MARK)

$r = 8.13 \times 10^{-7} = 8.1 \times 10^{-7}\ \text{m}$ (1 MARK)

FROM LESSON 4C

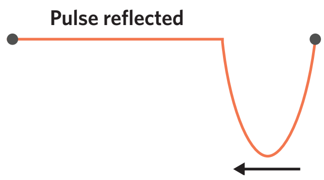
c.



- I have drawn a clockwise circular path.

FROM LESSON 4C

23.



- I have sketched the wave after it has been reflected.[1]

FROM LESSON 7D

10A ANSWERS

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10B Absorption and emission spectra

Progress questions

1. D. Electron standing waves explain the quantisation of electron orbitals and energy levels, since if they didn't form standing waves they would destructively interfere with themselves.

   59% of students answered this VCAA question correctly

2. A. The downwards arrow indicates a photon being emitted, and the energy will be $E_{ph} = \Delta E = 13.1 - 10.2 = 2.9$ eV.

3. C. $E_{ph} = hf = 4.14 \times 10^{-15} \times 1.7 \times 10^{14} = 0.70$ eV

   $E_{ph} = \Delta E \Rightarrow 0.70 = E_{new} - 12.1 \Rightarrow E_{new} = 12.8$ eV

4. A, B. Absorption spectra have dark bands where an atom absorbs photons, and emission spectra have light bands where it emits photons. They are unique to each type of atom.

5. B, C. Emission spectra have bright bands corresponding to the wavelengths of light emitted by a particular element, and they are unique to each element.

6. A. $E_{ph} = \frac{4.14 \times 10^{-15} \times 3.0 \times 10^{8}}{410 \times 10^{-9}} = 3.0$ eV

Deconstructed exam-style

7. C. The only electron orbitals that can exist around atoms are those where the electron forms a standing wave, which is not always possible.

8. [When an electron transitions from a higher energy level to lower energy level it emits a photon. Since these energy levels only occur at discrete intervals, photons are emitted with a discrete amount of energy.[1]]

   I have described how discrete photons are emitted from atoms.[1]

9. B. Photon energy is related to wavelength using $E = \frac{hc}{\lambda}$, so discrete photon energies must correspond to discrete wavelengths.

10. [An electron in a sodium atom can only exist at certain orbitals, corresponding to discrete energy levels.[1]] [Electrons emit photons with a discrete amount of energy when they transition from a higher to a lower energy level .[2]] [As the wavelength of light is related to its photon energy through $E = \frac{hc}{\lambda}$, a sodium vapour lamp will only emit certain discrete wavelengths of light, corresponding to the difference in energy levels.[3]]

    I have identified that electron energy levels are quantised.[1]

    I have explained how photons are emitted from electron transitions.[2]

    I have justified why sodium vapour lamps emit certain wavelengths of light.[3]

    24% of students answered this VCAA question correctly

Exam-style

11. D. In an energised gas, electrons moving down energy levels emit light. This is how vapour lamps produce light.

12. A. Absorption and emission of the same photon energy corresponds to two arrows of the same length (between the same levels) pointing in opposite directions.

13. D. Transitions resulting from electrons absorbing photons correspond to arrows pointing upwards.

14. B. The transition with the absorption of the smallest wavelength of light is the longest arrow that points upwards, since small wavelengths correspond to high energies, $E_{ph} = \frac{hc}{\lambda}$.

15. **a.** The smallest frequency corresponds to the smallest change in energy, according to $E = hf$.

    The smallest energy possible comes from the transition 116 → 109, which gives 7 eV. (1 MARK)

    $E = hf \Rightarrow 7 = 4.14 \times 10^{-15} \times f$

    $f = 1.69 \times 10^{15} = 2 \times 10^{15}$ Hz (1 MARK)

    37% of students answered this VCAA question correctly

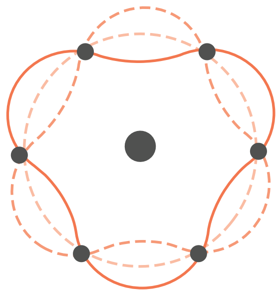
    b. $E_{ph} = \frac{hc}{\lambda} \Rightarrow E_{ph} = \frac{4.14 \times 10^{-15} \times 3.0 \times 10^{8}}{13.2 \times 10^{-9}}$ (1 MARK)

    $E_{ph} = 94.1 = 94$ eV (1 MARK)

    This is the energy of the photon that will be emitted when an electron transitions from the first excited state, $n = 2$, to the ground state, $n = 1$. (1 MARK)

    44% of students answered this VCAA question correctly

    c.

    I have drawn a standing wave with three complete wavelengths.

    I have drawn this wave on a circle about a nucleus.

16. A. Since the ionisation energy is the energy at which the electron will escape from the atom, if it absorbs a photon with at least that amount of energy it will be ejected.

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17. [The wave model of matter assigns wave-like properties to electrons, including a de Broglie wavelength.[1]][For an orbit to be exist an electron must form a standing wave, where the circumference of the orbit is an integer multiple of the de Broglie wavelength.[2]][Since this is only possible for certain orbits, and hence only for certain energy levels, the electron energy levels are quantised.[3]]

- I have stated that electrons have a de Broglie wavelength.[1]
- I have explained the requirements for electrons to form an orbital.[2]
- I have explained why the electron energy levels are quantised.[3]

21% of students answered this VCAA question correctly

18. a. $n_3 - n_1 = 3.19$ eV (1 MARK)

$n_3 - n_2 = 1.09$ eV (1 MARK)

$n_2 - n_1 = 2.10$ eV (1 MARK)

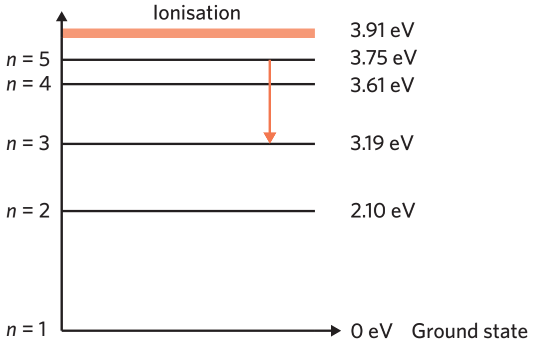
36% of students answered this VCAA question correctly

b. [It is not possible[1]][because there are no energy levels with a difference of 2.3 eV between them.[2]]

- I have stated whether the observation is possible.[1]
- I have stated why the observation is not possible.[2]

c. $\Delta E = hf = 4.14 \times 10^{-15} \times 1.353 \times 10^{14} = 0.560$ eV

d.



- I have drawn an arrow between $n = 5$ and $n = 3$.
- I have drawn the arrow pointing downwards.

e. [They should use the value $h = 4.14 \times 10^{-15}$ eV s.[1]][This is the easiest form of Planck's constant for them to use since the energy levels are given in terms of eV, as opposed to J.[2]]

- I have identified which value of Planck's constant is best to use.[1]
- I have justified my answer by referring to the units of energy used.[2]

19. B. If electrons existed in an orbit that did not form a standing wave, they would destructively interfere and the orbit would not be able to exist.

20. [As light passes through the exosphere, the elements in the exosphere will absorb certain wavelengths of the light, producing an absorption spectrum.[1]][By comparing the wavelengths present in the absorption spectrum to mercury's unique absorption spectrum, Jenn can determine if there is mercury present.[2]]

- I have described how absorption spectra are produced.[1]
- I have explained how absorption spectra can be used to detect if mercury is present.[2]

21. a. [Precision is a measure of the spread of recorded values.[1]] [Eimear's results have a range of 7 nm, whilst Dhilan's results range over 14 nm, so Eimear's results are more precise.[2]]

- I have stated the definition of precision.[1]
- I have determined whose results are more precise.[2]

FROM LESSON 12C

b. $E_{ph} = hf \Rightarrow E = 4.14 \times 10^{-15} \times 3.1 \times 10^{14}$ (1 MARK)

$E_{ph} = 1.28$ eV

$E_{ph} = \Delta E \Rightarrow 1.28 = 5.6 - E_n$ (1 MARK)

$E_n = 4.32 = 4.3$ eV (1 MARK)

22. B and D. x is between 6.7 and 9.8 eV, and must have a difference of 2.2 eV with either 6.7 or 9.8 eV.

23. Note that these energies must correspond to transitions to or from the energy level at x eV, since no other transitions give these specific energies.

The transition with $\Delta E = 2.2$ eV must be either $9.8 \to x$, which gives $x = 7.6$ eV, or $x \to 6.7$, which gives $x = 8.9$ eV. (1 MARK)

When $x = 7.6$ eV, the $\Delta E = 4.0$ eV transition goes to $7.6 - 4.0 = 3.6$ eV, which is not a possible energy level. (1 MARK)

Therefore the correct solution is $x = 8.9$ eV (1 MARK).

40% of students answered this VCAA question correctly

Previous lessons

24. $F = 0$ N. There is no magnetic force on the wire since the field is parallel to the current in the wire.

FROM LESSON 4C

25. [Significant diffraction will not occur if $\frac{\lambda}{w} \ll 1$.[1]][In this scenario, $\frac{\lambda}{w} = \frac{1.5 \times 10^{-9}}{6.0 \times 10^{-8}} = 2.5 \times 10^{-2}$.[2]][This is much less than 1, so significant diffraction will not occur.[3]]

- I have identified the condition for significant diffraction.[1]
- I have calculated the ratio $\frac{\lambda}{w}$.[2]
- I have explained that significant diffraction will not occur.[3]

FROM LESSON 7D

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Chapter 10 review

Section A

1. B. $\lambda = \frac{h}{mv} = \frac{6.63 \times 10^{-34}}{1.67 \times 10^{-27} \times 2.0 \times 10^{3}} = 2.0 \times 10^{-10}$ m

2. C. Light and matter have dual wave-particle nature, which are both demonstrated in the photon/electron double slit experiments.

3. B. There are three whole wavelengths shown, corresponding to $n = 3$.

   36% of students answered this VCAA question correctly.

4. D. The energies of the photons that form the spectral lines correspond to the differences between energy levels in an atom, which are quantised due to electron standing waves.

5. D. Shorter wavelengths are required to image smaller objects, but short wavelengths of light are more energetic making them hard to produce and more likely to damage what they're imaging.

Section B

6. a. $E = pc \Rightarrow 12.5 \times 1.6 \times 10^{-19} = p \times 3.0 \times 10^{8}$ (1 MARK)

   $p = 6.66 \times 10^{-27} = 6.7 \times 10^{-27}$ kg m s^{-1} (1 MARK)

   b. $E = hf \Rightarrow 10.1 = 4.14 \times 10^{-15} \times f$ (1 MARK)

   $f = 2.439 \times 10^{15} = 2.44 \times 10^{15}$ Hz (1 MARK)

   c. $\lambda = \frac{h}{p} \Rightarrow \lambda = \frac{6.63 \times 10^{-34}}{9.2 \times 10^{-28}}$ (1 MARK)

   $\lambda = 7.21 \times 10^{-7} = 7.2 \times 10^{-7}$ m (1 MARK)

7. a. The greatest change in energy, from $n = 3$ to $n = 1$, emits a photon with the greatest frequency, f_a.

   $\Delta E_{3\to1} = E_{ph,a} = hf_a \Rightarrow \Delta E_{3\to1} = 4.14 \times 10^{-15} \times 2.63 \times 10^{16}$ (1 MARK)

   $\Delta E_{3\to1} = 108.9 = 109$ eV (1 MARK)

   The greatest change in energy, from $n = 2$ to $n = 1$, emits a photon with the greatest frequency, f_b.

   $\Delta E_{2\to1} = E_{ph,b} = hf_b \Rightarrow \Delta E_{2\to1} = 4.14 \times 10^{-15} \times 2.22 \times 10^{16}$ (1 MARK)

   $\Delta E_{2\to1} = 91.91 = 91.9$ eV (1 MARK)

   56% of students answered this VCAA question correctly

   b. [An electron in the first excited state can absorb a 17.1 eV photon and move to the second excited state because the energy difference between these states is 17.1 eV.[1]][It cannot emit a 17.1 eV photon because 91.9 − 17.1 = 74.8 eV, and there is no energy level at this value.[2]]

   I have explained why the electron can absorb a 17.1 eV photon.[1]

   I have explained why the electron cannot emit a 17.1 eV photon.[2]

   32% of students answered this VCAA question correctly

8. a. $E = \frac{hc}{\lambda} = \frac{4.14 \times 10^{-15} \times 3.0 \times 10^{8}}{656 \times 10^{-9}}$ (1 MARK)

   $E = 1.89 = 1.9$ eV (1 MARK)

   b. [The difference in energy levels will be 1.9 eV, since $\Delta E = E_{ph}$.[1]]

   I have identified that the difference between energy levels is the energy of the photon.[1]

   c. [The gas cloud contains hydrogen.[1]][This is because each element has a unique absorption spectrum,[2]][and the wavelengths of the dark bands at 434 nm and 486 nm match the wavelengths of two dark bands present in the absorption spectrum of hydrogen.[3]]

   I have identified the gas cloud contains hydrogen.[1]

   I have described absorption spectra are unique to particular elements.[2]

   I have explained how the given spectrum only matches hydrogen.[3]

9. a. $E = \frac{hc}{\lambda} \Rightarrow 4.1 = \frac{4.14 \times 10^{-15} \times 3.0 \times 10^{8}}{\lambda}$ (1 MARK)

   $\lambda = 3.02 \times 10^{-7} = 3.0 \times 10^{-7}$ m (1 MARK)

   65% of students answered this VCAA question correctly

   b. [The requirement for the diffraction patterns to have the same spacing is for the photons and electrons to have the same wavelengths, and hence the same momentum.[1]][Since the diffraction patterns were different, the electrons and photons had different momentums.[2]][However, having different momentums does not stop them from having the same energy.[3]]

   I have identified the requirement for equal diffraction spacing.[1]

   I have determined that the electrons and photons had different momentums.[2]

   I have explained how different momentum is not equivalent to different energy.[3]

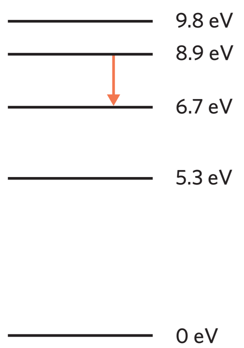
   10% of students answered this VCAA question correctly

   c. $\lambda = \frac{h}{\sqrt{2m \times KE}} \Rightarrow \lambda = \frac{6.63 \times 10^{-34}}{\sqrt{2 \times 9.1 \times 10^{-31} \times 4.1 \times 1.6 \times 10^{-19}}}$ (1 MARK)

   $\lambda = 6.06 \times 10^{-10} = 6.1 \times 10^{-10}$ m (1 MARK)

10. a. $E = \frac{hc}{\lambda} = \frac{4.14 \times 10^{-15} \times 3.0 \times 10^{8}}{565 \times 10^{-9}} = 2.2$ eV

   b.



   I have drawn an arrow pointing from the 8.9 eV to the 6.7 eV energy level.

   46% of students answered this VCAA question correctly

CHAPTER 10 REVIEW

c. There will be a total of 9 lines in the spectrum.[1] This is because there are four transitions down from the 9.8 eV level, three from the 8.9 eV level, two from the 6.7 eV level, and one from the 5.3 eV level, 10 total transitions. Two of these transitions have the same energy difference, from 9.8 eV to 4.9 eV and from 4.9 eV to 0 eV, so produce the same spectral line.[2]

- I have identified the total number of spectral lines.[1]
- I have explained the energy transitions each spectral line comes from.[2]

27% of students answered this VCAA question correctly

d. The electron could absorb a photon with energy 9.8 eV,[1] which corresponds to the energy difference between the $n = 1$ and $n = 4$ states.[2]

- I have stated the electron could absorb a photon with a certain energy.[1]
- I have explained the energy must be the difference between the $n = 1$ and $n = 4$ states.[2]

54% of students answered this VCAA question correctly

e. The lowest frequency corresponds to the smallest energy, which is between the 8.9 eV and 9.8 eV energy levels. (1 MARK)

$\Delta E = E_{ph} = hf \Rightarrow 9.8 - 8.9 = 4.14 \times 10^{-15} \times f$ (1 MARK)

$f = \dfrac{9.8 - 8.9}{4.14 \times 10^{-15}} = 2.2 \times 10^{14}$ Hz (1 MARK)

11. The screen detects discrete spots which supports the particle model[1] because the spots represent quantised amounts of light energy (photons) rather than a continuous stream of energy.[2] Over time, the discrete spots collectively form an interference pattern, which is something done by waves rather than particles.[3] The particle model of light predicts that the discrete spots should all land in one of two regions, corresponding to the two slits.[4]

- I have identified a result that supports the particle model of light.[1]
- I have explained why this result supports the particle model of light.[2]
- I have identified a result that does not support the particle model of light.[3]
- I have explained why this result does not support the particle model of light.[4]

12. a. A piece of evidence for the wave behaviour of electrons is electron diffraction.[1] This supports modelling electrons as behaving like waves because diffraction is a wave phenomenon.[2]

- I have identified a piece of evidence for the wave nature of electrons.[1]
- I have explained how the evidence supports modelling electrons as behaving like waves.[2]

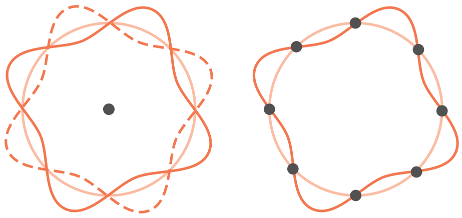
23% of students answered this VCAA question correctly

b. Electrons have a dual wave-particle nature.[1] For an electron orbital to be stable, the electron must form a standing wave, so the orbit must satisfy $n\lambda = 2\pi r$.[2] The different values of n correspond to the allowed orbits and their corresponding energy levels.[3]

- I have stated that electrons have a dual wave-particle nature.[1]
- I have explained how stable electron orbits must form standing waves.[2]
- I have explained how the quantised states lead to quantised energies.[3]

23% of students answered this VCAA question correctly

c.



- I have drawn a continuous standing wave.
- I have drawn four whole wavelengths around a circle.

40% of students answered this VCAA question correctly

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11A Special relativity concepts

Progress questions

1. B. Einstein's first postulate states that the laws of physics are the same in non-accelerating (inertial) frames of reference.

2. C. An inertial frame of reference is one which is not accelerating.

3. B. Experiments conducted in inertial (non-accelerating) frames will be identical, whereas experiments conducted in accelerating frames will differ.

   75% of students answered this VCAA exam question correctly.

4. A. Einstein's second postulate states the speed of light is c, regardless of the motion of the observer.

5. C. The speed of light in a vacuum is 3.0×10^{8} m s^{-1}, regardless of the motion of the observer, according to Einstein's second postulate.

6. B. The Michelson-Morely experiment refuted the existence of the ether, as the speed of light was always measured to be c.

7. B. The results of the Michelson-Morely experiment showed the speed of light is always c, as stated by Einstein's second postulate.

8. C. The relativistic kinetic energy of an object travelling at relativistic speeds is greater than its classical kinetic energy.

   60% of students answered this VCAA exam question correctly.

9. C. Special relativity predicts that all motion is relative to the frame of reference of the observer.

Deconstructed exam-style

10. [Einstein's second postulate of special relativity states the speed of light is c, regardless of the motion of the observer or the source of light.[1]]

    - I have stated Einstein's second postulate.[1]

11. [According to classical physics, the speed of light measured by an observer is dependent on the motion of the observer.[1]]

    - I have identified how the motion of the observer affects their measurement of the speed of light according to classical physics.[1]

12. [According to Einstein's second postulate of special relativity, the motion of an observer does not affect their measurement of the speed of light.[1]]

    - I have identified how the motion of the observer affects their measurement of the speed of light according to Einstein's second postulate.[1]

13. [Einstein's second postulate of special relativity states the speed of light is c, regardless of the motion of the observer or the source of light.[1]][According to classical mechanics, the speed of light measured would be dependent upon the reference frame it is measured in.[2]][This differs from Einstein's second postulate of special relativity, as the measurement of the speed of light does not depend on the motion of the observer or source.[3]]

    - I have stated Einstein's second postulate of special relativity.[1]
    - I have described how the speed of light would be measured according to classical mechanics.[2]
    - I have compared the differences between the concept of the speed of light in special relativity and classical mechanics.[3]

    9% of students answered this VCAA exam question correctly.

Exam-style

14. A. An object travelling at a constant velocity is not accelerating, so it is an inertial frame of reference.

    82% of students answered this VCAA exam question correctly.

15. C. All observers measure the same speed of light in a vacuum.

16. [Anna is incorrect.[1]][An object can accelerate while moving at a constant speed by changing its direction, such as by undergoing circular motion.[2]][Any object that is accelerating is not in an inertial frame of reference.[3]]

    - I have identified that Anna is incorrect.[1]
    - I have defined acceleration as the change in velocity of an object.[2]
    - I have stated accelerating objects are not in inertial frames of reference.[3]

    5% of students answered this VCAA exam question correctly.

17. D. By measuring the differences in the speed of light as it travelled in different directions, the experimenter attempted to show the existence of ether.

    FROM LESSON 12A

    64% of students answered this VCAA exam question correctly.

18. A. The speed of light is the same, regardless of the motion of the source.

19. $v = \frac{d}{t}$

    $3.0 \times 10^{8} = \frac{6.01 \times 10^{11}}{t}$ (1 MARK)

    $t = \frac{6.01 \times 10^{11}}{3.0 \times 10^{8}}$

    $t = 2.00 \times 10^{3} = 2.0 \times 10^{3}$ s (1 MARK)

    61% of students answered this VCAA exam question correctly.

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20. [The Michelson-Morely experiment showed there was no difference in the speed of light when it travelled in different directions,[1]] [which disproved the existence of the ether.[2]] [This supports Einstein's second postulate of special relativity, as the speed of light was measured to be the same regardless of the motion of the observer or the source.[3]]

- I have explained the observation of the Michelson-Morely experiment.[1]
- I have stated the result of the Michelson-Morely experiment.[2]
- I have described how the Michelson-Morely experiment supports Einstein's theory of special relativity.[3]

FROM LESSON 12A

21. [The possible basis of Hilary's response is Einstein's second postulate of special relativity, which states the speed of light is 3.0×10^8 m s^{-1}, regardless of the motion of the observer or the source.[1]] [The possible basis of Ryan's response is classical mechanics, which states the speed of light relative to the observer is 0.1×10^8 m s^{-1}.[2]] [Hilary is correct,[3]] [as classical mechanics is limited in considering the motion of objects approaching the speed of light.[4]]

- I have stated a possible basis of Hilary's response.[1]
- I have stated a possible basis of Ryan's response.[2]
- I have explicitly stated Hilary is correct.[3]
- I have stated classical mechanics is limited when considering the motion of objects approaching the speed of light.[4]

27% of students answered this VCAA exam question correctly.

Previous lessons

22. [As the current in the wire is perpendicular to the magnetic field, there is a magnetic force acting on sides *WX* and *YZ*.[1]] [By the right hand palm rule, as the current flows from *W* to *X* and the magnetic field is from left to right, the force on *WX* is directed down. The force on side *YZ* is directed upwards, as the current is in the opposite direction to side *WX*.[2]] [The coil begins to rotate as this creates a turning effect.[3]]

- I have stated conditions for magnetic force.[1]
- I have applied of right hand palm rule.[2]
- I have stated the coil rotates as the force creates a turning effect.[3]

36% of students answered this VCAA exam question correctly.

23. [Ariel hears more bass as lower frequencies have a longer wavelength, which diffract through the aperture of a doorway more than the high frequencies.[1]] [As she walks past the door she hears the higher frequencies travelling straight through the door and not diffracting as much.[2]] [This occurs because diffraction is proportional the ratio of the wavelength to aperture.[3]]

- I have explicitly addressed why Ariel hears the low frequency sounds from further away.[1]
- I have explicitly addressed why Ariel hears the higher frequencies only when she is close.[2]
- I have applied the theory of diffraction.[3]

11B Length contraction and time dilation

Progress questions

1. D. An object with mass can never reach the speed of light.
2. C. When $v = 0$ is substituted into the Lorentz factor equation, $\gamma = 1$.
3. B. $\gamma = \frac{1}{\sqrt{1 - \frac{v^2}{c^2}}} = \frac{1}{\sqrt{1 - 0.89^2}} = 2.2$
4. D. The proper length describes the length of an object measured by an observer who is at rest relative to the object.
5. B. The contracted length will be measured from the observer not in the same reference frame as the satellite, so the space station.
6. D. $L = \frac{L_0}{\gamma} \Rightarrow 2.6 \times 10^9 = \frac{L_0}{4.9} \Rightarrow L_0 = 1.3 \times 10^{10}$ m
7. D. Proper time is the time interval between two events, as measured by an observer for whom the two events occur at the same location of space.
8. B. Celeste would measure a proper time as they measure the two events, passing the two ends of the Moon, occurring in the same location (her UFO).
9. D. $t = t_0\gamma \Rightarrow t = 1.9 \times 1.2 = 2.3$ s

Deconstructed exam-style

10. B. $t = \frac{1}{5} \times 24 = 4.8$ hours
11. C. $\gamma = \frac{1}{\sqrt{1 - \frac{v^2}{c^2}}} = \frac{1}{\sqrt{1 - (0.78)^2}} = 1.598 = 1.6$
12. [The period of the planet's orbit as measured by the scientist is the dilated time.[1]]

- I have identified that the period of the planet's orbit is dilated time.[1]

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13. $t = \frac{1}{5} \times 24 = 4.8$ hours (1 MARK)

$$\gamma = \frac{1}{\sqrt{1 - \frac{v^2}{c^2}}} = \frac{1}{\sqrt{1 - \frac{(0.78c)^2}{c^2}}} = 1.598 = 1.6 \text{ (1 MARK)}$$

$t = t_0\gamma \Rightarrow 4.8 = t_0 \times 1.6$

$t_0 = 3.00 = 3.0$ hours (1 MARK)

53% of students answered this VCAA exam question correctly.

Exam-style

14. a. [Lucy does not measure the proper length of the train[1]] [as the train is not at rest in her frame of reference.[2]]

- I have identified that Lucy does not measure the proper length of the train.[1]
- I have explained why Lucy does not measure the proper length of the train.[2]

b. [Lucy measures the proper time for the train to pass.[1]] [The two events being measured by Lucy are the front and back of the train passing, and these both occur at the same location – where Lucy is standing.[2]]

- I have identified that Lucy measures the proper time.[1]
- I have explained why Lucy measures the proper time.[2]

15. D. The Lorentz factor is 1 when $v = 0$ m s^{-1}, and approaches infinity as v approaches c.

58% of students answered this VCAA exam question correctly.

16. $$\gamma = \frac{1}{\sqrt{1 - \frac{v^2}{c^2}}} = \frac{1}{\sqrt{1 - \frac{(2.79 \times 10^8)^2}{(3.0 \times 10^8)^2}}} \text{ (1 MARK)}$$

$\gamma = 2.72 = 2.7$ (1 MARK)

17. a. [The technician measures a different length of the spaceship because length contraction only occurs in the direction of relative motion.[1]] [In this case, the relative motion of the spaceship is parallel to its length, so the contraction will only occur along the length of the spaceship.[2]]

- I have identified that length contraction only occurs in the direction of motion.[1]
- I have explained why the technician only measures a contracted length and not width for the spaceship.[2]

42% of students answered this VCAA exam question correctly.

b. The technician measures the contracted length of the spaceship, $L = 122$ m.

Find Lorentz factor:

$$\gamma = \frac{1}{\sqrt{1 - \frac{v^2}{c^2}}} = \frac{1}{\sqrt{1 - 0.800^2}} = 1.667 \text{ (1 MARK)}$$

Find proper length, L_0:

$$L = \frac{L_0}{\gamma} \Rightarrow 122 = \frac{L_0}{1.667}$$

$L_0 = 203.3 = 203$ m (1 MARK)

57% of students answered this VCAA exam question correctly.

18. a. The proper time is the lifetime of the particle as measured from the particle's reference frame, $t_0 = 2.18 \times 10^{-6}$ s.

Jemma is measuring the lifetime of the particle from her reference frame, $t = t_0\gamma$.

Find Lorentz factor:

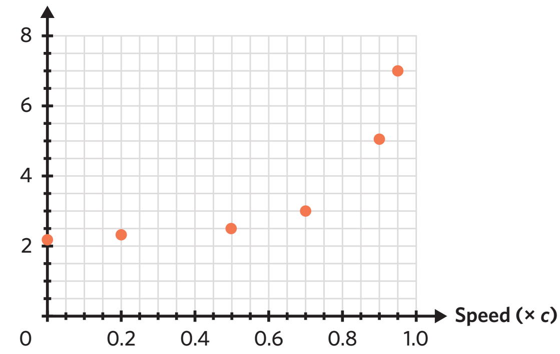
$$\gamma = \frac{1}{\sqrt{1 - \frac{v^2}{c^2}}} = \frac{1}{\sqrt{1 - 0.92^2}} = 2.552 \text{ (1 MARK)}$$

Find dilated time, t:

$t = t_0\gamma = 2.18 \times 10^{-6} \times 2.552$

$t = 5.562 \times 10^{-6} = 5.56 \times 10^{-6}$ s (1 MARK)

b.



- I have included an appropriate and consistent scale on the axes
- I have plotted each data point correctly
- I have labelled the axes
- I have included units on the axes

FROM LESSON 12D

19. Spacecraft 1 measures a proper time, therefore $t_0 = 5.00$ s.

Spacecraft 2 measures an observed time, therefore $t = 5.72$ s.

$t = t_0\gamma \Rightarrow 5.72 = 5.00 \times \gamma \Rightarrow \gamma = 1.44$ (1 MARK)

Find relative speed using Lorentz factor equation:

$$v = c\sqrt{1 - \frac{1}{\gamma^2}} = 3.0 \times 10^8 \times \sqrt{1 - \frac{1}{1.144^2}} \text{ (1 MARK)}$$

$v = 1.46 \times 10^8 = 1.5 \times 10^8$ m s^{-1} (1 MARK)

20. $$\gamma = \frac{1}{\sqrt{1 - \frac{v^2}{c^2}}} = \frac{1}{\sqrt{1 - \frac{(0.971c)^2}{c^2}}}$$

$\gamma = 4.183$ (1 MARK)

$$L = \frac{L_0}{\gamma} \Rightarrow 24 = \frac{L_0}{4.183}$$

$L_0 = 1.00 \times 10^2 = 1.0 \times 10^2$ m (1 MARK)

75% of students answered this VCAA exam question correctly.

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21. The passenger measures the proper length of the train, therefore $L_0 = 446$ m.

The observer measures the contracted length of the train, therefore $L = 114$ m.

$L = \frac{L_0}{\gamma} \Rightarrow 114 = \frac{446}{\gamma} \Rightarrow \gamma = 3.91$ (1 MARK)

Find relative speed using Lorentz factor equation:

$v = c\sqrt{1 - \frac{1}{\gamma^2}} = 3.0 \times 10^8 \times \sqrt{1 - \frac{1}{3.91^2}}$ (1 MARK)

$v = 2.90 \times 10^8 = 2.9 \times 10^8 \text{ m s}^{-1}$ (1 MARK)

53% of students answered this VCAA exam question correctly.

22. B. The relative speed between the neutrino and the rocket is the only speed that is relevant to this question.

So $L = \frac{L_0}{\gamma} = \frac{30.00}{1.400} = 21.428 = 21.43$ m.

23. a. [Quantitative.[1]]

I have identified if the data is qualitative or quantitative.[1]

FROM LESSON 12A

b. Note that this question does not require any time dilation to be calculated, as all the values are measured and calculated in the scientists' frame of reference.

$v = \frac{\Delta s}{\Delta t} \Rightarrow 0.9967 \times 3.0 \times 10^8 = \frac{1.42 \times 10^{-2}}{t}$ (1 MARK)

$t = 4.749 = 4.7 \times 10^{-11}$ s (1 MARK)

42% of students answered this VCAA exam question correctly.

Previous lessons

24. C. According to the right hand slap rule, the force acting on *AB* will act upwards.

FROM LESSON 4D

25. C. The yellow band is the second longest wavelength, and so should be the band second from the right (after the red band, which has the longest wavelength).

64% of students answered this VCAA exam question correctly.

FROM LESSON 8A

11C Relativity examples

Progress questions

1. C. The muons travel at close to the speed of light, which causes the distance they travel to be contracted in their reference frame or their half-lives to increase in the reference frame of an observer on Earth.

2. C. The effects of special relativity will be greater for the muons travelling at a higher velocity allowing more of them to reach the ground.

3. C. As the particle accelerator is moving relative to the particles, its measured length is contracted in their frame of reference.

4. B. $L = \frac{L_0}{\gamma} = \frac{5675}{22} = 2.6 \times 10^2$ m.

5. B. GPS satellites travel at speeds less than half the speed of light, and measure the time signals take to travel from Earth to the satellite.

6. C. The time passed on a GPS satellite runs slow, as the time measured by an observer on Earth is greater than the time to pass on the satellite itself.

Deconstructed exam-style

7. A. $L = \frac{L_0}{\gamma} = \frac{1200}{6.4} = 1.88 \times 10^2 = 1.9 \times 10^2$ m

8. $v = \frac{d}{t} \Rightarrow 0.988 \times 3.0 \times 10^8 = \frac{1.88 \times 10^2}{t}$

$t = 6.25 \times 10^{-7} = 6.3 \times 10^{-7}$ s

9. $L = \frac{L_0}{\gamma} = \frac{1200}{6.4}$ (1 MARK)

$L = 1.88 \times 10^2$ m

$v = \frac{d}{t} \Rightarrow 0.988 \times 3.0 \times 10^8 = \frac{1.88 \times 10^2}{t}$ (1 MARK)

$t = 6.26 \times 10^{-7} = 6.3 \times 10^{-7}$ s

As $t < 2.4 \times 10^{-6}$ s, the muon is able to reach the ground before decaying. (1 MARK)

Exam-style

10. D. $t = t_0\gamma \Rightarrow 16 \times 10^{-6} = 2.2 \times 10^{-6} \times \gamma$

$\gamma = 7.27 = 7.3$

11. a. An observer on Earth would measure a dilated time to have passed onboard the GPS satellite.

$t_{diff} = t - t_0$

$t_{diff} = t_0\gamma - t_0 = t_0(\gamma - 1)$ (1 MARK)

$t_{diff} = 6.67 \times 10^{-2}((1 + 4 \times 10^{-11}) - 1)$ (1 MARK)

$t_{diff} = 2.67 \times 10^{-12} = 2.7 \times 10^{-12}$ s (1 MARK)

b. [Due to the effects of special relativity, the clocks onboard GPS satellites tick slower than those on Earth, from the reference frame of an observer stationary on the Earth.[1]][The clocks on the GPS satellites are adjusted to tick at a quicker rate than those on Earth,[2]][so that the signals received on Earth from the GPS satellite are correct in the reference frame of an observer stationary on the Earth.[3]]

I have identified the clocks onboard GPS satellites tick at a slower rate than those on Earth.[1]

I have determined how the clocks onboard GPS satellites are adjusted to account for this difference.[2]

I have described why the clocks onboard GPS satellites must be adjusted to account for the effects of special relativity.[3]

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12. a. [Row 1 correctly lists the measured length of the particle accelerator in each different frame of reference.[1]] [Particle *Y*: $L = \frac{L_0}{\gamma_A} = \frac{2.8}{2.8} = 1.0$ km. Particle *Z*: $L = \frac{L_0}{\gamma_B} = \frac{2.8}{3.9} = 0.72$ km. Stationary scientists: $L = L_0 = 2.8$ km.[2]]

- I have identified that Row 1 is the correct list of the measured length of the particle accelerator in each frame of reference.[1]
- I have supported the answer using calculations of the measured length of the particle accelerator in each frame of reference.[2]

b. [As Particle *Y* is travelling slower than Particle *Z*, the measured length of the accelerator is longer for Particle *Y* than Particle *Z*.[1]] [Therefore the time it takes Particle *Y* to travel to the end of the particle accelerator is longer than it takes Particle *Z*.[2]] [As both particles have the same half-life in their own frame of reference, Particle *Y* is less likely to be observed reaching the end than Particle *Z*.[3]]

- I have explained that the measured length of the accelerator is longer in Particle *Y*'s frame of reference than Particle *Z*'s frame of reference.[1]
- I have related the time it takes Particle *Y* and Particle *Z* to reach the detector.[2]
- I have identified Particle *Y* is less likely than Particle *Z* to be observed reaching the end of the particle accelerator.[3]

FROM LESSON 12A

13. a. [The particle accelerator must be constructed using the proper length of the accelerator as measured by a stationary observer on Earth.[1]] [Due to the effects of special relativity, the proper length is greater than the contracted length.[2]] [The private investor has underestimated the true cost of material required, as they have only provided enough material to create a particle accelerator long enough for the contracted length measured in the particles' frame of reference.[3]]

- I have identified that the accelerator should be built using the proper length.[1]
- I have identified that the proper length is longer than the contracted length.[2]
- I have determined that the investor has underestimate the cost of the materials.[3]

FROM LESSON 12A

b. [One benefit of constructing the Large Hadron Collider has been the advancements in radiotherapy as well as future advancements in technology that its discoveries may bring.[1]] [One drawback of constructing the Large Hadron Collider has been the large amount of money that it cost; money that could have gone into projects with potentially larger benefits to society.[2]] [Overall, the future benefits to society that the LHC may provide outweigh the large costs associated with it.[3]]

- I have identified one piece of evidence in favour of building the LHC.[1]
- I have identified one piece of evidence against building the LHC.[2]
- I have use the evidence to evaluate whether benefits of the LHC outweigh its high costs.[3]

FROM LESSON 12A

14. C. Each pion is not moving relative to the events being measured – the half-life of the pion.

69% of students answered this VCAA exam question correctly.

15. $\gamma = \frac{1}{\sqrt{1 - \frac{v^2}{c^2}}} = \frac{1}{\sqrt{1 - \frac{(0.98 \times 3.0 \times 10^8)^2}{(3.0 \times 10^8)^2}}}$ (1 MARK)

$\gamma = 5.03$

$t = t_0\gamma = 26 \times 10^{-9} \times 5.03$ (1 MARK)

$t = 1.31 \times 10^{-7} = 1.3 \times 10^{-7}$ s (1 MARK)

71% of students answered this VCAA exam question correctly.

16. a. $1 \text{ hr} = 60 \times 60 = 3.6 \times 10^3$ s

The difference in time measured by a GPS satellite and to have passed on Earth is:

$t_{diff} = t - t_0$

$t_{diff} = \gamma t_0 - t_0 = (\gamma - 1)\, t_0$ (1 MARK)

$0.23 \times 10^{-6} = (\gamma - 1) \times (3.6 \times 10^3)$ (1 MARK)

$(\gamma - 1) = 6.39 \times 10^{-11} = 6.4 \times 10^{-11}$, as required

b. $\gamma - 1 = 6.4 \times 10^{-11} \Rightarrow \gamma = 1 + 6.4 \times 10^{-11}$

$v = c\sqrt{1 - \frac{1}{\gamma^2}} = c\sqrt{1 - \frac{1}{(1 + 6.4 \times 10^{-11})^2}}$ (1 MARK)

$v = 3.39 \times 10^3 = 3.4 \times 10^3$ m s^{-1} (1 MARK)

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c. [Due to the effects of special relativity, an observer on Earth would measure a dilated time to have passed on a GPS satellite receiving a signal from the ground.[1]] [In order to accurately determine the position of the source of the signal, the clocks onboard the GPS satellites must tick at quicker rate than those on Earth to account for the effects of special relativity.[2]] [If this is not corrected for, the GPS satellites are not able to accurately determine the location of the source.[3]]

- I have identified an observer on Earth would measure a dilated time to have passed on the GPS satellite.[1]
- I have related finding the position of the source to the time measured by the GPS satellite.[2]
- I have identified the consequence of not accounting for the effects of special relativity.[3]

17. a. $v = \frac{d}{t} \Rightarrow 0.99875 \times 3.0 \times 10^8 = \frac{9.14 \times 10^{-5}}{t}$ (1 MARK)

$t = 3.05 \times 10^{-13} = 3.1 \times 10^{-13}$ s (1 MARK)

42% of students answered this VCAA exam question correctly.

b. The particle measures a contracted length for the particle accelerator.

$L = \frac{L_0}{\gamma} = \frac{9.14 \times 10^{-5}}{20}$ (1 MARK)

$L = 4.57 \times 10^{-6} = 4.6 \times 10^{-6}$ m (1 MARK)

38% of students answered this VCAA exam question correctly.

c. [The effects of special relativity in the particles' frame of reference is responsible for more particles reaching the end of the accelerator than classical physics predicts.[1]] [Due to the particles' velocity, the distance between the two ends of the particle accelerator is contracted, when measured from the particles' frame of reference.[2]] [Therefore, it takes less time for the particles to reach the end of the accelerator, and more particles are observed by the scientists at the end of accelerator than classical physics predicts.[3]]

- I have explained that the effects of special relativity are responsible for more particles reaching the end of the accelerator than classical physics predicts.[1]
- I have explained that the distance between the two ends of the particle accelerator, as measured from the particles' frame of reference, is contracted.[2]
- I have related the contraction of the distance of the particle accelerator in the frame of reference of the particle, to an increase in the number of particles' observed by the scientists at the end of the accelerator.[3]

8% of students answered this VCAA exam question correctly.

18. From scientists perspective:

$t_{total} = t_{0,\,total}\gamma = 6.1 \times 3.8 \times 10^{-6}$ (1 MARK)

$t_{total} = 2.32 \times 10^{-5}$ s

$v = \frac{d_{straight}}{t_{straight}} \Rightarrow 2.96 \times 10^8 = \frac{1.2 \times 10^3 \times 4}{t_{straight}}$ (1 MARK)

$t_{straight} = 1.62 \times 10^{-5}$ s

$t_{total} = t_{curved} + t_{straight} \Rightarrow 2.32 \times 10^{-5} = t_{curved} + 1.62 \times 10^{-5}$ (1 MARK)

$t_{curved} = 6.96 \times 10^{-6} = 7.0 \times 10^{-6}$ s (1 MARK)

Previous lessons

19. [There is no change to the magnetic flux through the loop of wire,[1]] [as the plane of the loop is always parallel to the direction of the magnetic field.[2]]

- I have described how the flux through the loop changes.[1]
- I have justified my answer.[2]

FROM LESSON 5A

20. D. Lowering the frequency of the light increases its wavelength, which corresponds to a more spread out pattern as $\Delta x = \frac{\lambda L}{d}$.

FROM LESSON 8B

11D Mass-energy

Progress questions

1. C. Rest energy is calculated using $E_0 = mc^2$, and is the total energy of a mass which is stationary ($\gamma = 1$).

2. C. $E_{tot} = \gamma mc^2 = 1.56 \times 9.1 \times 10^{-31} \times (3.0 \times 10^8)^2 = 1.27 \times 10^{-13} = 1.3 \times 10^{-13}$ J.

3. C. The relativistic kinetic energy of an object will always be greater than the classical kinetic energy.

4. A. $KE = (\gamma - 1)mc^2 = (1.81 - 1) \times 1.67 \times 10^{-27} \times (3.0 \times 10^8)^2 = 1.2 \times 10^{-10}$ J.

82% of students answered this VCAA exam question correctly.

5. B. As energy was released as it decayed, the mass of the nucleus after decay is smaller ($m_f < m_i$). The difference in mass can be found by $\Delta m = \frac{\Delta E}{c^2} = \frac{3.6 \times 10^{-13}}{(3.0 \times 10^8)^2} = 4.0 \times 10^{-30}$ kg.

6. C. $E_{gamma\ ray} = E_{0\ e} = mc^2 = 9.1 \times 10^{-31} \times (3.0 \times 10^8)^2 = 8.2 \times 10^{-14}$ J.

Deconstructed exam-style

7. $m_i = 2 \times 3.3436 \times 10^{-27} = 6.6872 \times 10^{-27}$ kg

$m_f = 6.6465 \times 10^{-27}$ kg

8. $\Delta m = m_f - m_i = 6.6465 \times 10^{-27} - 6.6872 \times 10^{-27}$

$\Delta m = -4.07 \times 10^{-29}$ kg

9. C. The energy released due to a change in mass is its rest energy, $E_0 = mc^2$.

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10. $\Delta m = m_f - m_i = 6.6465 \times 10^{-27} - 6.6872 \times 10^{-27}$

$\Delta m = -4.07 \times 10^{-29}$ kg (1 MARK)

$\Delta E = \Delta mc^2 = (-4.07 \times 10^{-29}) \times (3 \times 10^8)^2$ (1 MARK)

$\Delta E = -3.66 \times 10^{-12} = -3.7 \times 10^{-12}$ J

The energy released is 3.7×10^{-12} J. (1 MARK)

Exam-style

11. a. $E_{tot} = \gamma mc^2$

$E_{tot} = 1.67 \times 1.67 \times 10^{-27} \times (3.0 \times 10^8)^2$ (1 MARK)

$E_{tot} = 2.51 \times 10^{-10} = 2.5 \times 10^{-10}$ J (1 MARK)

b. $KE = (\gamma - 1)mc^2$

$KE = (1.67 - 1) \times 1.67 \times 10^{-27} \times (3.0 \times 10^8)^2$ (1 MARK)

$KE = 1.00 \times 10^{-10} = 1.0 \times 10^{-10}$ J (1 MARK)

12. B. $\Delta E = \Delta mc^2 \Rightarrow 3.8 \times 10^{26} = \Delta m \times (3.0 \times 10^8)^2$

$\Delta m = 4.22 \times 10^9 = 4.2 \times 10^9$

13. a. $E_{tot,\,e} = E_{tot,\,p}$, as both are travelling at the same speed and have the same mass.

$E_{tot} = E_{tot,\,e} + E_{tot,\,p} = 2E_{tot,\,e} = 2\gamma_e m_e c^2$ (1 MARK)

$E_{tot} = 2 \times 2.29 \times 9.1 \times 10^{-31} \times (3.0 \times 10^8)^2$ (1 MARK)

$E_{tot} = 3.75 = 3.8 \times 10^{-13}$ J

b. As the total energy associated with the electron and positron are entirely converted into energy:

$E_{released} = E_{tot} = 3.8 \times 10^{-13}$ J

c. [As the scientists calculated the total energy of the system using the classical kinetic energy of the masses, they calculated a lower value than the true energy of the system[1]][as the relativistic kinetic energy is always greater than the classical kinetic energy of a mass.[2]][As the particles are travelling close to c, they should have calculated the kinetic energy using relativistic kinetic energy.[3]]

- I have identified the calculated total energy of the system was less than the true total energy of the system.[1]
- I have stated the relationship between relativistic kinetic energy and classical kinetic energy.[2]
- I have linked the experimental energy released to the calculation error made by the scientists.[3]

FROM LESSON 12A

14. [A particle with mass cannot be accelerated to the speed of light[1]][because the kinetic energy it requires approaches infinity as its speed approaches the speed of light,[2]][and the amount of energy in the universe is finite.[3]]

- I have stated a particle with mass cannot be accelerated to the speed of light.[1]
- I have identified the relativistic kinetic energy required would approach infinite.[2]
- I have stated the energy in the universe is finite.[3]

15. $\Delta E = \Delta mc^2 \Rightarrow 4.20 \times 10^{26} = \Delta m \times (3.0 \times 10^8)^2$ (1 MARK)

$\Delta m = 4.67 \times 10^9 = 4.7 \times 10^9$ kg s^{-1} (1 MARK)

16. $KE = (\gamma - 1)mc^2$

$1.8 \times 10^{-10} = (\gamma - 1) \times 1.67 \times 10^{-27} \times (3.0 \times 10^8)^2$ (1 MARK)

$\gamma = 2.20$

$v = c\sqrt{1 - \frac{1}{\gamma^2}} = 3.0 \times 10^8 \times \frac{1}{\sqrt{1 - \frac{1}{2.20^2}}}$ (1 MARK)

$v = 2.67 \times 10^8 = 2.7 \times 10^8$ m s^{-1} (1 MARK)

17. B. $E_o = mc^2 = 5.98 \times 10^{-10}$

$\Delta E = E_{tot\,f} - E_{tot\,i} = \gamma_f mc^2 - \gamma_i mc^2$

$\Delta E = 1.15 \times 5.96 \times 10^{-10} - 1.05 \times 5.96 \times 10^{-10} = 5.98 \times 10^{-11}$ J

63% of students answered this VCAA exam question correctly.

18. [A mass-energy transformation is taking place in the star.[1]]
[The transformation would decreases the mass of the star.[2]]

- I have stated a mass-energy transformation took place in the star.[1]
- I have stated the mass of the star would decrease as a result of the transformation.[2]

32% of students answered this VCAA exam question correctly.

19. $\Sigma E_{total\ products} + E_{supplied} = \Sigma E_{total\ reactants} + E_{released}$

$E_{pion} = E_{released}$ (1 MARK)

$\gamma_p m_p c^2 = 2.17 \times 10^{-10}$

$10.0 \times m_p \times (3.0 \times 10^8)^2 = 2.17 \times 10^{-10}$ (1 MARK)

$m_p = 2.41 \times 10^{-28} = 2.4 \times 10^{-28}$ kg (1 MARK)

20. a. $KE = 12E_o \Rightarrow (\gamma - 1)mc^2 = 12mc^2$

$\gamma = 13$

b. $v = c\sqrt{1 - \frac{1}{\gamma^2}}$

$v = 3.0 \times 10^8 \times \sqrt{1 - \frac{1}{13^2}}$ (1 MARK)

$v = 2.99 \times 10^8$ m s^{-1}

Classical KE: $KE_c = \frac{1}{2}mv^2$

$KE_c = \frac{1}{2} \times 3.34 \times 10^{-27} \times (2.99 \times 10^8)^2$ (1 MARK)

$KE_c = 1.49 \times 10^{-10}$ J

Relativistic KE: $KE_r = (\gamma - 1)mc^2$

$KE_r = (13 - 1) \times 3.34 \times 10^{-27} \times (3.0 \times 10^8)^2$ (1 MARK)

$KE_r = 3.61 \times 10^{-9}$ J

$diff = KE_r - KE_c$

$diff = 3.61 \times 10^{-9} - 1.49 \times 10^{-10}$ (1 MARK)

$diff = 3.46 \times 10^{-9} = 3.5 \times 10^{-9}$ J (1 MARK)

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21. B. The ratio $\frac{KE}{m_0c^2}$ is 0 at $v = 0$, as $KE = 0$. As v approaches c, KE approaches infinity, and so too does the ratio $\frac{KE}{m_0c^2}$.

59% of students answered this VCAA exam question correctly.

22. $E_{tot,\,e} = E_{tot,\,p}$, as both are travelling at the same speed and have the same mass. (1 MARK)

$E_{reactants} = E_{tot,\,e} + E_{tot,\,p} = 2E_{tot,\,e} = 2\gamma_e m_e c^2$

$E_{reactants} = 2 \times 2.93 \times 9.1 \times 10^{-31} \times (3.0 \times 10^8)^2$ (1 MARK)

$E_{reactants} = 4.80 \times 10^{-13}$ J

If all the energy is converted to mass:

$E_{products} = E_{reactants}$

$m_{products} \times (3.0 \times 10^8)^2 = 4.80 \times 10^{-13}$ (1 MARK)

$m_{products} = 5.33 \times 10^{-30}$ kg

The heaviest mass of the combined product that could be produced is 5.3×10^{-30} kg. (1 MARK)

23. [As the neutron is absorbed by the uranium nucleus, the total mass of the system does not change.[1]] [This is because the product of the first stage of the nuclear transformation has negligible kinetic energy.[2]] [As the unstable uranium isotope decays into high speed particles, the total mass of the system decreases.[3]] [This is because some of the mass must have been converted into the kinetic energy of the products.[4]]

- I have stated the total mass of the system does not change in the first stage.[1]
- I have explained that no mass of the system was converted into kinetic energy.[2]
- I have stated the total mass of the system decreases in the second stage.[3]
- I have explained that some of the mass of the system was converted into kinetic energy.[4]

Previous lessons

24. X, Y, W, Z. Magnetic flux increases as the angle between the loop and the magnetic field increases.

FROM LESSON 5A

25. [By increasing the reverse potential in the circuit, the stopping voltage is found experimentally when the current in the circuit just reaches zero.[1]] [The value of the voltage supplied by the battery (in V) has the same numerical value as the stopping voltage in eV.[2]]

- I have stated the stopping voltage is the voltage at which the current in the circuit reaches zero.[1]
- I have related the value of the supply voltage to the stopping voltage.[2]

FROM LESSON 9A

Chapter 11 review

Section A

1. D. The laws of physics are the same in all inertial frames of reference, so the results of the experiment for spacecraft 2 and 3 will agree.

2. A. In spacecraft 1's reference frame, the event of it first reaching and it fully passing the Earth happen at the same location, so it measures the proper time between these events.

3. B. The speed of light is always c, regardless of the motion of the observer or the source.

4. C. The graph of kinetic energy vs. speed is non-linear and should begin at the origin before approaching infinity.

5. B. $E_{tot} = \gamma mc^2$

$1.06 \times 10^{-12} = \gamma \times 9.1 \times 10^{-31} \times (3.0 \times 10^8)^2$

$\gamma = 12.9$

$L = \frac{L_0}{\gamma}$

$24 = \frac{L_0}{12.9}$

$L_0 = 311 = 3.1 \times 10^2$ m

$\Delta L = L_0 - L = 311 - 24$

$\Delta L = 287 = 2.9 \times 10^2$ m

Section B

6. **a.** $v = \frac{d}{t}$

$0.85 \times 3.0 \times 10^8 = \frac{5.84 \times 10^{16}}{t}$ (1 MARK)

$t = 2.29 \times 10^8 = 2.3 \times 10^8$ s (1 MARK)

b. [An observer on Earth measures an dilated time for the Blitztern spaceship to travel to the star system,[1]] [as they are moving relative to the to the spaceship.[2]]

- I have stated an observer on Earth would measure an dilated time.[1]
- I have identified the observer on Earth is moving relative to the event being measured.[2]

c. $\gamma = \frac{1}{\sqrt{1 - \frac{v^2}{c^2}}}$

$\gamma = \frac{1}{\sqrt{1 - \frac{(0.85c)^2}{c^2}}} = \frac{1}{\sqrt{1 - 0.85^2}} = 1.90$ (1 MARK)

$t = t_0\gamma$

$2.29 \times 10^8 = t_0 \times 1.90$ (1 MARK)

$t_0 = 1.21 \times 10^8 = 1.2 \times 10^8$ s (1 MARK)

d. $L = \frac{L_0}{\gamma}$

$L = \frac{5.84 \times 10^{16}}{1.90}$ (1 MARK)

$L = 3.08 \times 10^{16} = 3.1 \times 10^{16}$ m (1 MARK)

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7. As the clocks measure events on Earth as taking five times longer, $\gamma = 5$ (1 MARK)

$KE = (\gamma - 1)mc^2$

$KE = (5 - 1) \times 8000 \times (3.0 \times 10^8)^2$ (1 MARK)

$KE = 2.88 \times 10^{21} = 2.9 \times 10^{21}$ J (1 MARK)

30% of students answered this VCAA question correctly.

8. a. [The protons are not in an inertial frame of reference when speeding up around the circular track,[1]] [or when travelling at a constant speed around the circular track.[2]] [In both cases, the protons are accelerating as they undergo circular motion, which means their reference frame is non-inertial.[3]]

- I have identified the protons are not in an inertial frame of reference when speeding up around the circular track.[1]
- I have identified the protons are not in an inertial frame of reference when travelling at a constant speed around the circular track.[2]
- I have explained that objects undergoing circular motion are in non-inertial frames of reference.[3]

b. [The length travelled along the straight sections by the protons travelling at relativistic speeds in their own frame of reference is contracted, due to the effects of special relativity.[1]] [The length of the straight sections of the particle accelerator must be designed using their proper length,[2]] [which is longer than the contracted length the particles travel in their frame of reference.[3]]

- I have identified the protons travel a contracted length of the straight sections of the particle acceleration in their frame of reference.[1]
- I have stated the particle accelerator must be designed using its proper length.[2]
- I have explained why the design length of the straight sections of the particle accelerator must be longer than the length the protons travel in their own frame of reference.[3]

9. [The effects of special relativity in the scientist's frame of reference is responsible for more muons reaching the ground than classical physics predicts.[1]] [Due to the muons' velocity, the time measured for their half-life is dilated in the scientist's frame of reference.[2]] [Therefore fewer muons are likely to have decayed by the time they reach the ground, as they have a longer half-life in the scientist's frame of reference than classical physics predicts.[3]]

- I have identified that special relativity is responsible for more particles reaching the end of the laboratory measuring range than classical physics predicts.[1]
- I have related the particles' velocity to their half-life measured in the scientist's frame of reference.[2]
- I have related the dilated time of the particle's half-life in the scientist's frame of reference to the amount observed reaching the ground.[3]

33% of students answered this VCAA exam question correctly.

10. a. 1.3×10^4 km

b. $L = \dfrac{L_0}{\gamma}$

$L = \dfrac{1.3 \times 10^4}{3.2 \times 10^{11}}$ (1 MARK)

$L = 4.06 \times 10^{-8} = 4.1 \times 10^{-8}$ km (1 MARK)

c. $KE = (\gamma - 1)mc^2$

$KE = (3.2 \times 10^{11} - 1) \times 1.67 \times 10^{-27} \times (3.0 \times 10^8)^2$ (1 MARK)

$KE = 48.1 = 48$ J (1 MARK)

d. $KE = 0$ J

11. a. $\gamma = \dfrac{1}{\sqrt{1 - \frac{v^2}{c^2}}}$

$\gamma = \dfrac{1}{\sqrt{1 - \frac{(0.8c)^2}{c^2}}}$ (1 MARK)

$\gamma = 1.667$

$E_{total} = \gamma mc^2$

$E_{total} = 1.667 \times 5.30 \times 10^5 \times (3.0 \times 10^8)^2$ (1 MARK)

$E_{total} = 7.95 \times 10^{22} = 8.0 \times 10^{22}$ J (1 MARK)

b. $m_{fuel}c^2 = \Delta KE_{rocket}$

$m_{fuel}c^2 = (\gamma - 1)m_{rocket}c^2$ (1 MARK)

$m_{fuel} \times (3.0 \times 10^8)^2$
$= (1.667 - 1) \times 5.30 \times 10^5 \times (3.0 \times 10^8)^2$ (1 MARK)

$m_{fuel} = 3.53 \times 10^5 = 3.5 \times 10^5$ kg (1 MARK)

12. a. $L = \dfrac{L_0}{\gamma}$

$L = \dfrac{500}{1.5}$ (1 MARK)

$L = 3.33 \times 10^2 = 3.3 \times 10^2$ m (1 MARK)

74% of students answered this VCAA exam question correctly.

b. [A reference frame which is stationary relative to the Comet would be able to measure a proper length of the landing area,[1]] [as it would not be moving relative to the measurement being made of its length.[2]]

- I have stated a reference frame which is able to measure a proper length of the landing area.[1]
- I have identified the reference frame would be stationary relative to the measurement being made.[2]

82% of students answered this VCAA exam question correctly.

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13. [Narek is incorrect.[1]][Although the effects of special relativity are small, the Lorentz factor of the GPS satellite is still significant enough so that more time passes on an Earth clock than on the GPS satellites from an observer on Earth's frame of reference.[2]][Therefore, GPS clocks must be adjusted to account for this difference.[3]][Wilma is also incorrect.[4]][Although she is correct in saying that the effects of special relativity affect the clocks on GPS satellites,[5]][the clocks are adjusted to tick quicker in order to account for the effects of special relativity, not slower.[6]]

- I have stated Narek is incorrect.[1]
- I have identified an Earth observer would measure more time to have passed on Earth than on the GPS satellite.[2]
- I have identified the clocks on the GPS satellites must be adjusted to account for the effects of special relativity.[3]
- I have stated Wilma is incorrect.[4]
- I have identified that Wilma is correct in saying special relativity affects the clocks aboard GPS satellites.[5]
- I have identified the clocks aboard GPS satellites must be adjusted to tick quicker.[6]

14. The train driver measures the proper length of the train as they are stationary relative to the train.

$L = \frac{L_0}{\gamma} \Rightarrow 55 = \frac{95}{\gamma}$

$\gamma = 1.73$ (1 MARK)

$v = c\sqrt{1 - \frac{1}{\gamma^2}}$

$v = c\sqrt{1 - \frac{1}{1.73^2}}$

$v = 2.45 \times 10^8 = 2.5 \times 10^8 \text{ m s}^{-1}$. (1 MARK)

Unit 4 AOS 1 review

Section A

1. C. As the wave is travelling to the left, point A will move downwards.

2. A. The energies of the emitted photons are the differences between the energy levels shown.

3. B. The spacing of the bands is given by $\Delta x = \frac{\lambda L}{d}$. By changing the laser from red to green light, the wavelength of the light decreases. This decreases the spacing between bands.

4. D. $v = \frac{d}{t} \Rightarrow 3 \times 10^8 = \frac{2 \times 5}{t_0}$

$t_0 = 3.333 \times 10^{-8}$ s

$t = t_0\gamma = 3.333 \times 10^{-8} \times 1.25 = 4.17 \times 10^{-8} = 4.2 \times 10^{-8} \text{ s} = 42 \text{ ns}$

28% of students answered this VCAA exam question correctly.

5. D. From the photocurrent vs. voltage graph provided, the stopping voltage for E1 is smaller than E2, and so the KE_{max} for E1 is smaller than E2. According to $KE_{max} = hf - \phi$, as both E1 and E2 use the same frequency of light, E1 will have a higher work function.

Section B

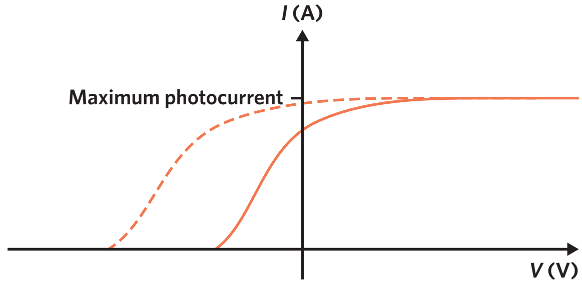
6. $E_{tot} = \gamma mc^2 = 3.20 \times 9.1 \times 10^{-31} \times (3.0 \times 10^8)^2$ (1 MARK)

$E_{tot} = 2.6208 \times 10^{-13} = 2.62 \times 10^{-13}$ J (1 MARK)

7. a. [Y represents the stopping voltage.[1]][Z represents the maximum photocurrent.[2]]

- I have identified that Y represents the stopping voltage.[1]
- I have identified that Z represents the maximum photocurrent.[2]

b.



- I have drawn the new graph with the same maximum photocurrent as the original.
- I have drawn the new graph with a greater stopping voltage (a more negative horizontal intercept) than the original.

8. a. $v = f\lambda \Rightarrow 3.0 \times 10^8 = 5.0 \times 10^{14} \times \lambda$

$\lambda = 6.0 \times 10^{-7}$ m

$\lambda = \frac{3.0 \times 10^8}{5.0 \times 10^{14}} = 6.0 \times 10^{-7}$ m

$p.d. = \left(n - \frac{1}{2}\right)\lambda = \left(2 - \frac{1}{2}\right) \times 6.0 \times 10^{-7}$ (1 MARK)

$p.d. = 9.0 \times 10^{-7}$ m (1 MARK)

60% of students answered this VCAA exam question correctly.

b. $p.d. = n\lambda \Rightarrow 9.0 \times 10^{-7} = 2 \times \lambda$ (1 MARK)

$\lambda = 4.5 \times 10^{-7}$m (1 MARK)

46% of students answered this VCAA exam question correctly.

9. Initial travelling wave:

$v = \frac{\lambda}{T} = \frac{0.080}{0.020} = 4.0 \text{ m s}^{-1}$ (1 MARK)

For a standing wave to form with one fixed end:

$f = \frac{nv}{4L} \Rightarrow 20 = \frac{n \times 4.0}{4 \times 0.50}$ (1 MARK)

$n = 10$ (1 MARK)

n must be odd for a string with one fixed end to form a standing wave, so DeAndre cannot form a standing wave with a frequency of 20 Hz. (1 MARK)

10. a. $E_{ph} = \Delta E = 13.2 - 10.2 = 3.0$ eV (1 MARK)

$E_{ph} = 3.0 \times 1.6 \times 10^{-19} = 4.8 \times 10^{-19}$ J (1 MARK)

b. $E = \frac{hc}{\lambda} \Rightarrow 4.8 \times 10^{-19} = \frac{6.63 \times 10^{-34} \times 3.0 \times 10^8}{\lambda}$ (1 MARK)

$\lambda = 4.14 \times 10^{-7} = 4.1 \times 10^{-7}$ m (1 MARK)

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c. 0.3 eV (1 MARK)

0.7 ev (1 MARK)

1.0 eV (1 MARK)

d. [In order for an electron to form a stable orbit around an atom, it must form a standing wave in which the circumference of the orbit is an integer multiple of the wavelength $n\lambda = 2\pi r$.[1]] [Since standing waves only occur at discrete wavelengths, and wavelength relates to energy, only discrete energy levels of electrons are allowed to exist.[2]]

- I have identified that electrons must form standing waves with $n\lambda = 2\pi r$.[1]
- I have determined that energy levels are discrete as only certain wavelengths of electrons can exist.[2]

11% of students answered this VCAA exam question correctly.

11. $2.68 \times 10^5 \text{ km s}^{-1} = 2.68 \times 10^8 \text{ m s}^{-1}$

$$\gamma = \frac{1}{\sqrt{1-\frac{v^2}{c^2}}} = \frac{1}{\sqrt{1-\frac{(2.68\times10^8)^2}{(3.0\times10^8)^2}}} = 2.23 \text{ (1 MARK)}$$

$KE = (\gamma - 1)mc^2$

$KE = (2.23 - 1) \times 4.9 \times 10^5 \times (3.0 \times 10^8)^2$ (1 MARK)

$KE = 5.40 \times 10^{22} = 5.4 \times 10^{22}$ J (1 MARK)

36% of students answered this VCAA exam question correctly.

12. $v = f\lambda \Rightarrow 340 = 425 \times \lambda$ (1 MARK)

$\lambda = 0.800$ m

$p.d. = n\lambda = 3 \times 0.800 = 2.400$ m (1 MARK)

Distance moved from centre is:

$\frac{pd}{2} = \frac{2.400}{2} = 1.200 = 1.20$ m (1 MARK)

OR

$v = f\lambda \Rightarrow 340 = 425 \times \lambda$ (1 MARK)

$\lambda = 0.800$ m

For a standing wave, the distance between adjacent antinodes is $\frac{\lambda}{2}$.

The distance from the central maximum to the third local maximum is:

$d = 3 \times \frac{\lambda}{2} = 3 \times \frac{0.8000}{2}$ (1 MARK)

$d = 1.200 = 1.20$ m (1 MARK)

5% of students answered this VCAA exam question correctly.

13. [This statement is incorrect.[1]] [Young's double-slit experiment demonstrates that light creates interference patterns, which is a property of waves.[2]]

- I have identified the statement is incorrect.[1]
- I have outlined that the interference pattern formed by light is due to interference, which is a wave property.[2]

41% of students answered this VCAA exam question correctly.

14. [Dorothy may predict this because she knows that increasing the intensity of light means that more energy is delivered by the light and it increased the photocurrent in the first experiment.[1]] [However, Dorothy's prediction is incorrect because the energy received by each electron depends on the energy of each photon, $E = \frac{hc}{\lambda}$, and not the intensity of light.[2]] [If the threshold frequency of the metal is not met, no electrons are emitted at any intensity of light.[3]]

- I have identified Dorothy may believe increasing intensity of light increases energy.[1]
- I have used stated the energy absorbed by electrons is from the individual energy of the electrons.[2]
- I have explained that the threshold frequency must be met to emit photoelectrons.[3]

17% of students answered this VCAA exam question correctly.

15. a. $L = \frac{L_o}{\gamma} = \frac{1.5}{3.20}$ (1 MARK)

$L = 0.469 = 0.47$ km (1 MARK)

This length is shorter in the muon's frame of reference than measured by a stationary observer due to the effect's of special relativity caused by the muon's relative velocity to Earth. (1 MARK)

b. $$\gamma = \frac{1}{\sqrt{1-\frac{v^2}{c^2}}} = \frac{1}{\sqrt{1-\frac{(4.5\times10^4)^2}{(3.0\times10^8)^2}}} \text{ (1 MARK)}$$

$\gamma = 1.000000011$

The difference in time measured by a GPS satellite and to have passed on Earth is:

$t_{diff} = t - t_0$

$t_{diff} = \gamma t_0 - t_0 = (\gamma - 1)t_0$ (1 MARK)

$t_{diff} = (1.000000011 - 1) \times (2.3 \times 10^{-6})$ (1 MARK)

$t_{diff} = 2.59 \times 10^{-14} = 2.6 \times 10^{-14}$ s (1 MARK)

16. [The wave model predicts that light energy is continuous and that an electron would absorb energy from light over time until it has sufficient energy to be emitted.[1]] [The negligible time delay between light being incident on a metal surface and the emission of photoelectrons provides evidence against this prediction.[2]] [The wave model also predicts that any frequency of light should be able to cause photoelectron emission.[3]] [The existence of a threshold frequency provides evidence against this wave model prediction.[4]]

- I have explained one incorrect wave model prediction.[1]
- I have identified the evidence against the wave model regarding the first cited prediction.[2]
- I have explained a second incorrect wave model prediction.[3]
- I have identified the evidence against the wave model regarding the second cited prediction.[4]

Other possible answers

- The wave model predicts that the maximum kinetic energy of an emitted photoelectron depends on the light intensity.

16% of students answered this VCAA exam question correctly.

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12A Asking questions, identifying variables and making predictions

Progress questions

1. C. The extension of the string is measured when different masses are attached to the spring.
2. B, D. Both the density of the air and the spring constant of the spring are possible controlled variables for the experiment, as they are not deliberately altered.
3. A, B. Both the diameter of the ball and the angle of inclination of the ramp can be recorded by numerical values.
4. B. Secondary data can come in either qualitative or quantitative form.
5. B. The purpose of a hypothesis is to propose a relationship between variables that can be tested in an experiment.
6. B, C, D. The scientific method does not guarantee conclusions obtained are correct, as there is always error associated with experiments.
7. C. A scientific theory explains a physical phenomenon.
8. B. A scientific model is a representation of a physical process.

Exam-style

9. a. [Secondary data.[1]]

   I have identified the data as secondary data.[1]

   b. [Primary data.[1]]

   I have identified the data as primary data.[1]

10. [A scientific law describes the relationship between entities for a particular phenomenon,[1]][while scientific theory goes into detail about how or why this phenomenon occurs.[2]]

    I have explained that a scientific law describes the relationship entities for a particular phenomenon.[1]

    I have explained that a scientific theory describes why this phenomenon occurs.[2]

11. a. [Scientific model.[1]]

    I have identified this statement as explaining/representing a scientific model.[1]

    b. [Scientific law.[1]]

    I have identified this statement as explaining/representing a scientific law.[1]

    c. [Scientific hypothesis.[1]]

    I have identified this statement as explaining/representing a scientific hypothesis.[1]

12. a. [The independent variable is the distance from the phone.[1]] [This is quantitative data.[2]]

    I have identified the independent variable as the distance from the phone.[1]

    I have identified this is measured as quantitative data.[2]

    b. [The dependent variable is the loudness of the sound.[1]] [This is qualitative data.[2]]

    I have identified the dependent variable is the loudness of the sound.[1]

    I have identified this is measured as qualitative data.[2]

    c. [A possible controlled variable is the frequency of the sound.[1]]

    I have identified a possible controlled variable of the sound.[2]

    Other possible answers include:
    - the volume the sound is played at.
    - the sound sensitivity of the listener's ears.
    - the humidity of the air.

13. [If the height a ball is dropped from is increased[1]][then the peak of the ball's initial bounce after it is dropped will increase[2]] [as the ball has more gravitational energy.[3]]

    I have identified the height the ball is dropped from as the independent variable.[1]

    I have identified the peak of the ball's initial bounce as the dependent variable.[2]

    I have created a predicted physics principle for this experiment.[3]

12B Scientific conventions

Progress questions

1. A, B, C. Kelvin, not fahrenheit, is the base SI unit for temperature.
2. C. To convert from kJ to J, the value is multiplied by 10^3.
3. C. Trailing zeros are significant, so all digits stated in the number 180 030 are significant.
4. B. The least number of decimal places in the addition is two, so the answer should be expressed with two decimal places.
5. A. The least number of significant figures in the multiplication is two, so the answer should be expressed to two significant figures.

6. A. To convert to scientific notation, the decimal place is moved 2 units to the right, so $n = -2$.

7. C. To convert to standard notation, the decimal place is moved 3 units to the right, so $8.7 \times 10^3 = 8700$ g.

Exam-style

8. a. 6.0×10^3

   b. 8.9×10^6

   c. 6.4×10^4

   d. 3.4×10^{-4}

   e. 1.3×10^{-2}

9. a. $600 \text{ ms} = 600 \times 10^{-3} \text{ s} = 6.00 \times 10^{-1} \text{ s}$

   b. $0.400 \text{ µg} = 0.400 \times 10^{-6} \text{ kg} = 4.00 \times 10^{-7} \text{ kg}$

   c. $23 \text{ MΩ} = 23 \times 10^6 \text{ Ω} = 2.3 \times 10^7 \text{ Ω}$

   d. $360 \text{ nm} = 360 \times 10^{-9} \text{ m} = 3.60 \times 10^{-7} \text{ m}$

   e. $7.0 \text{ pA} = 7.0 \times 10^{-12} \text{ A}$

10. [Yusif is correct and Nina is incorrect.[1]][For addition or subtraction, the final answer should use the least number of decimal places in the data set, whereas for multiplication or division, the final answer uses the least amount of significant figures in the data set.[2]]

    I have stated who is correct.[1]

    I have explained the relevant significant figure rules.[2]

11. a. [Oliver's solution should have two significant figures.[1]]

    I have identified that Oliver's solution should have two significant figures.

    b. $\frac{7.4}{200} = 3.70 \times 10^{-2} = 3.7 \times 10^{-2}$

12. $E = VQ = 6.00 \times 4.00$ (1 MARK)

    $E = 24.00 = 24.0$ J (1 MARK)

13. For this question we will need to convert our distance measurement to SI units.

    $0.135 \text{ km} = 0.135 \times 10^3 = 135 \text{ m}$

    $\textit{total distance} = d_h + d_f = 135 + 63.0 = 198$ m (3 significant figures since the least amount of decimal places is zero) (1 MARK)

    $\textit{speed} = \frac{\textit{total distance}}{\textit{time}} = \frac{198}{67.0}$ (1 MARK)

    $\textit{speed} = 2.955 = 2.96 \text{ m s}^{-1}$ (3 significant figures) (1 MARK)

12C Collecting data

Progress questions

1. A. The range of this data is relatively large, so the data is not precise.

2. D. The closer the average of the data is to the true value, the more accurate it is.

3. C. The resolution is the smallest measurable change, which in this case, is a millimetre if the ruler has millimetre markings.

4. A. The uncertainty is 1 cm as given after the ± symbol in the measurement.

5. D. Systematic error is not reduced by taking multiple readings, as it affects all readings equally.

6. A. Random errors can be reduced by using more precise instruments or by taking the average of multiple measurements, but it is not unavoidable.

7. C. Reproducibility is defined as the closeness of agreement of results when an experiment is replicated by a different experimenter under slightly different conditions.

8. B. Repeatability is defined as the closeness of agreement of results when an experiment is repeated by the same experimenter under the same conditions.

9. C. Your experimental partner's breakfast is not relevant information to the experiment but all other information listed is relevant information for the logbook.

Exam-style

10. B. The results of student X have the smallest range and are the closest to the true value.

11. D. The results of student Z have an average that is the furthest away from the true value.

12. A. The effects of random errors can be reduced by taking the average of multiple readings, but can never be eliminated completely.

    63% of students answered this VCAA exam question correctly.

13. a. Gen: $\frac{4.0 + 4.5 + 3.6 + 4.3}{4} = 4.1$ V (1 MARK)

    Jana: $\frac{3.8 + 4.1 + 4.2 + 3.9}{4} = 4.0$ V (1 MARK)

    b. Gen: $4.5 - 3.6 = 0.9$ V (1 MARK)

    Jana: $4.2 - 3.8 = 0.4$ V (1 MARK)

    c. [Gen's data is more accurate than Jana's data[1]][as Gen's average of 4.1 V is closer to the true voltage of 4.2 V than Jana's average of 4.0 V.[2]]

    I have identified which person's data is more accurate.[1]

    I have explained why the data is more accurate.[2]

    d. [Jana's data is more precise than Gen's data[1]][as the range of Jana's results (0.4 V) is smaller than the range of Gen's results (0.9 V).[2]]

    I have identified which person's data is more precise.[1]

    I have explained why the data is more precise.[2]

e. [Gen and Jana's experiment is not repeatable or reproducible as it is missing a logbook.[1]] [The logbook contains the required information to attempt a repeat by Gen and Jana or reproduction by another experimental team.[2]]

- I have commented on the repeatability and reproducibility of Gen and Jana's experiment.[1]
- I have explained why the experiment is neither repeatable nor reproducible.[2]

14. C, E, F, G, I

15. [Accuracy refers to how well a measurement agrees with the 'true' value of a measurement.[1]] [If a measuring device is not properly calibrated, this will introduce a systematic error that will shift measurements uniformly away from their 'true' value.[2]] [Therefore, proper calibration can increase the accuracy of data.[3]]

- I have explained the concept of accuracy.[1]
- I have explained the concept of systematic error.[2]
- I have related my answer to the context of the question.[3]

12D Representing and analysing data

Progress questions

1. B. The independent variable should be plotted on the horizontal axis.

2. C. Error bars indicate a range in which the 'true' value of a data point should lie.

3. D. From the equation $P = \frac{V^2}{R}$, the relationship between P and V is parabolic.

4. C. By squaring the V values, the relationship between the variables P and V^2 will be linear.

5. B, D. Lines of best fit do not necessarily have to pass through the origin, but should always pass through the error bars of each point on the graph.

6. B. The line of best fit should have approximately the same number of coordinates above and below the line.

7. A. Two coordinates the furthest apart which lie on the line of best fit are the best choice to calculate the gradient of the line.

8. B. The gradient represents the change in the y variable, Δp, divided by the change in the x variable, Δt.

9. D. The unit for the gradient can be found from $\frac{\text{unit on } y\text{-axis}}{\text{unit on } x\text{-axis}} = \frac{\text{kg m s}^{-1}}{\text{s}} = \text{kg m s}^{-2}$.

10. A. $gradient = \frac{\Delta p}{\Delta t} = F.$

11. A. $gradient = \frac{\Delta F}{\Delta x} = -k.$

Exam-style

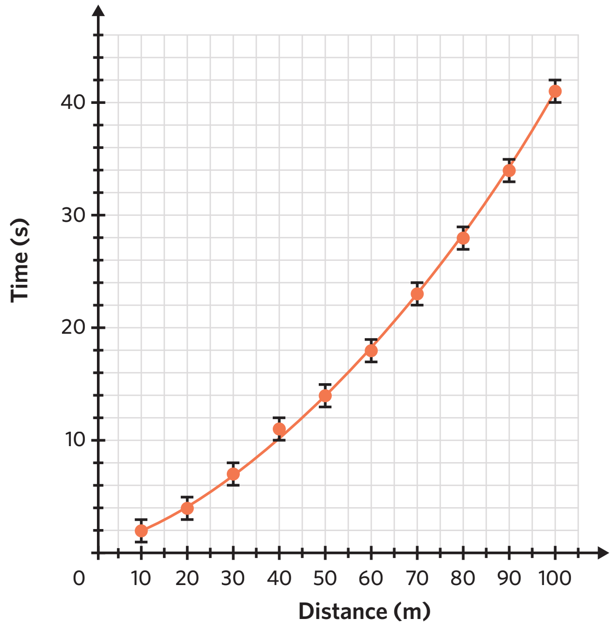
12. [To linearise the data, Nat should take the square root of the independent variable.[1]]

- I have identified Nat should take the square root of the independent variable to linearise the data.[1]

13. $gradient = \frac{y_2 - y_1}{x_2 - x_1} = \frac{7.6 - 0}{2.9 - 0}$ (1 MARK)

$gradient = 2.62 = 2.6$ (1 MARK)

14. Time (s) vs. distance (m)



- I have labelled the horizontal and vertical axes, correctly including correct units.
- I have included an appropriate and consistent scale on both horizontal and vertical axes.
- I have plotted each point of data correctly.
- I have drawn correctly sized uncertainty bars: (vertical: ±1 s).
- I have drawn a curved line of best fit which passes through all uncertainty bars.

15. [The straight line of best fit drawn does not go through all uncertainty bars.[1]] [The axes have also not been labelled.[2]] [A curved line of best fit could be drawn that passes through all uncertainty bars.[3]] [The horizontal and vertical axis could be labelled with the independent and dependent variable respectively, and their respective units.[4]]

- I have identified one error in the graph drawn.[1]
- I have identified a second error in the graph drawn.[2]
- I have suggested one change as to how the graph could be improved.[3]
- I have suggested a second change as to how the graph could be improved.[4]

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16. [A straight line of best fit may be fitted to the data points if a straight line can be drawn through the uncertainty bars of all points.[1]][Therefore, vertical uncertainty bars of equal size must be drawn on each data point,[2]][and then a smooth line attempted to be drawn through all of the uncertainty bars.[3]]

- I have explained how a straight line of best fit can be drawn if a straight line passes through the uncertainty bars of all data points.[1]
- I have identified that vertical uncertainty bars must be drawn on each data point.[2]
- I have identified that a straight line must be attempted to be drawn, that passes through each uncertainty bar.[3]

17. [The student is incorrect.[1]][The value of the gradient is the ratio of the change in the force to the change mass of an object.[2]][As the gradient of the graph is constant, according to $F = mg \Rightarrow \frac{F}{\Delta m} = g$, the value of acceleration due to gravity does not change.[3]]

- I have stated the student is incorrect.[1]
- I have explained the definition of a gradient.[2]
- I have explained the acceleration due to gravity does not change as the gradient of the graph is constant.[3]

18. Use any two points from the line of best fit that are relatively far apart to calculate the gradient.

$gradient = \frac{y_2 - y_1}{x_2 - x_1} = \frac{1.35 - 0.45}{0.70 - 0.22}$ (1 MARK)

$gradient = 1.88 \text{ s m}^{-1/2}$

$gradient = \frac{rise}{run} = \frac{T}{\sqrt{L}}$

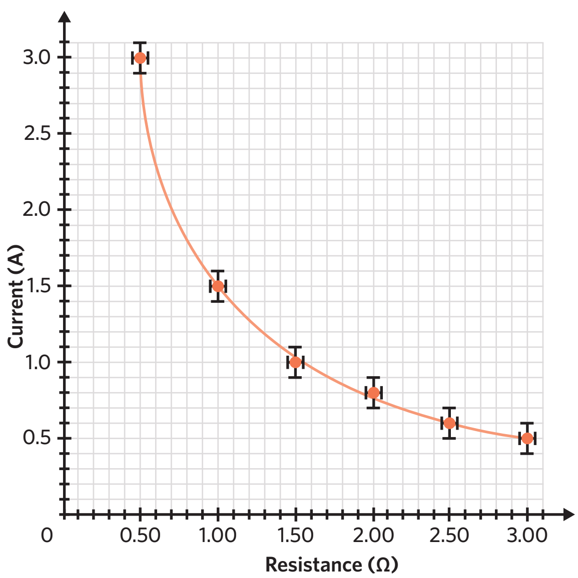
The original equation is $T = 2\pi\sqrt{\frac{L}{g}} \Rightarrow \frac{T}{\sqrt{L}}$

$= \frac{\pi}{\sqrt{g}} \Rightarrow gradient = \frac{\pi}{\sqrt{g}}$ (1 MARK)

$1.88 = \frac{\pi}{\sqrt{g}} \Rightarrow g = 11.1 = 11 \text{ m s}^{-2}$ (1 MARK)

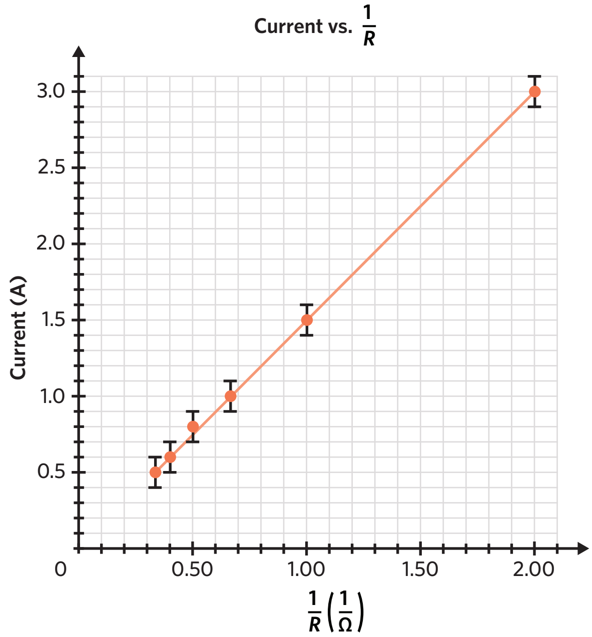
(between 9.0 m s^{-2} and 14 m s^{-2} is acceptable)

19. a.



- I have labelled the horizontal and vertical axes correctly, including correct units.
- I have included an appropriate and consistent scale on both axes.
- I have plotted each data point correctly.
- I have drawn correctly sized uncertainty bars: (horizontal: $\pm 0.05\ \Omega$, vertical: ± 0.1 A).
- I have drawn a curved line of best fit which passes through all uncertainty bars.

b.



- I have labelled the horizontal and vertical axes correctly, including correct units.
- I have included an appropriate and consistent scale on both axes.
- I have plotted each data point correctly.
- I have drawn correctly sized uncertainty bars: (vertical: ± 0.1 A)
- I have drawn a straight line of best fit which passes through all uncertainty bars.
- I have drawn a straight line of best fit which passes through all uncertainty bars.

c. [Wataru is correct that $I \propto \frac{1}{R}$,[1]][since a straight line fits the linearised data of I vs. $\frac{1}{R}$.[2]]

- I have identified that Wataru is correct.[1]
- I have explained that a straight lit fits the linearised data of I vs. $\frac{1}{R}$.[2]

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d. Use any two points from the line of best fit that are relatively far apart to calculate the gradient.

$gradient = \frac{y_2 - y_1}{x_2 - x_1} = \frac{3.00 - 0.75}{2.00 - 0.50}$ (1 MARK)

$gradient = 1.5\ A\ \Omega$

$gradient = \frac{rise}{run} = \frac{I}{\frac{1}{R}} = IR$

The original equation is $V = IR \Rightarrow gradient = V$ (1 MARK)

$V = 1.5$ V. This is the same as the voltage supplied by the battery (1 MARK)

(between 1.3 V and 1.7 V is acceptable)

12E Communicating findings

Progress questions

1. A, B. An explanation of the background theory relating to the investigation is best placed in the introduction, and an explanation of any possible sources of error that may have occurred is best placed in the discussion.

2. D. A results section should present raw data obtained in the experiment, along with a short description on the key information in those results and their relationship to the hypothesis.

3. B, D. Conclusions should avoid words such as “proved” or “disproved” and instead use terms such as “supported”, “partially supported” or “did not support”.

Exam-style

4. a. [How does changing the height a ball is dropped from affect the maximum height it bounces back to?[1]]

- I have written a research question that conveys the purpose of the investigation.[1]

b. [2. Measure the maximum height the ball reaches after it hits the ground, using a ruler.[1]]

- I have explicitly stated the maximum height the ball reaches should be measured in step 2.[1]

5. [Sadio should include background information to the investigation,[1]][an aim for the investigation,[2]][and a hypothesis for the investigation.[3]]

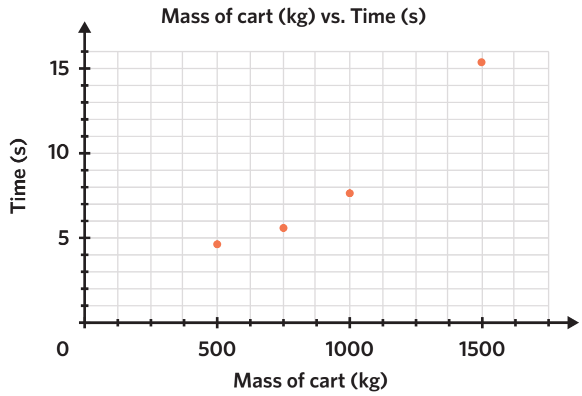
- I have identified Sadio should include background information to his investigation.[1]
- I have identified Sadio should include an aim for his investigation.[2]
- I have identified Sadio should include a hypothesis for his investigation.[3]

6. a.

Mass of cart (g)	Time the cart takes to come to rest (s)
500	4.6
750	5.8
1000	7.9
1500	15.4

- I have presented the results in an appropriate format.[1]
- I have included all relevant conventions to the presentation of results.[2]

Other possible answers include:



b. [The results do not support Kathie’s hypothesis that “increasing the mass of the cart will decrease the time it takes to come to rest”.[1]][The results show that the larger the mass of the cart, the longer it takes the cart to come to rest.[2]]

- I have identified that Kathie’s hypothesis is not supported by the results.[1]
- I have explained that the results show increasing the mass of the cart increase the time it takes for the cart to come to rest.[2]

7. [1 × small mass;[1]][1 × 60 cm string;[2]][1 × stopwatch.[3]]

- I have identified one piece of equipment required.[1]
- I have identified a second piece of equipment required.[2]
- I have identified a third piece of equipment required.[3]

Other possible answers include:

- 1 × 1 m ruler.

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8. a. [The students' conclusion is not adequate for a scientific investigation.[1]][When writing conclusions, words such as "prove" should be avoided.[2]]

I have identified the students' conclusion is not adequate for a scientific investigation.[1]

I have evaluated the use of the word "prove" in the student's conclusion.[2]

b. [The results from the investigation support the idea that light is a wave.[1]]

I have provided an alternative conclusion that uses "support" instead of "prove".[1]

9. [The student should get a mark of 3 out of 4.[1]][The student successfully shows the extent to which the results support the hypothesis[2]][and compares the results obtained to theoretical results.[3]][The student fails to analyse experimental design and possible sources of error.[4]][The student successfully links the overall findings to the aim.[5]]

I have identified a mark to award the student.[1]

I have explained whether the student shows the extent to which the results support the hypothesis.[2]

I have explained whether the student compares obtained results to theoretical results.[3]

I have explained whether the student analyses the experimental design and possible sources of error.[4]

I have explained whether the student links overall findings to the aim.[5]

Chapter 12 review

Section A

1. A. A hypothesis is a proposed explanation that predicts a relationship between variables and can be tested through experimentation.

84% of students answered this VCAA exam question correctly.

2. D. Words such as "prove" and "disprove" should be avoided when drawing conclusions about the investigation, and instead words such as "support" or "do not support" can be used.

3. C. Reproducibility is the closeness of agreement of results when an experiment is replicated by a different experimenter under slightly different conditions.

4. C. Accuracy is defined as the difference between the mean and the 'true' value, precision is defined as the range between measurements. Gwen's results have a smaller range of measurements, so her results are more precise than Arthur's.

59% of students answered this VCAA exam question correctly.

5. D. For an experiment to be valid there must be only one independent variable changed at a time.

Section B

6. a. [The independent variable is the length of the pendulum,[1]][and the dependent variable is the period of the pendulum's oscillation.[2]][A possible controlled variable is the mass attached to the pendulum.[3]]

I have identified the independent variable is the length of the pendulum.[1]

I have identified the dependent variable is the period of the pendulum's oscillation.[2]

I have identified a possible controlled variable.[3]

Other possible answers:

- a possible controlled variable is the amplitude of the pendulum's oscillation.

83% of students answered this VCAA exam question correctly.

b. [Taking a measurement of five oscillations rather than one oscillation reduces the uncertainty associated with the measurement of the pendulum's period of oscillation.[1]][This reduces random errors in the data.[2]]

I have explained why taking a measurement of five oscillations improves the quality of the data obtained.[1]

I have identified what type of error will be reduced.[2]

85% of students answered this VCAA exam question correctly.

c. [A video could be taken of the pendulum's oscillation, and used to measure the time for the pendulum's oscillation rather than using a stopwatch.[1]][The students could use a ruler with smaller gradations to measure the length of the pendulum.[2]]

I have identified one possible improvement to the experimental investigation.[1]

I have identified another possible improvement to the experimental investigation.[2]

Other possible answers:

- The students could take measurements for a larger range of pendulum lengths.

7. a. [The students taking multiple time measurements during the experiment is reduced the effect of random error and improve the quality of their data.[1]]

I have identified a reason as to why taking multiple time measurements will improve the quality of the data.[1]

Other possible answers:

- to reduce uncertainty in the data obtained
- to improve reliability of the data obtained

86% of students answered this VCAA exam question correctly.

CHAPTER 12 REVIEW

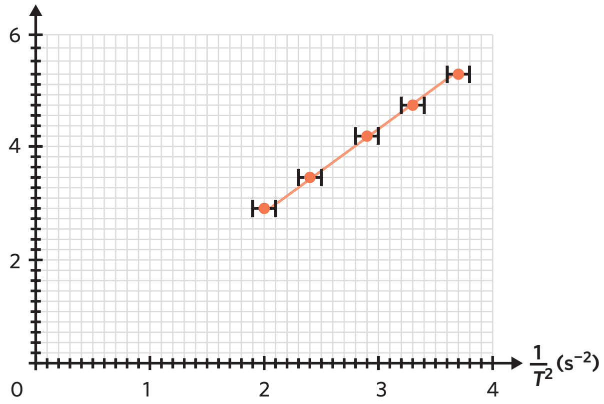
b.

Line number	1	2	3	4	5
Total mass of washers, m (kg)	0.30	0.36	0.42	0.48	0.54
Gravitational force acting on washers, *mg* (N)	**3.0**	**3.6**	**4.2**	**4.8**	**5.4**
Average time for 20 rotations (s)	14.0	12.8	11.8	11.0	10.4
Period, *T* (s)	**0.70**	**0.64**	**0.59**	**0.55**	**0.52**
$\frac{1}{T^2}$ (s^{-2})	**2.04**	**2.44**	**2.87**	**3.30**	**3.70**

- I have calculated the gravitational force acting on the washers correctly.
- I have calculated the period correctly.
- I have calculated $\frac{1}{T^2}$ correctly.

51% of students answered this VCAA exam question correctly.

c.



- I have correctly labelled the horizontal and vertical axis and included correct units.
- I have included an appropriate and consistent scale on the axes.
- I have plotted each point of data correctly.
- I have included uncertainty bars in the *x*-direction correctly.
- I have drawn a straight line of best fit.

32% of students answered this VCAA exam question correctly.

d. $gradient = \frac{y_2 - y_1}{x_2 - x_1} = \frac{5.0 - 3.4}{3.4 - 2.3}$ (1 MARK)

$gradient = 1.45 = 1.5 \text{ N s}^2$ (1 MARK)

(between 1.3 N s^2 and 1.7 N s^2 is acceptable)

39% of students answered this VCAA exam question correctly.

e. From the relationship $Mg = \frac{4\pi^2 Rm}{T^2}$, the gradient of the graph Mg vs. $\frac{1}{T^2}$ represents $4\pi^2 Rm$. (1 MARK)

$4\pi^2 Rm = 1.5$

$4\pi^2 \times 0.76 \times m = 1.5$ (1 MARK)

$m = 0.0499 = 0.050$ kg (1 MARK)

(between 0.043 kg and 0.057 kg is acceptable)

13% of students answered this VCAA exam question correctly.

8. a. $6.45 \text{ mm} = 6.45 \times 10^{-3}$ m

b. [A possible controlled variable is the charge on the two sphere.[1]][If the charge on the two spheres is not controlled, then the experiment may not be measuring what it claims the be measuring, and so the experiment would be invalid.[2]]

- I have identified a possible controlled variable.[1]
- I have explained why other variables must be controlled .[2]

c. [As $F = k\frac{q_1 q_2}{r^2}$, calculating the values of $\frac{1}{r^2}$ will allow the graph of F vs. $\frac{1}{r^2}$ to be plotted, which should have a straight line of best fit.[1]]

- I have explained why the values of $\frac{1}{r^2}$ must be calculated to linearise the data.[1]

d.

Seperation *r* (mm)	Force (N)	$\frac{1}{r^2}$ (m^{-2})
10.0	6.90×10^{-27}	$\mathbf{1.00 \times 10^4}$
20.0	1.73×10^{-27}	$\mathbf{2.50 \times 10^3}$
30.0	7.67×10^{-28}	$\mathbf{1.11 \times 10^3}$
40.0	4.31×10^{-28}	$\mathbf{6.25 \times 10^2}$

- I have calculated the values of $\frac{1}{r^2}$ correctly.
- I have represented the values of $\frac{1}{r^2}$ to three significant figures.

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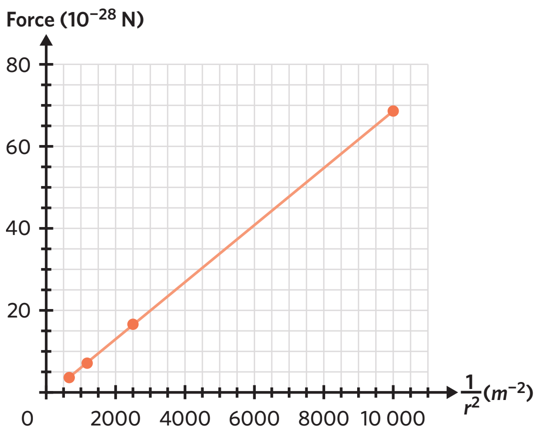
e.



I have correctly labelled the horizontal and vertical axis and included correct units.

I have included an appropriate and consistent scale on the axes.

I have plotted each point of data correctly.

I have drawn a straight line of best fit.

f. $gradient = \frac{rise}{run} = \frac{69.0 \times 10^{-28} - 4.31 \times 10^{-28}}{1.00 \times 10^4 - 625}$

$= 6.90 \times 10^{-31}$ N m^2 (1 MARK)

From the relationship $F = k\frac{q_1 q_2}{r^2}$, the gradient of the graph F vs. $\frac{1}{r^2}$ represents $k\,q_1\,q_2$. (1 MARK)

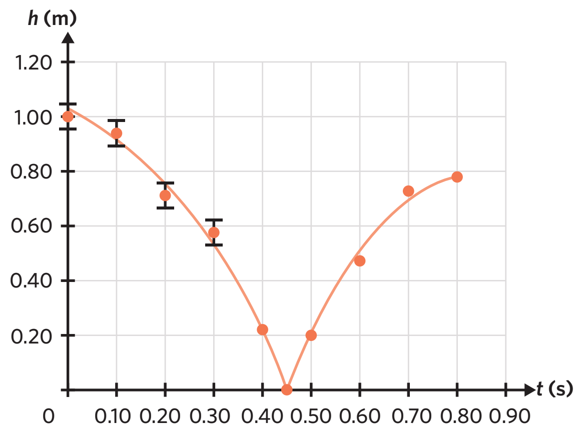
$6.90 \times 10^{-31} = kq_1q_2$

$6.90 \times 10^{-31} = k \times 5.00 \times 10^{-20} \times 1.50 \times 10^{-21}$ (1 MARK)

$k = 9.200 \times 10^9 = 9.20 \times 10^9$ N m^2 C^{-2} (1 MARK)

Note that a range of values are acceptable, depending on the line of best fit drawn in part e.

9. a.



I have labelled the y-axis with the correct variable and unit.

I have labelled the x-axis with the correct variable and unit.

I have drawn uncertainty bars in the y-direction correctly.

I have drawn a non-linear line of best fit correctly for the data before and after the ball bounces.

b. As $speed = \frac{distance}{time}$, the gradient of the height vs. time graph represents the speed of the ball.

$gradient = \frac{y_2 - y_1}{x_2 - x_1} = \frac{0 - 0.22}{0.45 - 0.40}$ (1 MARK)

$gradient = -4.40 = -4.4$ m s^{-1} (1 MARK)

The speed of the ball before impact is approximately 4.4 m s^{-1}. (1 MARK)

Note that a range of values are acceptable, depending on the non-linear line of best fit drawn in part e or the data points chosen to calculate the gradient of the line.

c. [The point at which the ball is travelling quickest is when the gradient of the curve of best fit is at its maximum value.[1]] [From the two curves of best fit, it appears the ball is travelling quickest before it bounces, as the gradient has a maximum value just before the ball reaches the ground.[2]]

I have explained the ball will be travelling quickest at the point where the gradient of the curve of best fit is at its maximum value.[1]

I have identified that this occurs just before the ball reaches the ground.[2]

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Glossary

A

absorption spectrum the specific set of frequencies or wavelengths of light that an element or compound absorbs due to electron energy transitions p. 482

acceleration the rate of change of velocity per unit time (vector) p. 5

accuracy a relative indicator of how well a measurement agrees with the 'true' value of a measurement p. 564

aim the purpose of an experiment p. 553

air resistance the force of air particles resisting the motion of objects through the air p. 80

alternating current (AC) electricity electricity with a periodically alternating direction of current and voltage p. 284, 320

alternator a device that transforms kinetic energy into AC electricity by electromagnetic induction; an AC generator p. 284

altitude the height of an object in relation to the surface of the planet p. 172

amplitude (waves) the magnitude of an oscillation's maximum value from the neutral point within a wave p. 355

amplitude the distance from the x-axis to the top or bottom of the wave p. 286

angle of inclination the angle between the flat surface of an inclined plane and the horizontal plane p. 31

antinode a point where constructive interference consistently occurs p. 367

aperture a hole, gap, or slit through which a wave travels p. 385

B

banked track an inclined circular track p. 58

bar magnet a permanent magnet in the shape of a bar p. 218

C

centripetal acceleration the rate of change of the instantaneous velocity of an object as it travels in a circular path p. 51

centripetal force the net force causing circular motion, which is always directed towards the centre of a body's circular path p. 49

charge a quantifiable property which relates to how strongly an object is affected by an electric field p. 207

coherent wave sources that create waves of the same frequency and constant phase difference in the same medium p. 367, 404

collision the coming together of two or more objects, where each object exerts a force on the other p. 93

compression (spring) the process of decreasing an object's length p. 137

conical pendulum a mass at the end of a string that undergoes horizontal circular motion p. 60

connected bodies two or more objects either in direct contact or attached by a string, rope, or cable p. 38

conservation of energy the total energy of an isolated system remains constant p. 109

contracted length the length of an object measured in a reference frame where the object is moving p. 507

controlled variable a variable that has been held constant in an experiment p. 551

conventional current current that is modelled as positive charges that flow from the positive to the negative terminal of a cell p. 236

current the rate of flow of electric charge, measured in amperes p. 309

curved line of best fit a curved line that indicates the relationship between the independent and dependent variables on a graph p. 577

cut-off potential see stopping voltage p. 422

D

de Broglie wavelength the wavelength associated with objects made of matter due to their momentum p. 466

dependent variable a variable that is measured by the experimenter, expected to be impacted by the independent variable p. 551

design angle the angle of a banked track for which a vehicle driving at the design speed will have no sideways friction force acting on it p. 58

design speed the speed a vehicle needs to travel around a banked track to have no sideways frictional force acting on it p. 58

diffraction the spread of a wave around an obstacle or through an aperture p. 384

dilated time the time interval between two events measured in a reference frame where the two events occur at different points in space p. 509

dipole a field in which field lines point both towards and away from the object(s) generating the field p. 210

direct current (DC) electricity with a constant direction of current p. 242

direct current (DC) electricity electricity with a constant direction of current and voltage p. 289

discrete limited to certain values (not continuous) p. 453, 478

displacement the change in position of an object (vector) p. 5

distance the total length of a given path between two points (scalar) p. 5

E

elastic collision a collision in which kinetic energy is conserved p. 120

electric field strength a measure of the electric force that acts per unit of charge at a point in space p. 207

electromagnet a magnet created by an electric current p. 218

electromagnetic induction the production of an electromotive force (EMF) due to the change in magnetic flux through a conducting loop p. 266

electromagnetic spectrum the range of all electromagnetic waves ordered by frequency and wavelength p. 396

electromagnetic wave a transverse wave composed of a changing electric field perpendicular to a changing magnetic field p. 396

electromotive force (EMF) the voltage created or supplied due to energy being transformed into electrical potential energy p. 266

electron-volt a measure of energy equal to 1.6×10^{-19} J p. 418

emission spectrum the specific set of frequencies or wavelengths of light that an element or compound emits due to electron energy transitions p. 482

energy dissipation the transformation of useful energy into other forms of energy p. 122

energy a scalar quantity describing the ability to cause a physical change p. 108

equilibrium position (spring-mass system) the position of the mass at which the net force on the mass is zero p. 148

error a mistake, issue, or limitiation with some aspect of the experiment causing results to deviate from the 'true' value p. 565

ether hypothetical medium that light travels through p. 498

event something that occurs at a particular location and time p. 509

extension the process of increasing an object's length p. 137

F

field a region of space in which each point is subject to a non-contact force p. 169

force a push or a pull with an associated magnitude and direction (vector) p. 18

frame of reference a perspective from which we measure the relative location and motion of objects p. 494

frequency the number of cycles completed per second p. 286, 355

friction a force that resists the relative motion of two surfaces in contact p. 31

frictional force a force that resists the relative motion of two surfaces in contact p. 25

fringe spacing the distance between adjacent bright or dark bands in an interference pattern p. 406

fundamental frequency the lowest frequency of a standing wave that will form in a given medium p. 378

G

generator a device that transforms kinetic energy into electricity (either AC or DC) by electromagnetic induction p. 284

GPS satellites a group of satellites that send and receive signals to accurately determine a location on Earth p. 522

gradient the graphical representation of the rate of change of one variable with respect to another p. 575

gravitational field strength a measure of the gravitational force acting on each unit of mass at a point in space p. 170

gravitational force the force experienced by an object due to the gravitational field of another object p. 24

gravitational potential energy (GPE) the stored energy associated with the position of an object in a gravitational field p. 127, 180

H

half-life the average time it takes for half the particles in a sample to decay p. 518

harmonic a standing wave with a frequency equal to an integer multiple of a fundamental frequency p. 378

hypothesis a proposed explanation that predicts a relationship between variables and can be tested through experimentation p. 552

I

ideal spring a spring that obeys Hooke's law, such that the force it exerts is proportional to its change in length p. 137

impulse the change in momentum of a body, as the result of a force acting over a time (vector) p. 94

inclined plane a flat surface that is at an angle to the horizontal plane p. 30

independent variable a variable that is deliberately manipulated by the experimenter p. 551

induced current the current produced in a conductor due to a changing magnetic flux p. 274

inelastic collision a collision in which kinetic energy is not conserved p. 120

inertial frame of reference a non-accelerating frame of reference p. 494

intensity the number of light particles incident per unit area per unit of time (according to the particle model of light) p. 429

interference superposition creating a larger (constructive) or smaller (destructive) resultant wave p. 366

inverter a device that converts direct current (DC) into alternating current (AC) p. 299

isolated system a collection of interacting objects for which there is no change in the total mass and energy p. 92

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K

kinetic energy (KE) the energy associated with an object's motion p. 108

L

law (scientific) a statement, based on repeated experiments or observations, that describes or predicts a phenomenon. p. 554

linearise the process of transforming data so that, when graphed, a linear line of best fit can be drawn through the data p. 572

logbook a complete chronological record of the experimental procedure and results p. 567

longitudinal wave a wave in which the oscillations are parallel to the direction of wave travel and energy transmission p. 355

M

magnetic field a vector field that arises from the movement of charge p. 218

magnetic flux a measure of the number of magnetic field lines passing through an area p. 262

magnitude the size or numerical value of a quantity without sign (positive or negative) or direction p. 557

mass-energy equivalence the principle that mass can be considered a form of energy; mass can be converted into energy and energy can be converted into mass p. 529

model (scientific) a representation of a physical process that cannot be directly experienced p. 554

momentum a property of an object in motion, which is dependent on the mass and the velocity of the object (vector) p. 92

monopole a field in which all field lines either point towards or away from the object(s) generating the field p. 169

muon an unstable subatomic particle p. 517

N

natural length the length of a spring when no external forces are acting on it p. 138

net force the vector sum of all forces acting on an object p. 21

Newton's first law of motion an object in motion will remain in motion unless acted upon by a net external force p. 22

node a point where destructive interference consistently occurs p. 367

non-contact force a force applied to an object by another body not in contact with it p. 169

non-uniform field a field that varies in magnitude or direction at different locations in space p. 169

normal force the contact force that acts at right angles to the surface on object is resting on p. 24

O

observation the acquisition of data using senses such as seeing and hearing or with scientific instruments p. 552

orbit a periodic curved path an object takes around another p. 191

oscillate move repetitively about a fixed position p. 149

P

parallel circuit an electric circuit where there are multiple pathways for current to flow p. 313

particle accelerator a machine used to accelerate charged particles p. 521

path difference the difference in distance travelled by two waves from their sources to the same point p. 367, 404

period the time taken to complete one cycle p. 48, 193, 286, 355

permanent magnet an object with material properties that cause it to produce a persistent magnetic field p. 218

personal error mistakes in the execution of an experiment or the analysis, caused by a lack of care that negatively impact or invalidate the conclusions of an experiment p. 565

photocurrent the electrical current produced by photoelectrons in the photoelectric effect p. 419

photoelectrons electrons emitted in the photoelectric effect p. 418

photon a massless particle of electromagnetic radiation with a discrete amount of energy p. 453

photovoltaic (PV) cell a device that converts light energy into electrical energy p. 296

point charge an electric charge considered to exist as a single point p. 207

postulate a statement which is accepted to be true as a basis for reasoning p. 495

potential difference see voltage p. 309

power the rate of change of energy with respect to time p. 113

precision a relative indicator of how closely different measurements of the same quantity agree with each other p. 564

primary data original data collected firsthand by researchers p. 552

projectile an object that has been launched or dropped without any form of self propulsion p. 79

proper length the length of an object measured in a reference frame where the object is at res p. 506

proper time the time interval between two events measured in a reference frame where the two events occur at the same point in space p. 509

Q

qualitative data data that cannot be described by numerical values p. 552

quantised see discrete p. 456, 477

quantitative data data that can be described by numerical values p. 552

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R

random error the unpredictable variations in the measurement of quantities p. 565

range the horizontal distance a projectile travels p. 82

relativistic kinetic energy the kinetic energy of a mass as calculated using special relativity p. 531

repeatability the closeness of agreement of results when an experiment is repeated by the same experimenter under the same conditions (using the same equipment and in the same laboratory) p. 568

reproducibility the closeness of agreement of results when an experiment is replicated by a different experimenter under slightly different conditions (using their own equipment and laboratory) p. 568

resistance a measure of the opposition to the flow of electric current p. 309

resistor an electrical component that resists the flow of electric current and causes a drop in voltage p. 309

resolution the smallest change in a quantity that is measurable p. 564

rest energy the energy of an object at rest, equivalent to the energy of its mass p. 530

root-mean-square (RMS) the DC voltage or current that would deliver the same average power as an AC source p. 320

S

satellite any object that gravitationally orbits another body, such as a planet or star p. 191

scalar a quantity that has only magnitude (size) p. 5

secondary data data that has been previously collected that is accessible to different researchers p. 552

semiconductor a material that can be modified to control how it conducts electricity p. 296

series circuit an electric circuit where there is only one pathway for current to flow p. 311

SI unit an accepted standard unit used for measuring a quantity p. 558

significant figures all digits quoted, starting with the first non-zero digit, giving an indication of the confidence in a measurement p. 559

slip rings a component used to maintain a constant electrical connection between a stationary external circuit and a rotating coil p. 246, 284

solar panel an array of photovoltaic cells connected to produce a desired voltage and current p. 298

solenoid an electromagnet made from coils of wire p. 218

speed the rate of change of distance per unit time (scalar) p. 5

split ring commutator a component used to reverse the electrical connection between a stationary external circuit and a rotating coil every half rotation p. 242, 289

spring constant a value that describes the stiffness of a spring p. 138

spring-mass system the combination of a spring and a mass attached to one end p. 147

standing wave two waves of the same frequency and amplitude travelling in opposite directions superimpose to create stationary regions of maximum and minimum displacement p. 376

static field a field that does not change over time p. 209

stopping voltage the voltage required to stop electrons with the highest kinetic energy and hence reduce photocurrent to zero p. 422

straight line of best fit a straight line that indicates the relationship between the independent and dependent variables on a graph p. 577

strain potential energy the energy stored by the deformation of an object; also known as elastic potential energy or spring potential energy p. 140

superposition the addition of overlapping waves in the same medium p. 366

systematic error a consistent, repeatable deviation in the measured results from the true values, often due to a problem with the experimental design or calibration of equipment p. 565

T

tension a pulling force that acts through an object connecting two bodies p. 24

theory (scientific) an explanation of a physical phenomenon that has been repeatedly confirmed by experimental evidence and observation p. 554

threshold frequency the minimum frequency of light required to liberate electrons from a metal surface p. 437

torque the turning effect due to a force acting at a perpendicular distance from an object's axis of rotation (vector) p. 242

total mass-energy the sum of the kinetic and rest energies of a mass or system p. 529

transformer a device that uses electromagnetic induction to transfer power from one electrical circuit to another p. 323

transverse wave a wave in which the oscillations are perpendicular to the direction of wave travel and energy transmission p. 355

travelling wave a wave that propagates through a medium, carrying energy from one location to another p. 376

trendline see straight line of best fit or curved line of best fit p. 577

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U

uncertainty the quantitative judgement of how well a measurement measures what it intends to p. 565

uniform circular motion the motion of an object travelling around a circle with a constant speed p. 48

uniform field a field that has the same magnitude and direction at all locations in space p. 169

V

validity the degree to which an experiment measures what it intends to measure p. 567

variable voltage source a voltage source that can provide a range of voltage levels in different directions to a circuit p. 420

vector a quantity that has magnitude (size) and direction p. 5

velocity the rate of change of displacement per unit time (vector) p. 5

voltage a measure of the difference in electric potential energy between two points p. 309

W

wave the transmission of energy via oscillations from one location to another without the net transfer of matter p. 355

wave cycle the process of a wave completing one full oscillation, ending up in a final configuration identical to the initial configuration p. 355

wave-particle duality the concept that light and matter can demonstrate both wave and particle properties p. 467

wave speed the speed at which a wave travels through a medium p. 358

wavelength the distance covered by one complete wave cycle p. 355

work function the minimum energy of light required to release the most loosely bound electron from a metal surface p. 421

work the change in energy caused by a force acting on an object in a direction parallel to its motion p. 109

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Formulas in this book

1A	average speed	$v = \frac{d}{t}$
	average velocity	$v = \frac{\Delta s}{\Delta t}$
	average acceleration	$a = \frac{\Delta v}{\Delta t} = \frac{v - u}{\Delta t}$
	the constant acceleration equations	$v = u + at$ $s = ut + \frac{1}{2}at^2$ $s = vt - \frac{1}{2}at^2$ $v^2 = u^2 + 2as$ $s = \frac{1}{2}(v + u)t$
1B	Newton's second law of motion	$F_{net} = ma$
	Newton's third law of motion	$F_{A\ on\ B} = -F_{B\ on\ A}$
	force due to gravity	$F_g = mg$
1C	components of gravity on inclined planes	$F_{g\parallel} = mg\sin(\theta)$ $F_{g\perp} = mg\cos(\theta)$
1E	circular speed	$v = \frac{2\pi r}{T}$
	centripetal force	$F_{net} = \frac{mv^2}{r} = \frac{4\pi^2 rm}{T^2}$
	centripetal acceleration	$a = \frac{v^2}{r} = \frac{4\pi^2 r}{T^2}$
1F	design angle	$\theta = \tan^{-1}\left(\frac{v^2}{rg}\right)$
	design speed	$v = \sqrt{rg\tan(\theta)}$
	tension in a conical pendulum	$T = \frac{mv^2}{r\sin(\theta)} = \frac{mg}{\cos(\theta)} = \sqrt{(mg)^2 + \left(\frac{mv^2}{r}\right)^2}$
1G	velocity when normal force is zero	$v = \sqrt{gr}$ when $F_N = 0$

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1I	momentum	$p = mv$
	conservation of momentum	$\sum p_i = \sum p_f$
	impulse	$I = \Delta p = m\Delta v = F\Delta t$
2A	kinetic energy	$KE = \frac{1}{2}mv^2$
	work	$W = \Delta E = Fs$
	power	$P = \frac{\Delta E}{\Delta t} = \frac{W}{\Delta t}$
2C	gravitational potential energy	$\Delta GPE = mg\Delta h$
2D	Hooke's law	$F_s = -k\Delta x$
	strain potential energy	$SPE = \frac{1}{2}k(\Delta x)^2$
3A	Newton's law of universal gravitation	$F_g = G\frac{m_1 m_2}{r^2}$
	gravitational field strength	$g = G\frac{M}{r^2}$
	inverse square law for gravitation	$g_2 = g_1\left(\frac{r_1}{r_2}\right)^2$
3C	orbital speed	$v = \sqrt{\frac{GM}{r}}$
	Kepler's third law	$4\pi^2 r^3 = GMT^2$
4A	electric force	$F = k\frac{q_1 q_2}{r^2} = qE$
	electric field strength due to a point charge	$E = k\frac{Q}{r^2}$
	inverse square law for electric fields	$E_2 = E_1\left(\frac{r_1}{r_2}\right)^2$
	electric field strength between charged parallel plates	$E = \frac{V}{d}$

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	work in an electric field	$W = qEd = qV$
	energy transformation of a charge moving between charged parallel plates	$\frac{1}{2}m(\Delta v)^2 = qV$
4C	magnetic force on a charged particle	$F = qvB$
	magnetic force on a current-carrying wire	$F = nBIL$
	radius of a charged particle in a magnetic field	$r = \frac{mv}{qB}$
5A	magnetic flux	$\Phi_B = B_\perp A$
	electromotive force (EMF)	$\varepsilon = -N\frac{\Delta\Phi_B}{\Delta t}$
5C	frequency	$f = \frac{1}{T}$
6A	Ohm's law	$V = IR$
	power (electricity)	$P = VI = I^2R = \frac{V^2}{R}$
	resistors in series	$R_{eq} = R_1 + R_2 + ... + R_n$
6B	RMS voltage	$V_{RMS} = \frac{1}{\sqrt{2}}V_{peak}$
	RMS current	$I_{RMS} = \frac{1}{\sqrt{2}}I_{peak}$
	ideal transformer ratios	$\frac{V_1}{V_2} = \frac{N_1}{N_2} = \frac{I_2}{I_1}$
7A	wave equation	$v = f\lambda$
7B	path difference for constructive interference	$p.d. = n\lambda$, where $n = 0, 1, 2, ...$
	path difference for destructive interference	$p.d. = \left(n + \frac{1}{2}\right)\lambda$, where $n = 0, 1, 2, ...$
7C	standing wave wavelength	$\lambda = \frac{2L}{n}$
	standing wave frequency	$f = \frac{nv}{2L}$

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7D	diffraction ratio	$diffraction \propto \frac{\lambda}{w}$
8B	fringe spacing	$\Delta x = \frac{\lambda L}{d}$
9C	energy of light	$E_{light} = hf$
	maximum kinetic energy of photoelectrons	$KE_{max} = hf - \phi$
	threshold frequency	$\phi = hf_0$
9D	photon energy	$E_{ph} = hf = \frac{hc}{\lambda}$
10A	de Broglie wavelength	$\lambda = \frac{h}{p}$
	photon energy and momentum	$E_{ph} = pc$
10B	atomic energy transitions	$E_{ph} = \Delta E$
11B	the Lorentz factor	$\gamma = \frac{1}{\sqrt{1 - \frac{v^2}{c^2}}}$
	time dilation	$t = t_0\gamma$
	length contraction	$L = \frac{L_0}{\gamma}$
11D	total mass-energy	$E_{tot} = \gamma mc^2$
	rest mass-energy	$E_0 = mc^2$
	relativistic kinetic energy	$KE = (\gamma - 1)mc^2$
	mass-energy conversion	$\Delta E = \Delta mc^2$
12D	gradient of a straight line	$gradient = \frac{rise}{run} = \frac{y_2 - y_1}{x_2 - x_1}$

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Constants

1B	acceleration due to gravity at Earth's surface	$g = 9.8\ \text{m s}^{-2}$
3A	universal gravitational constant	$G = 6.67 \times 10^{-11}\ \text{N m}^2\ \text{kg}^{-2}$
	mass of Earth	$M_E = 5.98 \times 10^{24}\ \text{kg}$
	radius of Earth	$R_E = 6.37 \times 10^{6}\ \text{m}$
4A	Coulomb constant	$k = 8.99 \times 10^{9}\ \text{N m}^2\ \text{C}^{-2}$
	mass of the electron	$m_e = 9.1 \times 10^{-31}\ \text{kg}$
	magnitude of the charge of the electron	$e = 1.6 \times 10^{-19}\ \text{C}$
8A	speed of light in a vacuum	$c = 3.0 \times 10^{8}\ \text{m s}^{-1}$
10A	Planck's constant	$h = 6.63 \times 10^{-34}\ \text{J s}$ $h = 4.14 \times 10^{-15}\ \text{eV s}$

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Acknowledgements

Images

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