PHYSICS

VCE UNITS 1 AND 2

1

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Contents

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Physics 1 VCE Units 1 and 2 has the following features.

A list of skills and knowledge, which draws on students' prior learning

An overview of the Key knowledge and outcomes addressed in this chapter

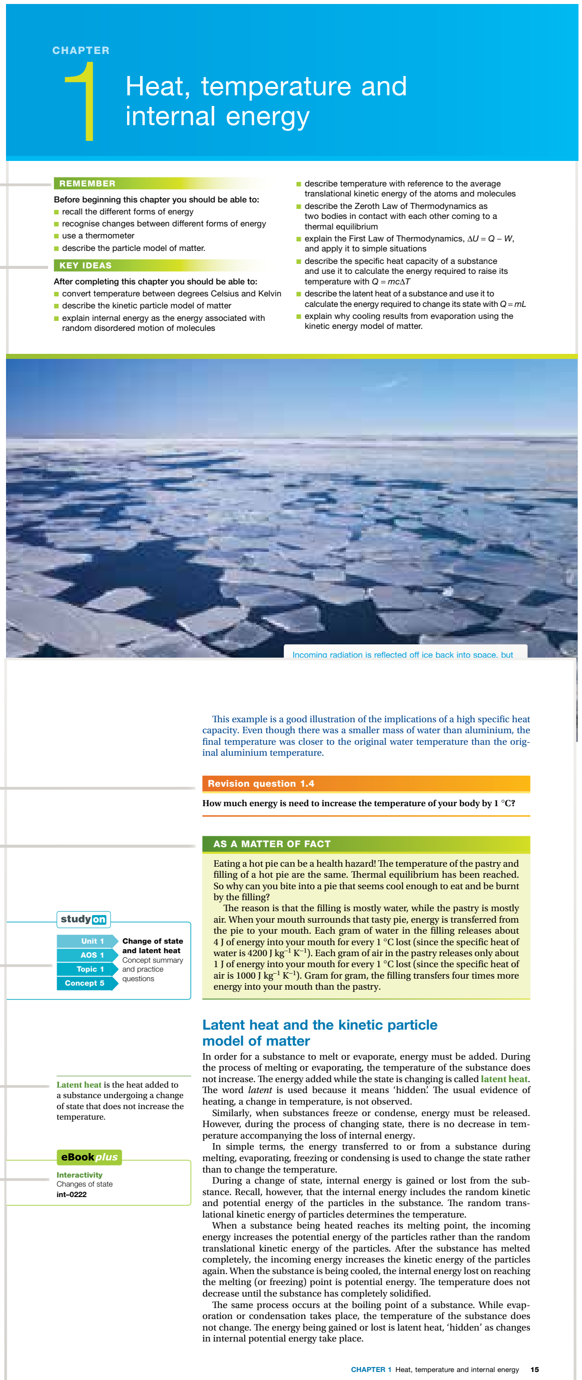
Sample problems with worked solutions to enhance understanding. These are often followed by revision questions.

As a matter of fact and *Physics in focus* panels to highlight applications of physics, show relevance and add interest

References to studyON Concept summary encapsulate key knowledge and provide questions with answers and worked solutions to reinforce learning.

Definitions and formulae to summarise key knowledge

eLessons, interactivities, weblinks and eModelling Excel spreadsheets that enhance understanding and bring concepts to life



CHAPTER 1

Heat, temperature and internal energy

REMEMBER

Before beginning this chapter you should be able to:
- recall the different forms of energy
- recognise changes between different forms of energy
- use a thermometer
- describe the particle model of matter.

KEY IDEAS

After completing this chapter you should be able to:
- convert temperature between degrees Celsius and Kelvin
- describe the kinetic particle model of matter
- explain internal energy as the energy associated with random disordered motion of molecules
- describe temperature with reference to the average translational kinetic energy of the atoms and molecules
- describe the Zeroth Law of Thermodynamics as two bodies in contact with each other coming to a thermal equilibrium
- explain the First Law of Thermodynamics, $\Delta U = Q - W$, and apply it to simple situations
- describe the specific heat capacity of a substance and use it to calculate the energy required to raise its temperature with $Q = mc\Delta T$
- describe the latent heat of a substance and use it to calculate the energy required to change its state with $Q = mL$
- explain why cooling results from evaporation using the kinetic energy model of matter.

Incoming radiation is reflected off ice back into space, but

This example is a good illustration of the implications of a high specific heat capacity. Even though there was a smaller mass of water than aluminium, the final temperature was closer to the original water temperature than the original aluminium temperature.

Revision question 1.4

How much energy is need to increase the temperature of your body by 1 °C?

AS A MATTER OF FACT

Eating a hot pie can be a health hazard! The temperature of the pastry and filling of a hot pie are the same. Thermal equilibrium has been reached. So why can you bite into a pie that seems cool enough to eat and be burnt by the filling?

The reason is that the filling is mostly water, while the pastry is mostly air. When your mouth surrounds that tasty pie, energy is transferred from the pie to your mouth. Each gram of water in the filling releases about 4 J of energy into your mouth for every 1 °C lost (since the specific heat of water is 4200 J kg^{-1} K^{-1}). Each gram of air in the pastry releases only about 1 J of energy into your mouth for every 1 °C lost (since the specific heat of air is 1000 J kg^{-1} K^{-1}). Gram for gram, the filling transfers four times more energy into your mouth than the pastry.

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Change of state and latent heat
Concept summary and practice questions

Latent heat and the kinetic particle model of matter

In order for a substance to melt or evaporate, energy must be added. During the process of melting or evaporating, the temperature of the substance does not increase. The energy added while the state is changing is called **latent heat**. The word *latent* is used because it means 'hidden'. The usual evidence of heating, a change in temperature, is not observed.

Similarly, when substances freeze or condense, energy must be released. However, during the process of changing state, there is no decrease in temperature accompanying the loss of internal energy.

In simple terms, the energy transferred to or from a substance during melting, evaporating, freezing or condensing is used to change the state rather than to change the temperature.

During a change of state, internal energy is gained or lost from the substance. Recall, however, that the internal energy includes the random kinetic and potential energy of the particles in the substance. The random translational kinetic energy of particles determines the temperature.

When a substance being heated reaches its melting point, the incoming energy increases the potential energy of the particles rather than the random translational kinetic energy of the particles. After the substance has melted completely, the incoming energy increases the kinetic energy of the particles again. When the substance is being cooled, the internal energy lost on reaching the melting (or freezing) point is potential energy. The temperature does not decrease until the substance has completely solidified.

The same process occurs at the boiling point of a substance. While evaporation or condensation takes place, the temperature of the substance does not change. The energy being gained or lost is latent heat, 'hidden' as changes in internal potential energy take place.

Latent heat is the heat added to a substance undergoing a change of state that does not increase the temperature.

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Interactivity
Changes of state
int–0222

CHAPTER 1 Heat, temperature and internal energy 15 studyON topic tests have additional multiple choice, short answer and extended response questions, that are different to the end of chapter review questions.

Chapter summaries give a detailed overview of key knowledge.

Review questions reinforce understanding and are divided by headings to make content easy to identify.

Chapter review

studyon
Unit 1
AOS 1
Topic 1
Heat, temperature and internal energy
Sit Topic test

Summary

- A thermometer measures temperature, and various properties of materials can be used to make one.
- There are different temperature scales, with Celsius and Kelvin being the common ones. Temperatures in one scale can be converted to any other.
- The kinetic particle model of matter explains heat phenomena.
- Internal energy is the energy associated with the random movement of molecules and it comes in many forms, including translational kinetic energy, rotational and vibrational kinetic energy, and potential energy.
- Temperature is a measure of the average translational kinetic energy of the atoms and molecules in a substance.
- Objects at different temperatures, if placed in contact, will reach a common temperature. This process is called thermal equilibrium and is described as the Zeroth Law of Thermodynamics.
- The First Law of Thermodynamics states that if energy is transferred to or from a system, then the total energy must be conserved, with any changes in the internal energy of the system given by $\Delta U = Q - W$, where ΔU is the change in internal energy, Q is the heat added to the system and W is the work done by the system.
- The specific heat capacity, c, of a substance is the amount of energy required to increase the temperature of 1 kg of the substance by 1 °C.
- When substances of different specific heat capacities and different temperatures are mixed, the final temperature can be determined by using the conservation of energy and the relationship $Q = mc\Delta T$ for each substance.
- The latent heat, L, of a substance is the amount of energy required to change the state from solid to liquid or liquid to gas of 1 kg of the substance. For a substance of mass m kg, the energy required is given by $Q = mL$.
- Evaporation of a liquid occurs because some of the faster particles have sufficient energy and speed to break free of the surface. The removal of these particles lowers the overall average kinetic energy of the remaining particles and consequently the temperature of the liquid.

Questions

Temperature conversion

1. Why is the Celsius scale of temperature commonly used rather than the Kelvin scale?
2. What is the main advantage of an absolute scale of temperature?
3. Estimate each of the following temperatures in Kelvin:
   (a) the maximum temperature in Melbourne on a hot summer's day
   (b) the minimum temperature in Melbourne on a cold, frosty winter's morning
   (c) the current room temperature
   (d) the temperature of cold tap water
   (e) the boiling point of water.
4. The temperature of very cold water in a small test tube is measured with a large mercury-in-glass thermometer. The temperature measured is unexpectedly high. Suggest a reason why this might be the case.

Particle model of matter

5. James Joule showed that mechanical energy could be transformed into the internal energy of a substance or object. The temperature of a nail, for example, can be raised by hitting it with a hammer. List as many examples as you can of the use of mechanical energy to increase the temperature of a substance or object.
6. Explain in terms of the kinetic particle model why a red-hot pin dropped into a cup of water has less effect on the water's temperature than a red-hot nail dropped into the same cup of water.
7. If today's maximum temperature was 14 °C and tomorrow's maximum temperature is expected to be 28 °C, will tomorrow be twice as hot? Explain your answer.
8. Explain why energy is transferred from your body into the cold sea while swimming even though you have less internal energy than the surrounding cold water.
9. Why can't you put your hand on your own forehead to estimate your body temperature?
10. It is said that thermometers indirectly measure the temperature of an object by measuring their own temperature. Explain this statement by referring to the concept of thermal equilibrium.
11. Adam says that 'A thermometer measures the average temperature between itself and the object it is measuring,' while Bob says that 'A thermometer directly measures the temperature of the object.' Explain why each is wrong.

First Law of Thermodynamics

12. For each of the following, calculate the values of Q, W and ΔU and indicate whether the temperature increases, decreases or stays the same.
   (a) A gas in a fixed container is heated by 500 J.

18 UNIT 1

Investigations section (also available in Word in the eBookPLUS) range from simple experiments to extended practical work.

INVESTIGATION 1.1

The good oil on heating

Switch on a hotplate to about half its maximum setting. While waiting for the temperature of the hotplate to stabilise, pour 50 mL of water at room temperature into a 100 mL beaker and measure its mass. Add cooking oil to an identical beaker so that the beaker and oil have the same total mass as the beaker of water. Record the temperature of each liquid.

Place the beaker of water on the hotplate and, while gently stirring, use a stopwatch to record the time taken for the temperature of the water to increase by 10 °C.

Place the beaker of cooking oil on the hot plate and, while gently stirring, record the time taken for the temperature of the cooking oil to increase by 10 °C.

1. Which liquid required more energy to increase its temperature by 10 °C?
2. Which liquid has the greater resistance to change in temperature?

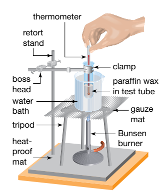
Repeat the procedure above using 100 mL of water at room temperature. Before commencing, however, predict how long it will take the water to increase its temperature by 10 °C.

3. By what factor did the amount of energy required to increase the temperature by 10 °C change when the amount of water was doubled?
4. Was the result consistent with your prediction? If not, suggest some reasons for the inconsistency.
5. If the cooking oil and water were supplied with the same amount of energy by heating for the same amount of time on the same flame, which would experience the greater increase in temperature?

INVESTIGATION 1.2

Cooling

Place some solid paraffin wax into a large test tube. Heat the test tube in a water bath until the temperature of the paraffin wax is about 80 °C.



A water bath is used to heat the paraffin wax.

CHAPTER 20

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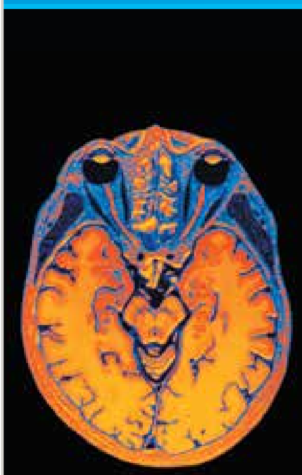
How is radiation used to maintain human health?



Using computer analysis, the data from images of 'slices' through the body can be combined to produce a three-dimensional image of the area under investigation.

REMEMBER

Before beginning this chapter, you should be able to:

- recall that all matter is made up of atoms
- explain the arrangement of particles in an atom, in particular that atoms have a central nucleus containing protons and neutrons
- recall that energy cannot be created, just transformed from one type to another or transferred from one object to another
- recall the features of a wave, including speed, frequency and wavelength
- distinguish between transverse and longitudinal waves
- outline the properties of waves, including reflection, refraction and scattering
- describe what is meant by critical angle and outline the conditions needed for total internal reflection
- recall the nature of alpha, beta and gamma radiation
- describe what is meant by half-life.

KEY IDEAS

After completing this chapter, you should be able to:

- describe how X-rays are produced
- describe the use of X-rays and CAT scans in medical imaging and diagnosis
- recognise and name radioisotopes that are used to obtain scans of organs
- describe the use of PET scans in medical diagnosis
- explain how MRI works and how it is used in medical diagnosis
- compare the information obtained from images produced by X-rays, CAT, PET and MRI scans
- make simple interpretations of images produced by ultrasound, X-rays, CAT, PET and MRI scans
- discuss the advantages and disadvantages of imaging techniques in medical diagnosis.

ions

The Introduction page, the Chapter summary and Review questions for each of the twelve Option chapters are available in one section. The full Option chapter with all content is available on the eBookPLUS.

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UNIT 1

AREA OF STUDY 1

AREA OF STUDY 2

AREA OF STUDY 3

CHAPTER

1 Heat, temperature and internal energy

REMEMBER

Before beginning this chapter you should be able to:

- recall the different forms of energy
- recognise changes between different forms of energy
- use a thermometer
- describe the particle model of matter.

KEY IDEAS

After completing this chapter you should be able to:

- convert temperature between degrees Celsius and Kelvin
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- describe the latent heat of a substance and use it to calculate the energy required to change its state with $Q = mL$
- explain why cooling results from evaporation using the kinetic energy model of matter.

Incoming radiation is reflected off ice back into space, but is absorbed by the water. How will increasing air and ocean temperatures change this scene?

Measuring temperature

Our bodies tell us when it is hot or cold. Our fingers warn us when we touch a hot object. However, for all that, our senses are not reliable.

Try this at home: Place three bowls of water in front of you. Put iced water in the bowl on the left, water hot enough for a bath in the bowl on the right, and room temperature water in the one in the middle. Place a hand in each of the two outer bowls, leave them there for a few minutes, then place both hands in the middle bowl. As you would expect, your left hand tells you the water is warmer, while your right hand tells you it is colder.

studyon

Unit 1	Temperature scales
AOS 1	Concept summary
Topic 1	and practice
Concept 1	questions

Thermometers were designed as a way to measure temperature accurately. A good thermometer needs a material that changes in a measurable way as its temperature changes. Many materials, including water, expand when heated, so the first thermometer, built in 1630, used water in a narrow tube with a filled bulb at the bottom. The water rose up the tube as the bulb was warmed.

German physicist Daniel Fahrenheit replaced the water with mercury in 1724. Liquid thermometers now use alcohol with a dye added. Fahrenheit developed a scale to measure the temperature, using the lowest temperature he could reach, an ice and salt mixture, as zero degrees, and the temperature of the human body as 100 degrees. Fahrenheit also showed that a particular liquid will always boil at the same temperature. Swedish astronomer Anders Celsius developed another temperature scale in 1742, which is the one we use today. Celsius used melting ice and steam from boiling water to define 0 °C and 100 °C for his scale.

A third temperature scale was proposed in 1848 by William Thomson, later to be ennobled as Lord Kelvin. He proposed the scale based on the better understanding of heat and temperature that had developed by that time (see page 10). This scale uses the symbol 'K' to stand for 'Kelvin'.

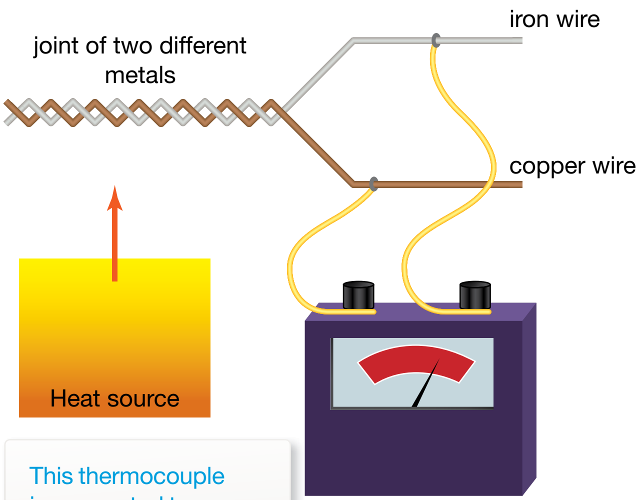
TABLE 1.1 Some temperatures on the Kelvin and Celsius scales

Event	Temperature	
	K	°C
Absolute zero	0	–273
Helium gas liquefies	4	–269
Lead becomes a superconductor	7	–266
Nitrogen gas liquefies	63	–210
Lowest recorded air temperature on the Earth's surface (Vostok, Antarctica)	184	–89
Mercury freezes	234	–39
Water freezes	273	0
Normal human body temperature	310	37
Highest recorded air temperature on the Earth's surface (Death Valley, USA)	330	57
Mercury boils	630	357
Iron melts	1535	1262
Surface of the Sun	5778	5505

ODD FACT

The lowest temperature: In 2015, the temperature of a cloud of 100 000 rubidium atoms was reduced to 50×10^{-12} degrees Kelvin (above absolute zero). The average speed of the atoms was less than 70 micrometres per second.

Other materials, including gases and metals, also expand with temperature and are used as thermometers. A bimetallic strip is two lengths of different metals, usually steel and copper, joined together. The two metals expand at



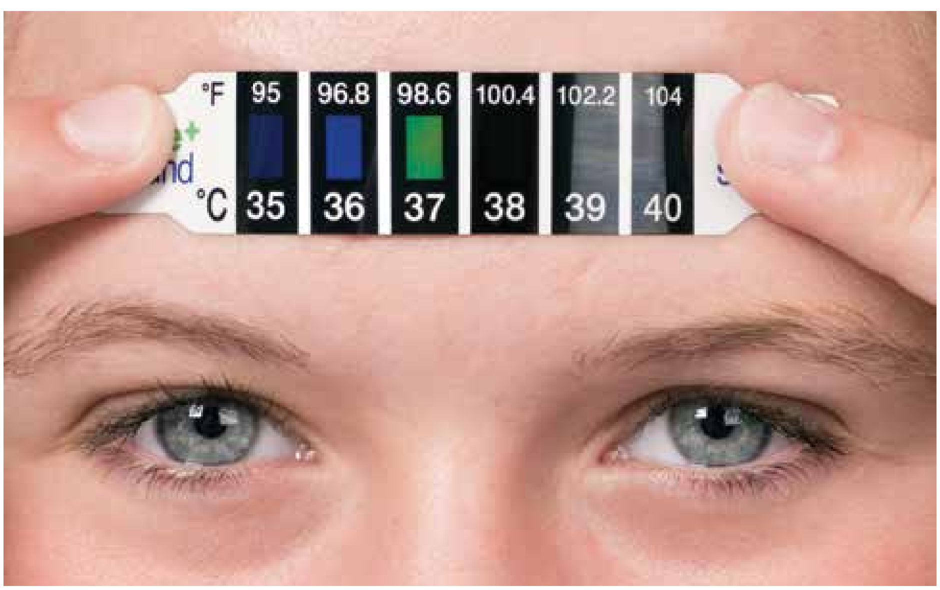
This thermocouple is connected to a voltmeter which reads differing voltages as the thermocouple changes temperature.

different rates, so the strip bends one way as the temperature rises, or the other as it cools. A bimetallic strip can be used as a thermometer, a thermostat or as a compensating mechanism in clocks.

Other properties that change with temperature that can be employed in designing a thermometer are:

- electrical resistance of metals, which increases with temperature
- electrical voltage from a thermocouple, which is two lengths of different metals with their ends joined; if one end is heated, a voltage is produced
- colour change; liquid crystals change colour with temperature
- colour emitted by a hot object; in steel making, the temperature of hot steel is measured by its colour.

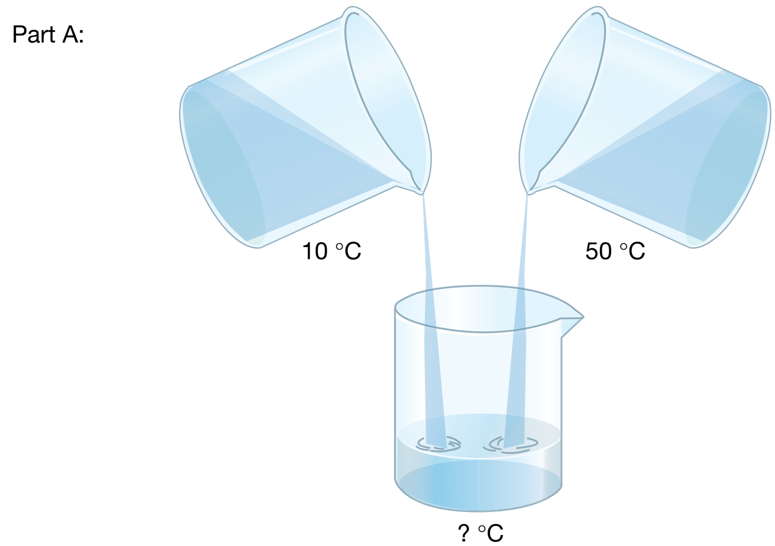
This steel is nearly 1000 °C and has recently been poured in a mould to shape it. The steel will continue to glow until it has cooled to about 400 °C.

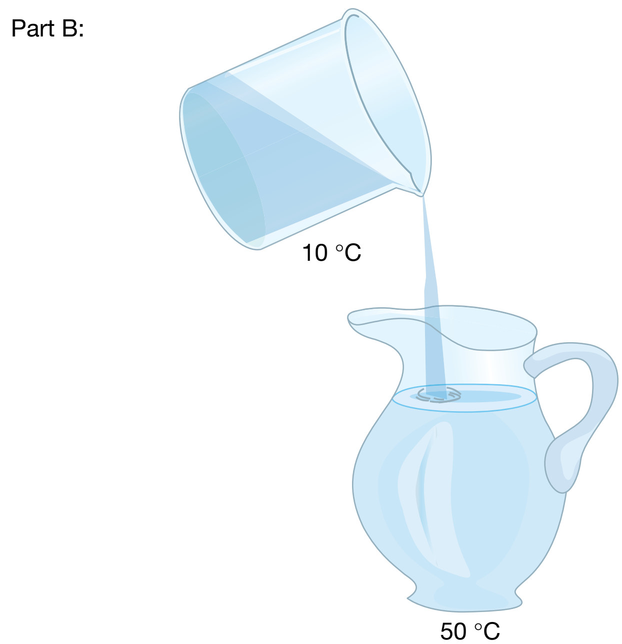


This liquid crystal thermometer indicates body temperature when the liquid crystals change colour. The thermometer is registering 37 °C.

What is the difference between heat and temperature?

If you mix a beaker of cold water at 10 °C with a beaker of hot water at 50 °C, you expect the final temperature to be about 30 °C. But if you mix the beaker of cold water with a jug of hot water, the final temperature will be a lot closer to 50 °C.





Obviously if an object has more mass, it contains more heat, but how are temperature and heat related?

Consider these two analogies to temperature and heat:

(a) If you drop a marble on your big toe from a height of 1 metre, you would notice it, but it would not hurt. However, if you dropped a 1 kg mass from only 10 cm it would hurt.

The height is to temperature as the impact is to heat.

(b) If you rub your shoes across a carpet, you can generate a voltage as high as 10 000 volts, but the electric shock is no more than a twitch. However, a 6-volt car battery can deliver a charge to start the engine.

The voltage is to temperature as the spark is to heat.

These analogies don't really help to explain what heat is. If an object cools down, there seems to be no physical difference other than the drop in temperature. The object does not weigh less because it has lost heat! What is being transferred when a hot object warms up a cold object?

In 1798 Benjamin Thompson, later to be called Count Rumford, conducted an experiment on the nature of heat. The barrel of a cannon is made by drilling a cylindrical hole in a solid piece of metal. Rumford observed that metal and the drill became quite hot. He devised an experiment to investigate the source of the heat and how much heat is produced. Rumford put the drill and the end of the cannon in a wooden box filled with water. He measured the mass of water and the rate at which the temperature rose. He showed that the amount of heat produced was not related to the amount of metal that was drilled out. He concluded that the amount of heat produced depended only on the work done against friction. He said that heat was in fact a form of energy, not an invisible substance that is transferred from hot objects to cold objects. Instead a hot object had heat energy, in the same way as a moving object has **kinetic energy** or an object high off the ground has gravitational potential energy.

Kinetic energy is the energy associated with the movement of objects. Like all forms of energy, kinetic energy is a scalar quantity.

AS A MATTER OF FACT

Count Rumford was born Benjamin Thompson in Massachusetts in 1753. By the age of 16 he was conducting experiments on heat. By 1775, when the American War of Independence began, he was already a wealthy man and of some standing in his community. He joined the British side of the war, becoming a senior advisor. While with the army, he also investigated and published a paper on the force of gunpowder.

At the end of the war, he moved to England, where he was known as a research scientist. A few years later he moved to Bavaria, in what is now southern Germany, and spent 11 years there. He moved in royal circles and eventually became Bavaria's Army Minister, tasked with reorganising the army. As part of those duties, he investigated methods of cooking, heating and lighting. He developed a soup, now called Rumford's soup, as a nutritious ration for soldiers. He also used the soup to establish soup kitchens for the poor throughout Bavaria. For his services he was made a Count of the Holy Roman Empire, taking the name 'Rumford' from his birth place.

On return to England, his activities included: (i) redesigning an industrial furnace, which revolutionised the production of quicklime, a component of cement, and also used for lighting ('limelight'); (ii) redesigning the domestic fireplace to narrow the chimney at the hearth to increase the updraught, resulting in greater efficiency and no smoke coming back into the room; and (iii) inventing thermal underwear, a kitchen range and a drip coffeepot.

'Ten chemical elements were discovered at the Royal Institution and 15 Nobel Prize winners have worked there.'

With Joseph Banks and others, Rumford established the Royal Institution (RI) in London as a scientific research establishment with a strong emphasis on public education. Initial funding came from the 'Society for Bettering the Conditions and Improving the Comforts of the Poor,' with which Count Rumford was centrally involved. Famous scientists in its early years included Humphrey Davy and Michael Faraday. Fifteen Nobel Prize winners have worked at the RI, and 10 chemical elements were discovered there.

Revision question 1.1

Devise an experiment to investigate the heat generated when two hands are rubbed together.

Rumford's ideas about heat were not taken up for a few decades. But in 1840 James Prescott Joule conducted a series of experiments to find a quantitative link between mechanical energy and heat. In other words, how much energy is required to increase the temperature of a mass by 1 °C?

Joule used different methods and compared the results:

- Using gravity: A falling mass spins a paddle wheel in an insulated barrel of water, raising the temperature of the water.
- Using electricity: Mechanical work is done turning a dynamo to produce an electric current in a wire, which heats the water.
- Compressing a gas: Mechanical work is used to compress a gas, which raises the gas's temperature.
- Using a battery: Chemical reactions at the battery terminals produce a current, which heats the water.
- Using gravity: Measure the temperature of water at the top and bottom of a waterfall.

Joule obtained approximately identical answers for all methods. This confirmed heat as a form of energy. To honour his achievement, the SI unit of energy is the **joule** (J). The unit, joule, is used to measure the kinetic energy of a runner, the light energy in a beam, the chemical energy stored in a battery, the electrical energy in a circuit, the potential energy in a lift on the top floor and the heat energy when water boils.

The **joule** is the SI unit of work or energy. One joule is the energy expended when a force of 1 newton acts through a distance of 1 metre.

One joule is approximately the amount of energy needed to lift a 100 g apple through a height of 1 m. The usual metric prefixes make the use of the unit more convenient. For example:

1 kJ (kilojoule) = 10^3 J 1 MJ (megajoule) = 10^6 J 1 GJ (gigajoule) = 10^9 J

The chemical energy available from a bowl of breakfast cereal is usually hundreds of thousands of joules and is more likely to be listed on the packet in kilojoules. The amount of energy needed to boil an average kettle full of cold water is about 500 kJ.

Examples of 1 joule include:

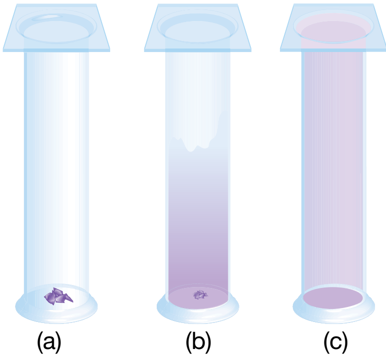
- the kinetic energy of a tennis ball moving at about 6 m/s
- the heat energy needed to raise the temperature of 1 gram of dry air by 1 °C
- the heat energy needed to raise the temperature of 1 gram of water by 0.24 °C
- the energy released when an apple falls 1 m to the ground
- the amount of sunlight hitting a square centimetre every 10 seconds when the Sun is directly above
- the amount of sound energy entering your eardrum at a loud concert over 3 hours
- the amount of electrical energy used by a plasma TV screen while on standby every 2.5 seconds
- the energy released by the combustion of 18 micrograms of methane.

Explaining heat: the kinetic theory of matter

The kinetic theory of matter, which considers all objects as assemblies of particles in motion, is an old one, first described by Lucretius in 55 AD. The kinetic view of matter was developed over time by Hooke, Bernoulli, Boltzmann and Maxwell.

The evidence for the existence of particles includes:

- gases and liquids diffuse, that is, a combination of two gases or two liquids quickly becomes a mixture, for example a dye spreading in water. Even solids can diffuse, if a sheet of lead is clamped to a sheet of gold, over time the metals merge to a depth of a few millimetres.
- the mixing of two liquids gives a final volume that is less than the sum of their original volumes
- a solid dissolves in a liquid.



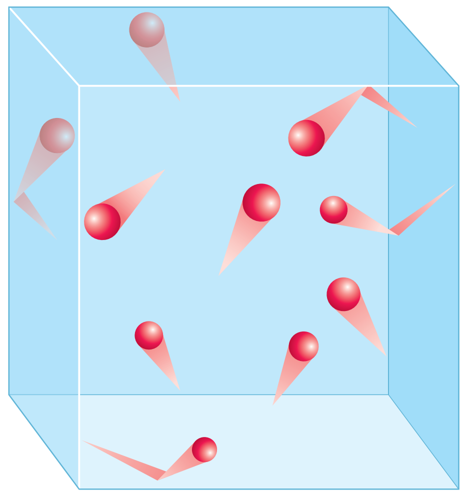
Iodine crystals sublimate (turn directly into a gas) when heated. (a) This diagram shows a gas jar with iodine crystals. (b) As the crystals warm up, they produce a purple gas that diffuses throughout the jar. (c) After a long period of time, the crystals have completely sublimated.

The kinetic theory of matter assumes that:

- all matter is made up of particles in constant, random and rapid motion
- there is space between the particles.

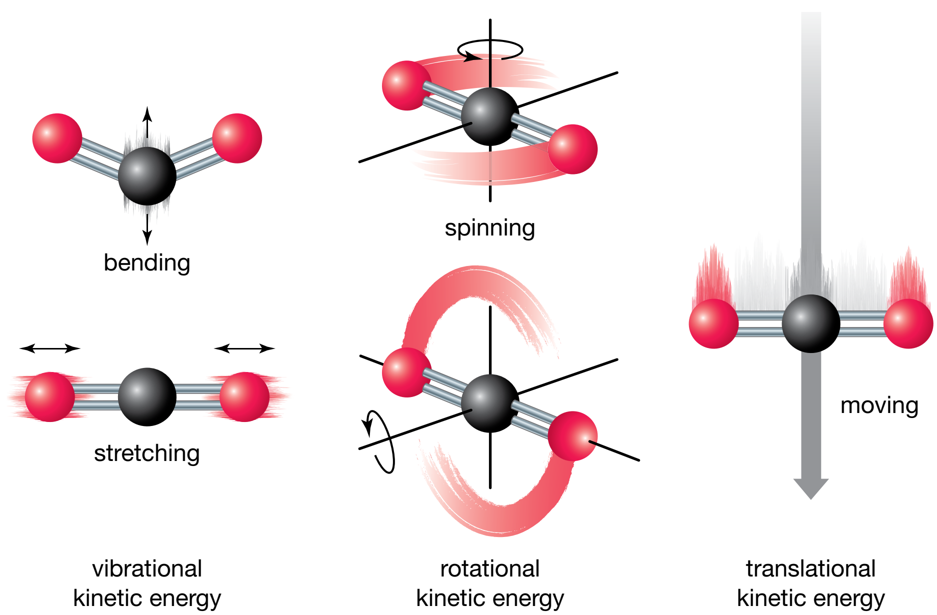
The energy associated with the motion of the particles in an object is called the internal energy of the object. The particles can move and interact in many ways, so there are a number of contributions to the internal energy. For example:

Gases: In a gas made up of single atoms, such as helium, the atoms move around, randomly colliding with each other and the walls of the container. So each atom has some translational kinetic energy.



Moving single atoms have translational kinetic energy.

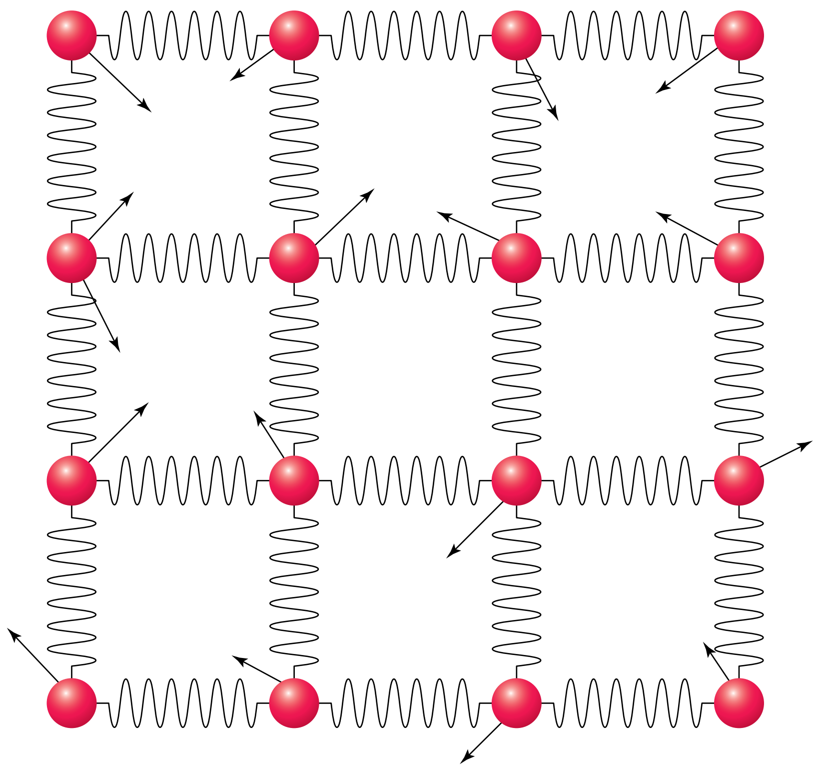
However, if the gas is made up of molecules with two or more atoms, the molecules can also stretch, contract and spin, so these molecules also have other types of kinetic energy called vibrational and rotational kinetic energy.



The movements of a molecule

Liquids: Like a gas, molecules in a liquid are free to move, but within the confines of the surface of the liquid. There is some attraction between molecules, which means there is some energy stored as molecules approach each other. Stored energy is called potential energy. It is the energy that must be overcome for a liquid to evaporate or boil.

Solids: In a solid, atoms jiggle rather than move around. They have kinetic energy, but they also have a lot of potential energy stored in the strong attractive force that holds the atoms together. This means that a lot of energy is required to melt a solid.



Movement of atoms in a solid

TABLE 1.2

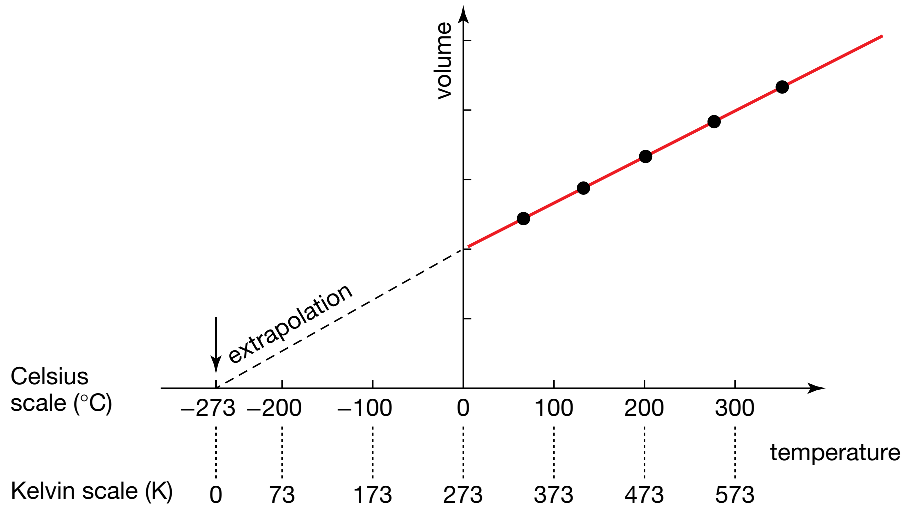
	Internal energy	
	Movement that is NOT related to temperature	**Movement that is related to temperature**
Atoms in a gas	None	Moving and colliding
Molecules in a gas	Spinning, stretching, compressing and bending	Moving and colliding
Molecules in a liquid	Spinning, stretching, compressing and bending	Moving and colliding
Atoms in a solid	Pulling and pushing	Jiggling
Energy types	Other types of kinetic energy, potential energy	Translational kinetic energy

Temperature is a measure of the average translational kinetic energy of particles.

Temperature is a measure of the average translational kinetic energy of particles. The other contributions to the internal energy do not affect the temperature. This becomes important when materials melt or boil because the added heat must go somewhere, but the temperature does not change.

The kinetic theory of matter is the origin of the Kelvin temperature scale. If temperature depends on the movement of particles, then the slower they move, the lower the temperature. When the particles stop moving, the temperature will be the lowest that is physically possible. This temperature was adopted as absolute zero. But how do we measure it and what is its value?

In the early 1800s gases were a good material to work with to explore the nature of matter. An amount of gas in a glass vessel could be heated and the variables of temperature, volume and pressure to keep the volume fixed could be easily measured. Joseph Gay-Lussac and Jacques Charles independently investigated how the volume of gases changed with temperature if they were kept under a constant pressure. They found that all gases kept at constant pressure expand or contract by 1/273 of their volume at 0 °C for each Celsius degree rise or fall in temperature.



From that result you can conclude that if you cooled the gas, and it stayed as a gas and did not liquefy, you could cool it to a low enough temperature that its volume reduced to zero. The temperature would be absolute zero. According to their experiments, absolute zero was –273 °C. Nowadays more accurate experiments put the value at –273.15 °C.

In degrees Kelvin, absolute zero is 0 K. The increments in the Kelvin temperature scale are the same size as those in the Celsius scale, so if the temperature increased by 5 °C, it also increased by 5 K. The conversion formula between the two temperature scales is:

$$\text{degrees Kelvin} = \text{degrees Celsius} + 273$$

Sample problem 1.1

What is the Kelvin temperature at which ice melts?

Solution: Ice melts at 0 °C, so the equivalent Kelvin temperature is 0 + 273 = 273 K.

Note: In 1968, the international General Conference on Weight and Measures decided that Kelvin temperatures do not use the ° symbol as do Celsius and Fahrenheit temperatures.

Revision question 1.2

(a) Carbon dioxide sublimates, that is, goes directly from solid to gas, at –78.5 °C. What is this temperature in degrees Kelvin?

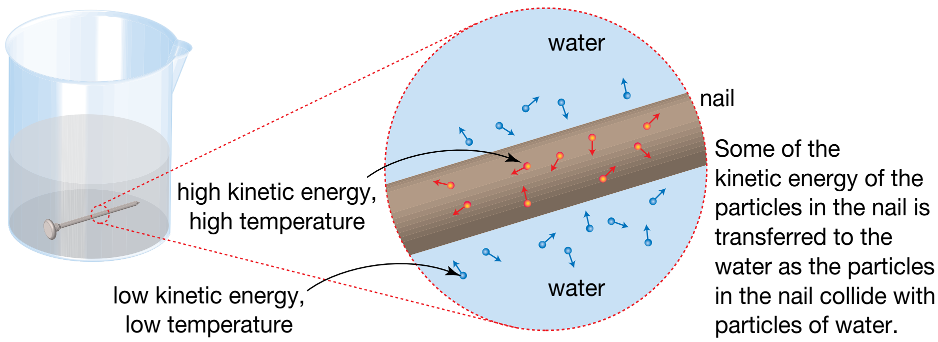
(b) The temperature of the surface of the Mars was measured by the Viking lander and ranged from 256 K to 166 K. What are the equivalent temperatures in degrees Celsius?

Thermal equilibrium

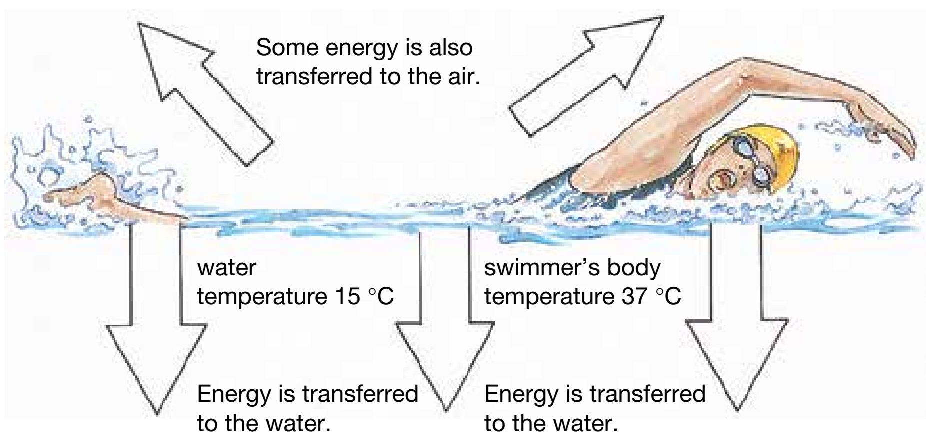
Thermal equilibrium occurs when the temperature of two regions is uniform.

Energy is always transferred from a region of high temperature to a region of lower temperature until both regions reach the same temperature. When the temperature is uniform, a state of **thermal equilibrium** is said to exist.

So when a hot nail is dropped into a beaker of cold water, energy will be transferred from the hot nail into the water even though the hot nail has less total internal energy than the water. When thermal equilibrium is reached, the temperature of both the water and the nail is the same. The particles of water and the particles in the nail have the same amount of random translational kinetic energy. The figure below shows how the kinetic particle model can be used to explain the direction of energy transfer in the beaker.



The particles in the nail have more kinetic energy (on average) than those that make up the water. They collide with the particles of water, losing some of their kinetic energy and increasing the kinetic energy of individual particles of water. The temperature of the surrounding water increases.



When you swim in a cold pool, energy is transferred from your body into the water. The water has much more total internal energy than your body because there is so much of it. However, the particles in your body have more random translational kinetic energy that can be transferred to the particles of cold water. Hopefully, you would not remain in the water long enough for thermal equilibrium to be reached.

What is implicit in the above discussion on thermal equilibrium and internal energy, is the subtle, but important, point made by James Clerk Maxwell that 'All heat is of the same kind.'

Laws of thermodynamics

Three laws of thermodynamics were progressively developed during the 19th century, but in the 20th century it became apparent that the principle of thermal equilibrium could be seen as the logical underpinning of these three laws. Consequently the Zeroth Law of Thermodynamics became accepted.

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Unit 1 | AOS 1 | Topic 1 | Concept 2

Zeroth Law of Thermodynamics
Concept summary and practice questions

Zeroth Law of Thermodynamics

Consider three objects: A, B and C. It is the case that A is in thermal equilibrium with B, and C is also in thermal equilibrium with B. Since 'All heat is of the same kind', it follows that A is in thermal equilibrium with C.

In practice this means that all three objects, A, B and C, are at the same temperature, and the law enables the comparison of temperatures.

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Unit 1 | AOS 1 | Topic 1 | Concept 3

First Law of Thermodynamics
Concept summary and practice questions

First Law of Thermodynamics

The **First Law of Thermodynamics** states that energy is conserved and cannot be created or destroyed. If there is an energy change in a system, all the energy must be accounted for. From a thermodynamics point of view, the internal energy of a substance and any change in it are a crucial part of this accounting exercise.

Consider a volume of air inside a balloon that is placed in direct sunlight. The air inside the balloon will get hotter and the balloon will expand slightly.

First Law of Thermodynamics:
$\Delta U = Q - W$
or $Q = U + W$
where
Q is the heat energy in joules
W is the work done in joules
U is the internal energy in joules.

The First Law of Thermodynamics says:

Change in the internal energy **of** the air = Heat energy applied **to** the air − Work done **by** the air

Using symbols: $\Delta U = Q - W$

The energy from the Sun heats the air inside the balloon, increasing the kinetic energy of the air molecules. The air molecules lose some of this energy as they repeatedly collide with the wall of the balloon, forcing it outwards.

The First Law of Thermodynamics applies to many situations: cylinders in a car engine, hot air balloons, food consumption, pumping up a tyre and the weather. Consequently, the word 'system' is often used as a generic name when discussing thermodynamics.

Note: The words in bold, '**of**', '**to**' and '**by**', and the minus sign are important in the equation as Q and W can be either positive or negative.

Guide:

If a system absorbs heat, e.g. energy from sunlight, then $Q > 0$.
If a system releases heat, e.g. when you sweat, then $Q < 0$.
If a system does work on the surroundings, e.g. hot balloon expands, then $W > 0$.
If the surroundings do work on the system, e.g. pumping up a tyre, then $W < 0$.

Sample problem 1.2

(a) A balloon is placed in direct sunlight. The sunlight supplies 200 joules of energy to the balloon. The air inside pushes out the balloon surface, doing 50 joules of work. By how much does the internal energy of the air inside change?

(b) While doing some heavy lifting, you do 2500 joules of work on the weights, while releasing 3000 joules of heat. By how much did your internal energy change?

Solution: (a) $Q = 200$ J, $W = 50$ J, so $\Delta U = 200 - 50 = 150$ J. The internal energy of the air in the balloon increased by 150 J.

(b) $Q = -3000$ J, $W = 2500$ J, so $\Delta U = -3000 - 2500 = -5500$ J. Your internal energy decreased by 5500 J.

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Unit 1 | AOS 1 | Topic 1 | Concept 4

Specific heat capacity
Concept summary and practice questions

Revision question 1.3

A block of ice is melted by 100 joules of energy. What is the size and the sign of W and ΔU?

Specific heat capacity

Once the temperature of materials could be accurately measured, it became apparent that, when heated, some materials increased in temperature more quickly than others. The property of the material that describes this phenomenon is called the specific heat capacity and is defined as the amount of energy required to increase the temperature of 1 kg of the substance by 1 °C (or K).

It takes more energy to increase the temperature of water by 1 °C than any other common substance. Water also needs to lose more energy to decrease in temperature. In simple terms, this means that water maintains its temperature well, cooling down and heating up more slowly than other materials.

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Investigation 1.1:
The good oil on heating
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TABLE 1.3 Specific heat capacity of some common substances

Substance	Specific heat capacity (J kg^{-1} K^{-1})
Helium	5193
Water	4200
Human body (average)	3500
Cooking oil	2800
Ethylene glycol (used in car ‘antifreeze’)	2400
Ice	2100
Steam	2000
Fertile topsoil	1800
Neon	1030
Air	1003
Aluminium	897
Carbon dioxide	839
Desert sand	820
Glass (standard)	670
Argon	520
Iron and steel (average)	450
Zinc	387
Copper	385
Lead	129

Specific heat capacities differ because of two factors:

- the different contributions to the internal energy by the forms of energy other than translational kinetic energy, and
- the varying mass of individual atoms and molecules.

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Interactivity
Thermal equilibrium
int–6390

The internal energy of single-atom gases, such as helium, neon and argon, consists of only translational kinetic energy. So the specific heat capacities should be the same if you account for their difference in mass. Look up the atomic weight for each gas and multiply it by each gas's specific heat capacity and compare your answers.

The quantity of energy, Q, transferred to or from a substance in order to change its temperature is directly proportional to three factors:

- the mass of the substance (m)
- the change in temperature (ΔT)
- the specific heat capacity of the substance (c).

Thus,

$$Q = mc\Delta T$$

Sample problem 1.3

(a) How much energy is needed to heat 8.0 L (about 8.0 kg) of water from a room temperature of 15 °C to 85 °C (just right for washing dishes)?

(b) A chef pours 200 g of cold water with a temperature of 15 °C into a hot aluminium saucepan with a mass of 250 g and a temperature of 120 °C. What will be the common temperature of the water and saucepan when thermal equilibrium is reached? Assume that no energy is transferred to or from the surroundings.

Solution: (a) $Q = mc\Delta T$

where

$c = 4200 \text{ J kg}^{-1} \text{ K}^{-1}$ (from table 1.2)

$m = 8.0 \text{ kg}$

$\Delta T = 70 \text{ K}$ (same change as 70 °C)

Therefore,

$Q = 8.0 \text{ kg} \times 4200 \text{ J kg}^{-1} \text{ K}^{-1} \times 70 \text{ K}$ (substituting data)

$= 2\,352\,000 \text{ J}$ (solving)

$= 2352 \text{ kJ}$ (using the most appropriate units)

$= 2.4 \times 10^3 \text{ kJ}.$

The energy needed is best expressed as 2400 kJ.

(b) The solution to this question relies on the following three factors.

1. Energy is transferred from the saucepan into the water until both the saucepan and the water reach the same temperature (T_f °C).
2. The amount of internal energy (Q_w) gained by the water will be the same as the amount of internal energy lost by the saucepan (Q_s).
3. The internal energy gained or lost can be expressed as $mc\Delta T$. (ΔT can be expressed in K or °C since change in temperature is the same in both units.)

Therefore,

$$Q_w = Q_s$$

$$m_w c_w \Delta T_w = m_s c_s \Delta T_s$$

where

change in temperature of the water, $\Delta T_w = T_f - 15$ °C

change in temperature of the saucepan, $\Delta T_s = 120$ °C $- T_f$.

$0.200 \text{ g} \times 4200 \text{ J kg}^{-1} \text{°C}^{-1} \times (T_f - 15 \text{ °C}) = 0.250 \text{ g} \times 900 \text{ J kg}^{-1} \text{°C}^{-1} \times (120 - T_f)$ (substituting data)

$840T_f - 12\,600 = 27\,000 - 225T_f$ (simplifying and expanding brackets)

$1065T_f = 39\,600$

$T_f = 37$ °C (solving)

The saucepan and water will reach a common temperature of 37 °C.

This example is a good illustration of the implications of a high specific heat capacity. Even though there was a smaller mass of water than aluminium, the final temperature was closer to the original water temperature than the original aluminium temperature.

Revision question 1.4

How much energy is need to increase the temperature of your body by 1 °C?

AS A MATTER OF FACT

Eating a hot pie can be a health hazard! The temperature of the pastry and filling of a hot pie are the same. Thermal equilibrium has been reached. So why can you bite into a pie that seems cool enough to eat and be burnt by the filling?

The reason is that the filling is mostly water, while the pastry is mostly air. When your mouth surrounds that tasty pie, energy is transferred from the pie to your mouth. Each gram of water in the filling releases about 4 J of energy into your mouth for every 1 °C lost (since the specific heat of water is 4200 J kg^{-1} K^{-1}). Each gram of air in the pastry releases only about 1 J of energy into your mouth for every 1 °C lost (since the specific heat of air is 1000 J kg^{-1} K^{-1}). Gram for gram, the filling transfers four times more energy into your mouth than the pastry.

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Unit 1 | AOS 1 | Topic 1 | Concept 5

Change of state and latent heat
Concept summary and practice questions

Latent heat and the kinetic particle model of matter

Latent heat is the heat added to a substance undergoing a change of state that does not increase the temperature.

In order for a substance to melt or evaporate, energy must be added. During the process of melting or evaporating, the temperature of the substance does not increase. The energy added while the state is changing is called **latent heat**. The word *latent* is used because it means 'hidden'. The usual evidence of heating, a change in temperature, is not observed.

Similarly, when substances freeze or condense, energy must be released. However, during the process of changing state, there is no decrease in temperature accompanying the loss of internal energy.

In simple terms, the energy transferred to or from a substance during melting, evaporating, freezing or condensing is used to change the state rather than to change the temperature.

During a change of state, internal energy is gained or lost from the substance. Recall, however, that the internal energy includes the random kinetic and potential energy of the particles in the substance. The random translational kinetic energy of particles determines the temperature.

When a substance being heated reaches its melting point, the incoming energy increases the potential energy of the particles rather than the random translational kinetic energy of the particles. After the substance has melted completely, the incoming energy increases the kinetic energy of the particles again. When the substance is being cooled, the internal energy lost on reaching the melting (or freezing) point is potential energy. The temperature does not decrease until the substance has completely solidified.

The same process occurs at the boiling point of a substance. While evaporation or condensation takes place, the temperature of the substance does not change. The energy being gained or lost is latent heat, 'hidden' as changes in internal potential energy take place.

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Interactivity
Changes of state
int-0222

The **specific latent heat of fusion** is the quantity of energy required to change 1 kilogram of a substance from a solid to a liquid without a change in temperature.

Specific latent heat of fusion

The **specific latent heat of fusion** is the quantity of energy required to change 1 kilogram of a substance from a solid to a liquid without a change in temperature. Note that the same quantity of energy is lost without a change in temperature during the change from a liquid to a solid. The specific latent heat of fusion of water is 334 kJ kg^{-1}.

The **specific latent heat of vaporisation** is the quantity of energy required to change 1 kilogram of a substance from a liquid to a gas without a change in temperature.

Specific latent heat of vaporisation

The **specific latent heat of vaporisation** is the quantity of energy required to change 1 kilogram of a substance from a liquid to a gas without a change in temperature. Note that the same quantity of energy is lost without a change in temperature during the change from a gas to a liquid. The specific latent heat of vaporisation of water is 2.3×10^3 kJ kg^{-1}.

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Investigation 1.2:
Cooling
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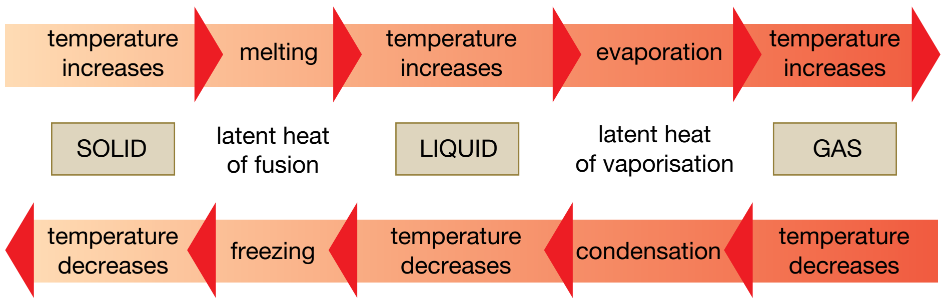
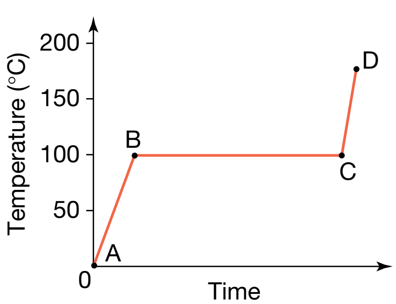


Changes of state and latent heat

Table 1.4 below details both the specific latent heat of fusion and the specific latent heat of vaporisation of a number of common substances.

TABLE 1.4 Specific latent heat of some common substances

Substance	Specific latent heat of fusion (J kg^{-1})	Specific latent heat of vaporisation (J kg^{-1})
Water	3.3×10^5	2.3×10^6
Oxygen	6.9×10^3	1.1×10^5
Sodium chloride	4.9×10^5	2.9×10^6
Aluminium	2.2×10^3	1.7×10^4
Iron	2.8×10^5	6.3×10^6



A heating curve for water being heated at a constant rate

The graph on the left shows how the temperature of water increases as it is heated at a constant rate. During the interval BC, the temperature is not increasing. The water is changing state. The energy transferred to the water is not increasing the random translational kinetic energy of water particles. Note that the gradient of the section AB is considerably less than the gradient of the section CD. What difference in the properties of water and steam does this reflect?

Algebraically, the quantity of energy, Q, required to change the state of a substance without a change in temperature can be expressed as:

$$Q = mL$$

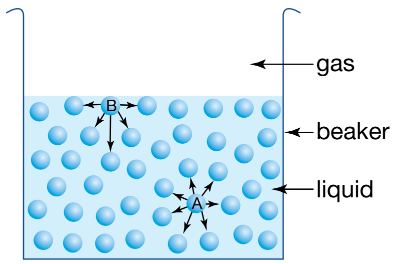
where

m = mass of the substance
L = specific latent heat of fusion or vaporisation.

Evaporation

Your skin is not completely watertight, which allows water from the skin and tissues beneath it to evaporate. The latent heat of vaporisation required for the water to change state from liquid to gas is obtained from the body, reducing its temperature. Evaporation of water from the mouth and lungs also takes place during the process of breathing. Even without sweating, the energy used to evaporate water in the body accounts for about 17% of the total heat transfer from the body to the environment.

Water evaporates even though its temperature is well below its boiling point. The temperature is dependent on the average translational kinetic energy of the water molecules. Those molecules with a kinetic energy greater than average will be moving faster than the others. Some of them will be moving fast enough to break the bonds holding them to the water and escape from the liquid surface. The escaping molecules obtained their additional energy from the rest of the liquid water, thus reducing its temperature.



Particle A experiences forces of attraction from the other surrounding particles in all directions. Particle B does not experience as many forces, so it will need less kinetic energy to escape the forces of attraction and evaporate.

AS A MATTER OF FACT

A burn caused by steam at 100 °C is considerably more serious than a burn caused by the same mass of boiling water. Each kilogram of hot steam transfers 2600 kJ of energy to your skin as it condenses to water at 100 °C. Each kilogram of newly condensed steam then transfers 4.2 kJ for each °C drop in temperature as it cools to your body temperature of about 37 °C. That's about 265 kJ. The total quantity of energy transferred by each kilogram of steam is therefore about 2865 kJ. A kilogram of boiling water would transfer 265 kJ of energy as it cooled to your body temperature.

Chapter review

Summary

- A thermometer measures temperature, and various properties of materials can be used to make one.
- There are different temperature scales, with Celsius and Kelvin being the common ones. Temperatures in one scale can be converted to any other.
- The kinetic particle model of matter explains heat phenomena.
- Internal energy is the energy associated with the random movement of molecules and it comes in many forms, including translational kinetic energy, rotational and vibrational kinetic energy, and potential energy.
- Temperature is a measure of the average translational kinetic energy of the atoms and molecules in a substance.
- Objects at different temperatures, if placed in contact, will reach a common temperature. This process is called thermal equilibrium and is described as the Zeroth Law of Thermodynamics.
- The First Law of Thermodynamics states that if energy is transferred to or from a system, then the total energy must be conserved, with any changes in the internal energy of the system given by $\Delta U = Q - W$, where ΔU is the change in internal energy, Q is the heat added to the system and W is the work done by the system.
- The specific heat capacity, c, of a substance is the amount of energy required to increase the temperature of 1 kg of the substance by 1 °C.
- When substances of different specific heat capacities and different temperatures are mixed, the final temperature can be determined by using the conservation of energy and the relationship $Q = mc\Delta T$ for each substance.
- The latent heat, L, of a substance is the amount of energy required to change the state from solid to liquid or liquid to gas of 1 kg of the substance. For a substance of mass m kg, the energy required is given by $Q = mL$.
- Evaporation of a liquid occurs because some of the faster particles have sufficient energy and speed to break free of the surface. The removal of these particles lowers the overall average kinetic energy of the remaining particles and consequently the temperature of the liquid.

Questions

Temperature conversion

1. Why is the Celsius scale of temperature commonly used rather than the Kelvin scale?
2. What is the main advantage of an absolute scale of temperature?
3. Estimate each of the following temperatures in Kelvin:
   (a) the maximum temperature in Melbourne on a hot summer's day
   (b) the minimum temperature in Melbourne on a cold, frosty winter's morning
   (c) the current room temperature
   (d) the temperature of cold tap water
   (e) the boiling point of water.
4. The temperature of very cold water in a small test tube is measured with a large mercury-in-glass thermometer. The temperature measured is unexpectedly high. Suggest a reason why this might be the case.

Particle model of matter

5. James Joule showed that mechanical energy could be transformed into the internal energy of a substance or object. The temperature of a nail, for example, can be raised by hitting it with a hammer. List as many examples as you can of the use of mechanical energy to increase the temperature of a substance or object.
6. Explain in terms of the kinetic particle model why a red-hot pin dropped into a cup of water has less effect on the water's temperature than a red-hot nail dropped into the same cup of water.
7. If today's maximum temperature was 14 °C and tomorrow's maximum temperature is expected to be 28 °C, will tomorrow be twice as hot? Explain your answer.
8. Explain why energy is transferred from your body into the cold sea while swimming even though you have less internal energy than the surrounding cold water.
9. Why can't you put your hand on your own forehead to estimate your body temperature?
10. It is said that thermometers indirectly measure the temperature of an object by measuring their own temperature. Explain this statement by referring to the concept of thermal equilibrium.
11. Adam says that 'A thermometer measures the average temperature between itself and the object it is measuring,' while Bob says that 'A thermometer directly measures the temperature of the object.' Explain why each is wrong.

First Law of Thermodynamics

12. For each of the following, calculate the values of Q, W and ΔU and indicate whether the temperature increases, decreases or stays the same.
   (a) A gas in a fixed container is heated by 500 J.

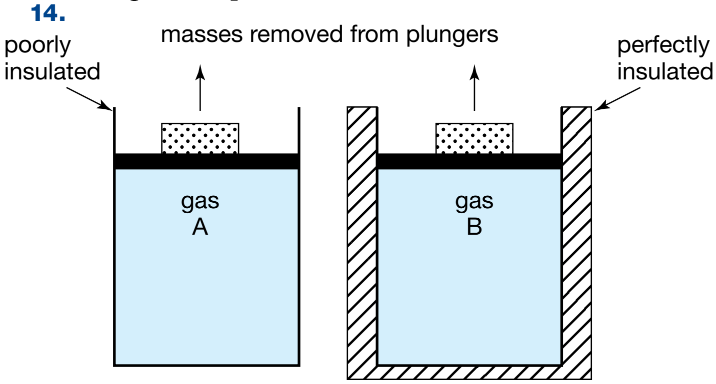
(b) A gas in a container with a flexible lid is cooled by ice with 250 J of energy extracted.

(c) A gas in a container with a plunger is squashed by a heavy mass moving down, losing 150 J of gravitational potential energy.

(d) A stretched rubber band at room temperature with 5 J of stored energy is released.

13. A can filled with a high-pressure gas has a balloon attached over the top. What happens to the temperature of the gas inside the can as you allow the gas to expand into the balloon?

14.



In the figure above, two beakers are filled with the same gas. A plunger is fitted so that no gas escapes; friction is negligible between the plunger and the beaker walls.

The block is removed from each plunger, the plunger moves upward.

(a) In each case, does the gas do work or is work done on the gas? Explain your reasoning in a few sentences.

(b) Is there a larger transfer of thermal energy as heat between Gas A and the surroundings or between Gas B and the surroundings? Explain your reasoning in a few sentences. Draw an arrow on each figure indicating the direction of thermal energy flow.

(c) For the expansion of Gas A, how do the work and heat involved in this process affect the internal energy of the gas? Explain your reasoning in a few sentences.

(d) For the expansion of Gas B, how do the work and heat involved in this process affect the internal energy of the gas? Explain your reasoning in a few sentences.

15. A barbecue uses gas from a gas bottle as its energy source. After the BBQ has been running a while, ice is noticed around the top of the gas bottle. Explain the physics principles behind this observation.

16. Two insulated containers are connected by a valve. The valve is closed. One container is filled with gas, the other is a vacuum. The valve is opened. Is there any change in temperature? Is there any change in the internal energy? What are the values of Q and W in this situation?

17. Consider these three scenarios then complete the table below, using either 0, – or +.

A. An insulated container, such as a thermos flask, has a piston that can be moved up and down without letting the air out. The piston is pushed down.

B. A metal tin with a lid is heated.

C. A metal tin with a sliding lid and a mass on top is heated.

	A	B	C
Heat (+ is in)			
Work (+ is out)			
ΔU			

Specific heat capacity

Use the table below to answer the following questions.

Substance	Specific heat capacity ($J\ kg^{-1}\ K^{-1}$)
Helium	5193
Water	4200
Human body (average)	3500
Cooking oil	2800
Ethylene glycol (used in car 'antifreeze')	2400
Ice	2100
Steam	2000
Fertile topsoil	1800
Neon	1030
Air	1003
Aluminium	897
Carbon dioxide	839
Desert sand	820
Glass (standard)	670
Argon	520
Iron and steel (average)	450
Zinc	387
Copper	385
Lead	129

18. The same hotplate is used to heat 50 g of ethylene glycol (used in car antifreeze) and 50 g of cooking oil. Both substances are heated for 2 minutes. Use the data in the table above to determine:

(a) which liquid needs more energy to raise its temperature by 1 °C

(b) which liquid will experience the greater increase in temperature.

19. The quantity of energy needed to increase the temperature of a substance is directly proportional to the mass, specific heat capacity and the change in temperature of the substance. If 200 kJ is used to increase the temperature of a particular quantity of a substance, how much energy would be needed to bring:

(a) twice as much of the substance through the same change in temperature?

(b) three times as much of the substance through a temperature change twice as great?

20. Use the table on page 19 to answer the following questions.
(a) Why is the specific heat capacity of the human body so high?
(b) Why is the specific heat capacity of desert sand so much lower than that of fertile topsoil?
(c) When heating water to boiling point in a saucepan, some of the energy transferred from the hotplate is used to increase the temperature of the saucepan. Which would you expect to gain the most energy from the hotplate: an aluminium, copper or steel saucepan?
(d) Make some general comments about the order of substances listed in the table on page 19.

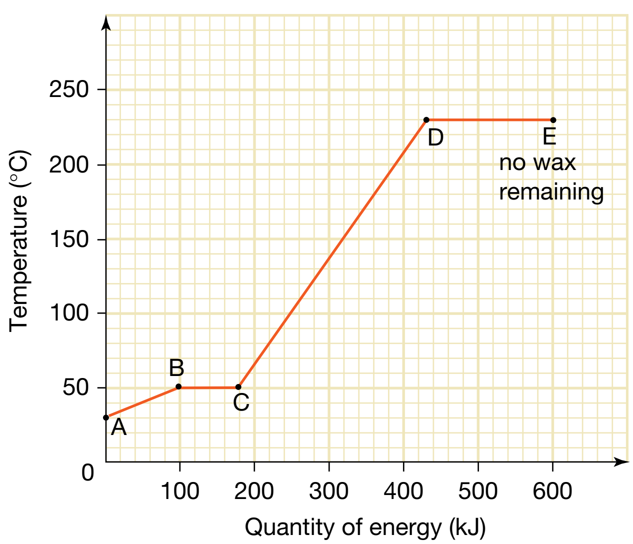
21. An 800 g rubber hot-water bottle that has been stored at a room temperature of 15 °C is filled with 1.5 kg of water at a temperature of 80 °C. Before being placed in a cold bed, thermal equilibrium between the rubber and water is reached. What is the common temperature of the rubber and water at this time? (Assume that no energy is lost to the surroundings. The specific heat capacity of rubber is 1700 J kg^{-1} K^{-1}. The specific heat capacity of water is 4200 J kg^{-1} K^{-1}.)

Latent heat

22. Use the data below to determine the quantity of energy needed to evaporate 500 g of water without a change in temperature.

Substance	Specific latent heat of fusion (J Kg^{-1})	Specific latent heat of vaporisation (J Kg^{-1})
Water	3.3×10^5	2.3×10^6

23. The graph below shows the heating curve obtained when 500 g of candle wax in solid form was heated from room temperature in a beaker of boiling water.



(a) What is the boiling point of the candle wax?
(b) During the interval BC, there is no increase in temperature even though heating continued. What was the energy transferred to the candle wax being used for during this interval?
(c) In which state of matter was the candle wax during the interval CD?
(d) Use the heating curve to determine the latent heat of fusion of candle wax.
(e) Which is higher: the specific heat capacity of solid candle wax or the specific heat capacity of liquid candle wax? Explain your answer.
(f) Explain in terms of the kinetic particle model what is happening during the interval DE.

24. How much energy does it take to completely convert 2 kg of ice at –5 °C into steam at 100 °C? Assume no energy loss to the surroundings.

25. How much ice at 0 °C could be melted with 1 kg of steam at 100 °C, assuming no loss of energy to the surroundings? Use the specific latent heat values quoted in table 1.4 on page 16. The specific heat capacity of water is 4200 J kg^{-1} K^{-1}.

26. Explain why vegetables cook faster by being steamed than boiled.

27. Why are burns caused by steam more serious than those caused by boiling water?

28. In hot weather, sweat evaporates from the skin. Where does the energy required to evaporate the sweat come from?

29. Explain the importance of keeping a lid on a simmering saucepan of water in terms of latent heat of vaporisation.

30. Explain in terms of the kinetic particle model why you can put your hand safely in a 300 °C oven for a few seconds, while if you touch a metal tray in the same oven your hand will be burned.

31. How does the evaporation of water cause a reduction in the temperature of the surrounding air?

32. Give two reasons why you feel cooler when the wind is blowing than you would in still air at the same temperature.

33. In humid weather, evaporation of perspiration takes place as it does in dry weather. However, the cooling effect is greatly reduced. Why?

CHAPTER

2 Energy in transit

Thermal imaging shows the temperature of these people. Their faces and hands are red and white as these areas are producing heat and are not covered by clothing.

REMEMBER

Before beginning this chapter you should be able to:

- describe the kinetic particle model of matter
- explain internal energy as the energy associated with random motion of molecules
- describe temperature with reference to the average translational kinetic energy of atoms and molecules.

KEY IDEAS

After completing this chapter you should be able to:

- describe the process of energy transfer by conduction, convection and radiation
- identify regions of the electromagnetic spectrum as radio, microwave, infra-red, visible, ultraviolet, x-ray and gamma waves
- compare the total energy, across the electromagnetic spectrum, emitted by objects at different temperatures
- describe the power radiated by objects of different temperatures using Stefan–Boltzmann Law: $P \propto T^4$
- calculate the peak wavelength of the re-radiated electromagnetic radiation from the Earth using Wien's Law: $\lambda_{max}T = \text{constant}$.

Transfer of energy

During heating and cooling, energy is always transferred from a region of high temperature to a region of lower temperature. There are many situations in which it is necessary to control the rate at which the energy is transferred.

- Warm-blooded animals, including humans, need to maintain their body temperature in hot and cold conditions. Cooling of the body must be reduced in cold conditions. In hot conditions, it is important that cooling takes place to avoid an increase in body temperature.
- Keeping your home warm in winter and cool in summer can be a costly exercise, both in terms of energy resources and money. Applying knowledge of how heat is transferred from one place to another can help you to find ways to reduce how much your house cools in winter and heats up in summer, thus reducing your energy bills.

Reducing heat transfer to and from buildings saves precious energy resources, and reduces gas and electricity bills.

Conduction is the transfer of heat through a substance as a result of collisions between neighbouring vibrating particles.

Convection is the transfer of heat in a fluid (a liquid or gas) as a result of the movement of particles within the fluid.

Radiation is heat transfer without the presence of particles.

Insulators are materials that are poor conductors of heat.

- The storage of many foods in cold temperatures is necessary to keep them from spoiling. In warm climates most beverages are enjoyed more if they are cold. The transfer of heat from the warmer surroundings needs to be kept to a minimum.

There are three different processes through which energy can be transferred during heating and cooling: **conduction**, **convection** and **radiation**.

study on

Unit 1	**Conduction**
AOS 1	Concept summary and practice questions
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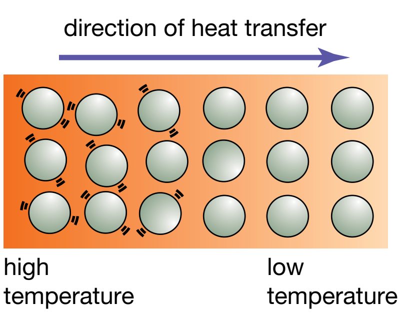
Conduction

Conduction is the transfer of heat through a substance as a result of collisions between neighbouring vibrating particles. The particles in the higher temperature region have more random kinetic energy than those in the lower temperature region. As shown in the figure at left, the more energetic particles collide with the less energetic particles, giving up some of their kinetic energy. This transfer of kinetic energy from particle to particle continues until thermal equilibrium is reached. There is no net movement of particles during the process of conduction.

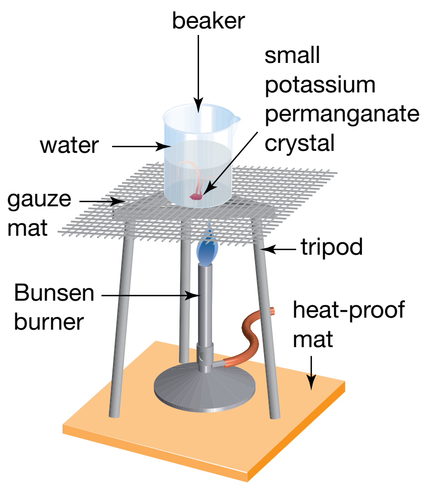


Conduction is the transfer of heat due to collisions between neighbouring particles.

Solids are better conductors of heat than liquids and gases. In solids, the particles are more tightly bound and closer together than in liquids and gases. Thus, kinetic energy can be transferred more quickly. Metals are the best conductors of heat because free electrons are able to transfer kinetic energy more readily to other electrons and atoms.

Materials that are poor conductors are called **insulators**. Materials such as polystyrene foam, wool and fibreglass batts are effective insulators because they contain pockets of still air. Air is a very poor conductor of heat. If air is free to move, however, heat can be transferred by a different method — convection.

A **convection current** is a movement of particles during the transfer of heat through a substance.



Purple particles from a crystal of potassium permanganate carefully placed at the bottom of the beaker are forced around the beaker by convection currents in the heated water.

studyon

Unit 1
AOS 1
Topic 2
Concept 4

Convection
Concept summary and practice questions

Convection

Convection is the transfer of heat through a substance as a result of the movement of particles between regions of different temperatures. Convection takes place in liquids and gases where particles are free to move around. In solids, the particles vibrate about a fixed position and convection does not occur.

The movement of particles during convection is called a **convection current**. Faster moving particles in hot regions rise while slower moving particles in cool regions fall. The particles in the warm water near the flame in the figure on the left are moving faster and are further apart than those in the cooler water further from the flame. The cooler, denser water sinks, forcing the warm, less dense water upwards. This process continues as the warm water rises, gradually cools and eventually sinks again, replacing newly heated water.

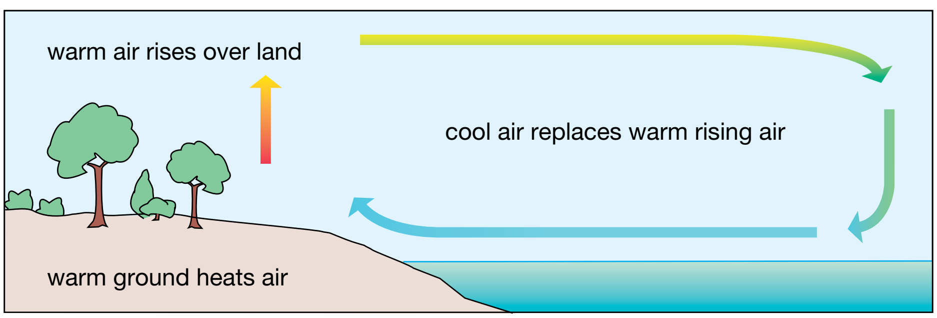
Convection currents are apparent in ovens that do not have fans. As the air circulates, the whole oven becomes hot. However, the top part of the oven always contains the hottest, least dense air. As the air cools, it sinks and is replaced by less dense hot air for as long as the energy source at the bottom of the oven remains on. Fans can be used to push air around the oven, providing a more even temperature.

Home-heating systems use convection to move warm air around. Ducted heating vents are, where possible, located in the floor. Without the aid of powerful fans, the warm air rises, circulates around the room until it cools and sinks, being replaced with more warm air. In homes built on concrete slabs, ducted heating vents are in the ceiling. Fans are necessary to push the warm air downwards so that it can circulate more efficiently.

In summer, loose fitting clothing is more comfortable because it allows air to circulate. Thus, heat can be transferred from your body by convection as the warm air near your skin rises and escapes upwards.

Hot summer days

During hot summer days, radiant energy from the Sun heats the land and sea. The land, however, has a lower specific heat capacity than the sea, and soon has a higher temperature than the water. The air near the ground becomes hot as a result of conduction. As this air gets hot, it expands, becoming less dense than the cooler, denser air over the sea. The air over the sea rushes in towards the land, replacing the rising warm air, causing what is known as a sea breeze. Coastal areas generally experience less extreme maximum temperatures than inland areas as a result of sea breezes.



A sea breeze is caused by convection currents resulting from temperature differences between the land and the sea.

On the south coast of Australia, strong northerly winds blowing from the land will occasionally prevent convection from causing a sea breeze. When this happens in summer, temperatures can soar — often above 40 °C.

During the night, if the land becomes colder than the sea, convection currents push cool air from the land towards the sea, creating a land breeze.

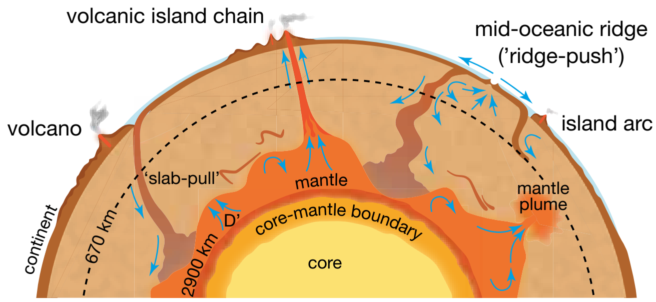
Convection inside the Earth

Energy transfer by convection is common in gases and liquids, but it can also occur in solids under the right conditions. The high temperatures, about 2000 °C, and pressures in the Earth's mantle are enough to make solid rock move, only very slowly of course. The speed of the rock movement is a few centimetres per year.

The heat energy in the Earth comes from the radioactive decay of elements such as uranium. The heat energy is not evenly distributed and hot spots occur under the mantle. The hot lighter rock at these points slowly rises, while denser rock at colder spots slowly sinks. This sets up a convection cell in the Earth's mantle with the surface crust moving horizontally across the Earth.

The molten rock wells up at mid-ocean ridges and moves out. The rock eventually meets the edge of a continental plate and cools further, becoming denser, then sinks back towards the mantle in a deep ocean trench.

New crust is formed at a ridge and returns to the mantle at a trench.



Radiation

The **electromagnetic spectrum** is the full range of wavelengths of all electromagnetic waves.

Heat can be transferred without the presence of particles by the process of radiation. All objects with a temperature above absolute zero (0 K) emit small amounts of **electromagnetic radiation**. Visible light, microwaves, infra-red radiation, ultraviolet radiation and x-rays are all examples of electromagnetic radiation. All electromagnetic radiation is transmitted through empty space at a speed of 3.0×10^8 m s^{-1}, which is most commonly known as the speed of light.

Electromagnetic radiation can be absorbed by, reflected from or transmitted through substances. Scientists have used a wave model to explain much of the behaviour of electromagnetic waves. These electromagnetic waves transfer energy, and reflect and refract in ways that are similar to waves on water.

What distinguishes the different types of electromagnetic radiation from each other is:

- their wavelength (the distance the wave takes to repeat itself)
- their frequency (the number of wavelengths passing every second)
- the amount of energy they transfer.

These properties in turn determine their ability to be transmitted through transparent or opaque objects, their heating effect and their effect on living tissue.

The figure below shows the electromagnetic spectrum and demonstrates that higher energy radiation corresponds to low wavelength.

study on

Unit 1	Radiation as heat transfer
AOS 1	Concept summary and practice questions
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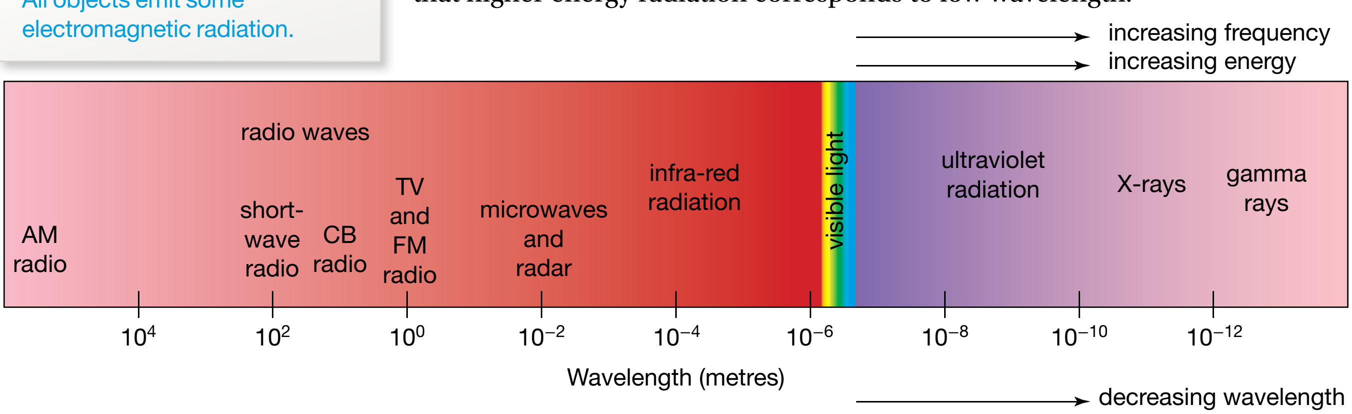
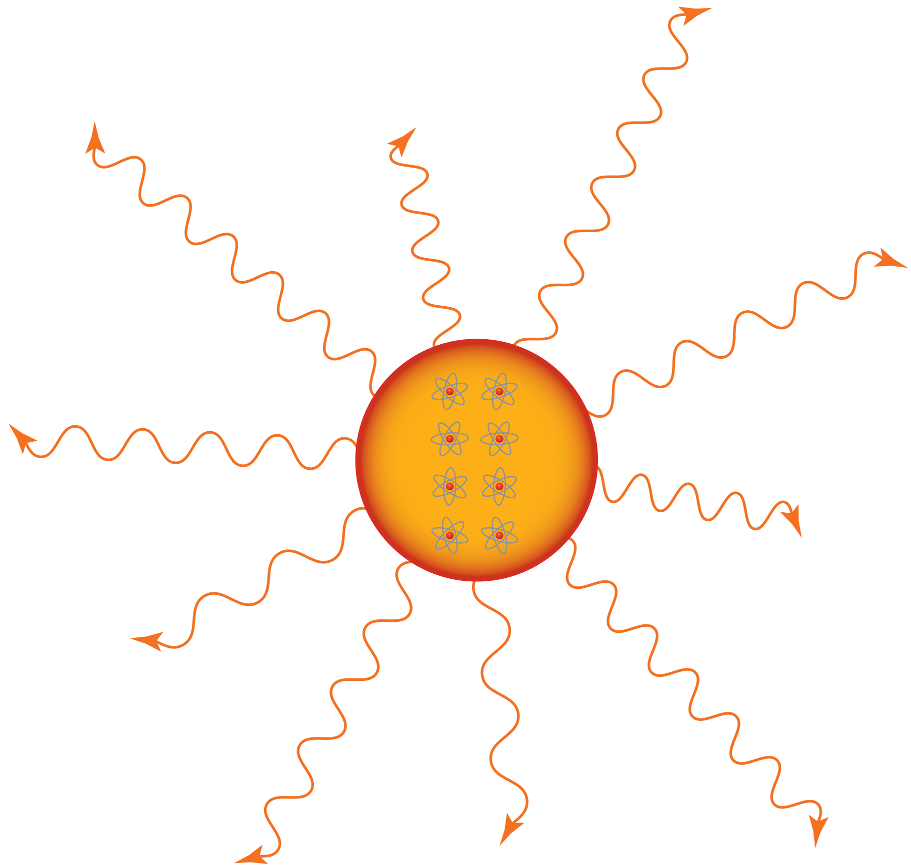
Concept 6	

The electromagnetic spectrum. All objects emit some electromagnetic radiation.



Why do hot objects emit electromagnetic radiation?

All matter is made up of atoms. At any temperature above absolute zero, these atoms are moving and colliding into each other. The atoms contain positive and negative charges. The motion of the atoms and their collisions with other atoms affect the motion of the electrons. Because they are charged and moving around, the electrons produce electromagnetic radiation. Electrons moving in an antenna produce a radio signal, but in a hot object the motion is more random with a range of speeds.



Electromagnetic radiation from a hot body

So, a hot object produces radiation across a broad range of wavelengths. If its temperature increases, the atoms move faster and have more frequent and more energetic collisions. These produce more intense radiation with higher frequencies and shorter wavelengths.

During the late 19th century, scientists conducted investigations into how much radiation was produced across the spectrum and how this distribution changed with temperature. The results are displayed in the figure on the next page.

The graphs for different temperatures are roughly the same shape. Starting from the right with long wavelengths, there is very little infra-red radiation emitted. As the wavelength gets shorter, the radiation produced increases to a maximum; finally as the wavelength shortens even further, the amount of radiation drops away quite quickly. The graphs for higher temperatures have a peak at a shorter wavelength and also have a much larger area under the graph, meaning a lot more energy is emitted.

Early researchers such as Jozef Stefan were keen to find patterns and relationships in the data and to be able to explain their observations. In 1879, Stefan compared the area under the graph for different temperatures. This area is the total energy emitted every second across all wavelengths, in other words, the power.

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Red hot!
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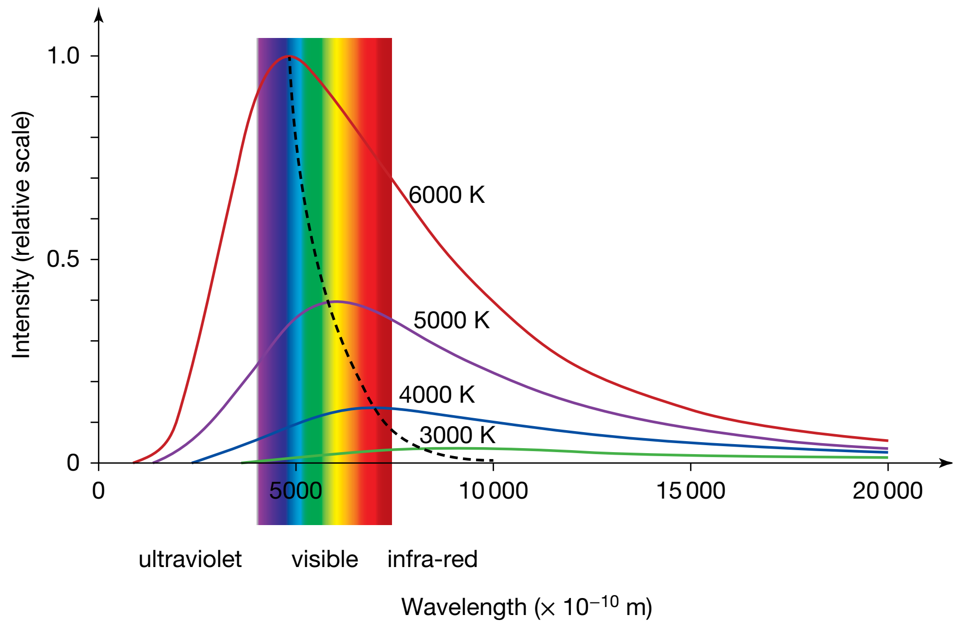


Intensity for different wavelengths across the electromagnetic spectrum for four different temperatures: 3000 K, 4000 K, 5000 K and 6000 K

He found that the power was proportional to absolute temperature to the power of 4, that is,

power ∝ T^4.

This means that if the absolute temperature of a hot object doubles from 1000 K to 2000 K, the amount of energy emitted every second increases by 2^4 ($2 \times 2 \times 2 \times 2 = 16$ times).

Using this relationship, Stefan was able to estimate the temperature of the surface of the Sun as 5430 °C or 5700 K, which is very close to the value known today of 5778 K.

Ludwig Boltzmann later proved this from a theoretical standpoint, and so the power ∝ T^4 relationship is called the Stefan–Boltzmann law.

This relationship applies to all objects, but the constant of proportionality depends on the size of the object and other factors.

Sample problem 2.1

(a) When iron reaches about 480 °C it begins to glow with a red colour. How much more energy is emitted by the iron at this temperature, compared to when it is at a room temperature of 20 °C?

(b) How much hotter than 20 °C would the iron need to be to emit 10 times as much energy?

Solution: (a) **STEP 1**

Change the temperature to Kelvin.
Temperature of hot iron = 480 °C + 273 = 753 K
Temperature of cold iron = 20 °C + 273 = 293 K

STEP 2

Calculate the ratio.
Ratio of power (hot to cold) = Ratio of temperatures to the power of 4

$$\frac{P_{hot}}{P_{cold}} = \left(\frac{T_{hot}}{T_{cold}}\right)^4 = \left(\frac{753}{293}\right)^4 = 44$$

The hot iron emits 44 times as much energy every second as it does when it is at room temperature.

(b) **STEP 1**

Change the temperature to Kelvin.
Temperature of cold iron = 20 °C + 273 = 293 K

STEP 2

Calculate the ratio.
Ratio of power (hot to cold) = Ratio of temperatures to the power of 4

$$\frac{P_{hot}}{P_{cold}} = \left(\frac{T_{hot}}{T_{cold}}\right)^4$$

$$10 = \left(\frac{T_{hot}}{293}\right)^4$$

This can be rearranged to give $10^{\frac{1}{4}} = \frac{T_{hot}}{293}$.
To calculate $10^{\frac{1}{4}}$, you can use the x^y key on your calculator.

First enter the number for x, in this case 10, then push the x^y key, then enter the number for y, in this case 0.25, which is $\frac{1}{4}$ as a decimal. Then hit the equals key. You should get the answer 1.778.

$$1.778 = \frac{T_{hot}}{293}$$

$$T_{hot} = 1.778 \times 293 = 521\,\text{K}$$

STEP 3

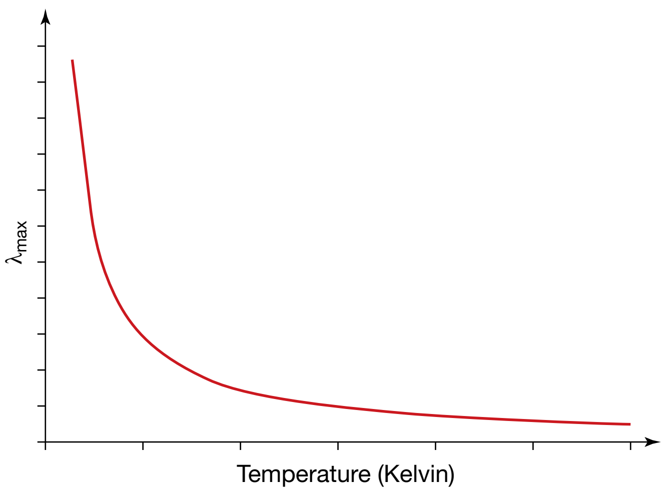
Change the temperature to Celsius.
Temperature of hot iron = 521 − 273 = 248 °C

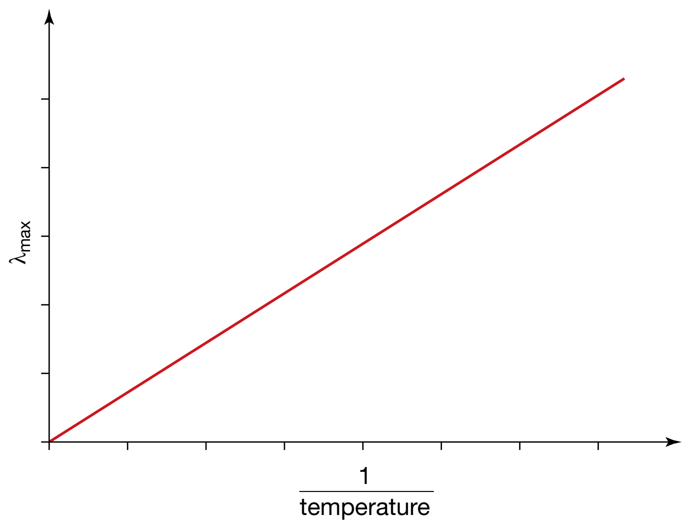
At 248 °C, the iron will emit 10 times as much energy every second as iron at 20 °C.

Revision question 2.1

The Sun has a surface temperature of 5778 K and radiates energy at a rate of 3.846×10^{26} watts. How much energy would a star of similar size radiate if its surface temperature was 8000 K?

Wilhelm Wien (pronounced *Veen*) in 1893 was able to show that as the temperature increased, the wavelength of maximum intensity of energy emitted decreased, and indeed the two quantities were inversely proportional. That is, the wavelength is proportional to the inverse of the temperature. This can be seen in the graph on the right.





Wien's law can be written as $\lambda_{max} \times T$ = constant. The value of this constant is 2.90×10^{-3} mK (metre–degree Kelvin).

Sample problem 2.2

(a) At what wavelength is the peak intensity of the light coming from a star whose surface temperature is 11 000 K (about twice as hot as the Sun)?
(b) In what section of the spectrum is this wavelength?

Solution: (a) $$\lambda_{max} = \frac{2.90 \times 10^{-3}\,\text{mK}}{11\,000\,\text{K}}$$

$$= 2.636 \times 10^{-7}\,\text{m}$$

1 nanometre = 10^{-9} m, so $\lambda_{max} = 263.6 \times 10^{-9}$ m = 264 nm

(b) 264 nm is beyond the violet end of the visible spectrum, so it is in the ultraviolet section of the electromagnetic spectrum.

Revision question 2.2

Determine the surface temperature of a star that emits light at a maximum intensity of 450 nm.

Chapter review

studyon
Unit 1 — AOS 1 — Topic 2
Energy in transit
Sit Topic test

Summary

- Heat energy can be transferred by conduction, convection and radiation.
- Conduction is the transfer of heat energy through a material by collisions between adjacent particles.
- Some materials conduct heat energy well and are called conductors. Others do not and are called insulators.
- Convection is the transfer of heat energy through a substance, usually a liquid or a gas, by the movement of particles between regions of different temperature. Hotter material is less dense because faster moving particles push each other further apart. If free to move, the less dense and hotter material will rise, displacing cooler material.
- The movement of plates in the Earth's crust is caused by convection from heat energy within the Earth.
- Radiation is the transfer of heat energy by the emission of electromagnetic radiation.
- The emitted radiation comes from a range of wavelengths across the electromagnetic spectrum.
- The graph of the energy contribution of different wavelengths of emitted radiation has a characteristic shape.
- For a given temperature, there is a specific wavelength at which the most energy is emitted. Its symbol is λ_{max}.
- The graph of the energy contribution of different wavelengths for a higher temperature has a lower λ_{max} and a larger area under the graph.
- λ_{max} is inversely proportional to the temperature measured in Kelvin ($\lambda_{max}T = \text{constant}$).
- The amount of energy emitted per second is called power.
- The area under the graph of energy contribution against wavelength is a measure of power.
- The area under the graph is proportional to the Kelvin temperature raised to the power of four. This can be expressed as power $\propto T^4$.

Questions

Transfer of energy

1. Explain with the aid of a well-labelled diagram how heat is transferred through a substance by conduction.

2. Why are liquids and gases generally poorer conductors of heat than solids?

3. Explain in terms of conduction and convection why you don't heat a test tube of water with the Bunsen burner flame near the top of the test tube.

4. Explain with the aid of a well-labelled diagram how convection occurs in a liquid that is being heated from below.

5. Why is it not possible for heat to be transferred through solids by convection?

6. At what speed does radiant energy move through space? What is significant about this speed?

7. When you swim in a still body of water on a hot afternoon there is a noticeable temperature difference between the water at the surface and the deeper water.
(a) Explain why this difference occurs.
(b) If the water is rough, the difference is less noticeable. Why?

8. The daytime temperature of an area can decrease for several days after a major bushfire. Why does this happen?

9. The microwave cooking instructions for frozen pies state that pies should be left to stand for two minutes after heating. What happens to the pie while it stands?

10. Standing near the concrete wall of a city building after a hot day you can instantly feel its warmth from a few metres away.
(a) How is the energy transferred to you?
(b) What caused the building to get hot during the day?

11. Why is it not practical to drink hot coffee in an aluminium picnic cup?

12. Why do ducts in the ceiling need more powerful fans than those in the floor?

13. Why do conventional ovens without fans have heating elements at the bottom. What is the advantage of having an oven with a fan?

Stefan–Boltzmann Law

14. A 100 W light globe has a tungsten filament, which has a temperature of 2775 K when switched on.
(a) How much radiation does the filament emit at 20 °C?
(b) The voltage on the light globe is reduced to increase the lifetime of the filament. The temperature of the filament is now 2000 K. What is the power saving?
(c) The voltage is now increased so that the power output is 200 W. What is the new filament temperature in Kelvin?

15. (a) A piece of iron has a yellow glow when it reaches 1150 °C. How much more energy is emitted every second at this temperature compared to when the iron glows red at 480 °C?

(b) At what temperature in degrees Celsius would the iron give off 10 times as much energy as it does at 480 °C?

Wien's Law

16. What is the wavelength of the light with the peak intensity from our solar system's closest neighbouring star, Proxima Centauri, which has an average surface temperature of 3042 K?

17. Our Sun gives off most of its light in the 'yellow' portion of the electromagnetic spectrum. Its λ_{max} is 510 nm. Calculate the average surface temperature of the Sun.

18. The Earth's surface has an average temperature of 288 K. What is the wavelength of maximum emission from the Earth's surface?

19. The human body has a surface temperature of about 37 °C.

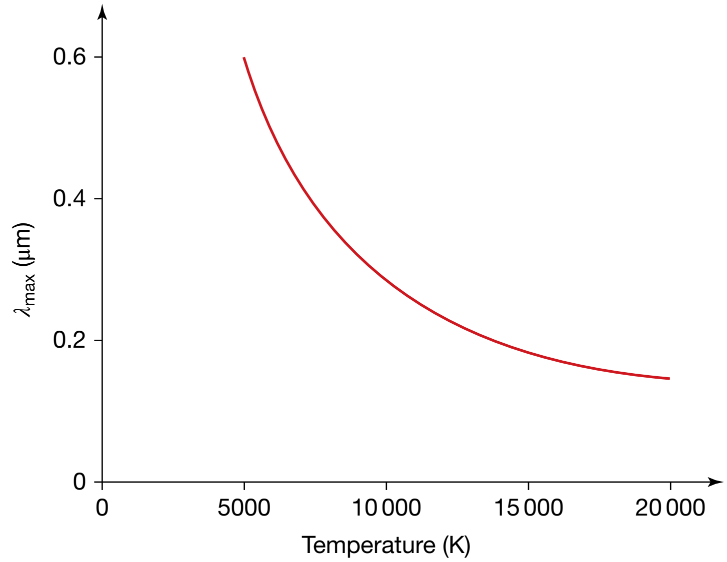
(a) What is the wavelength at which the human body emits the most radiation?

(b) In what part of the spectrum is this wavelength ?

20. (a) A violet star has a spectrum with a peak intensity at a wavelength of 4×10^{-7} m. Determine the temperature at the surface of this star.

(b) A red star has a spectrum with a peak intensity at a wavelength of 7×10^{-7} m. Determine the temperature at the surface of this star.

21. The graph above right shows how λ_{max} (the wavelength of the peak of the radiation spectrum) for a range of stars varies with their surface temperatures.



(a) Use values from the graph to confirm Wien's Law.

(b) Use the graph to estimate the surface temperature of a star whose intensity peaks at a wavelength of: (i) 0.4 μm (ii) 0.27 μm.

(c) Use the graph to estimate the peak wavelength for a star with a surface temperature of: (i) 15 000 K (ii) 5550 K.

22. Suppose the surface temperature of the Sun was about 12 000 K, rather than about 6000 K.

(a) How much more thermal radiation would the Sun emit?

(b) What would happen to the Sun's wavelength of peak emission?

23. Two stars have identical diameters. One has a temperature of 5800 K; the other has a temperature of 2900 K. What are the colours of these stars? Which is brighter and by how much?

CHAPTER

3 The physics of climate change

REMEMBER

Before beginning this chapter you should be able to:

- convert temperature from degrees Celsius to Kelvin
- describe heat transfer processes by conduction, convection, radiation and evaporation
- identify regions of the electromagnetic spectrum as radio, microwave, infra-red, visible, ultraviolet, X-ray and gamma waves
- describe the electromagnetic radiation emitted by the Sun as mainly ultraviolet, visible and infra-red.

KEY IDEAS

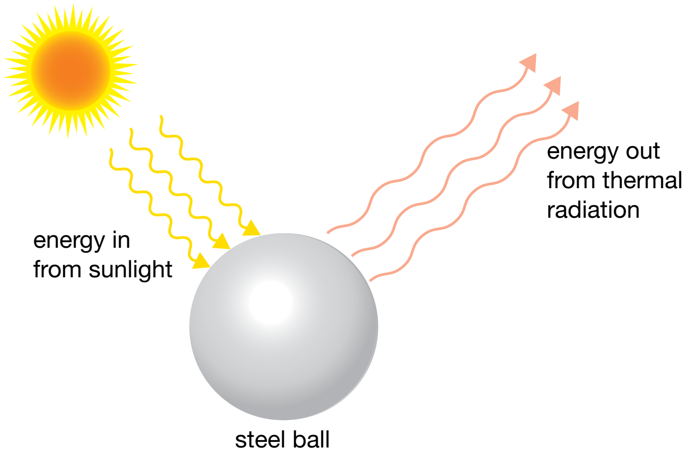
After completing this chapter you should be able to:

- explain how greenhouse gases (including methane, water and carbon dioxide) absorb and re-emit infra-red radiation
- model the greenhouse effect as the flow and retention of thermal energy from the Sun and the Earth's surface and atmosphere
- analyse changes in the thermal energy of the surface of the Earth and of the Earth's atmosphere
- analyse the evidence for the influence of human contributions to the enhanced greenhouse effect, including surface materials and the balance of gases in the atmosphere.

The Muir Glacier, Alaska: 13 August 1941 and (inset) 31 August 2004

Energy in balance

Every object attempts to achieve thermal equilibrium, that is, a balance between energy absorbed and energy emitted. Imagine a steel ball placed in direct sunlight as shown in the figure below.



The absorbed energy increases the temperature of the ball; the increased temperature means that the ball will radiate more thermal energy. If the amount of energy radiated is less than the amount absorbed, the temperature of the ball will continue to increase, leading to more energy being emitted, until a temperature is reached where energy in and energy out balance.

Similarly, if a cloud moves in front of the Sun, the energy absorbed by the ball would suddenly decrease to less than the amount of energy being emitted. The temperature of the ball would drop and continue to fall until the amount of energy emitted matched the energy absorbed and a new equilibrium was reached.

The Earth as viewed from space is like the steel ball. The energy falling on the Earth from the Sun is fairly constant. At the equator, an average of about 684 joules of energy from the Sun hits each square metre of the Earth's surface every second; that is, 684 $W\,m^{-2}$, where 1 watt is a unit of power or the rate of energy delivery and equals 1 joule per second. This value varies from day to day by as much as 2 $W\,m^{-2}$, as well as having an approximate 11-year cycle of a similar magnitude.

AS A MATTER OF FACT

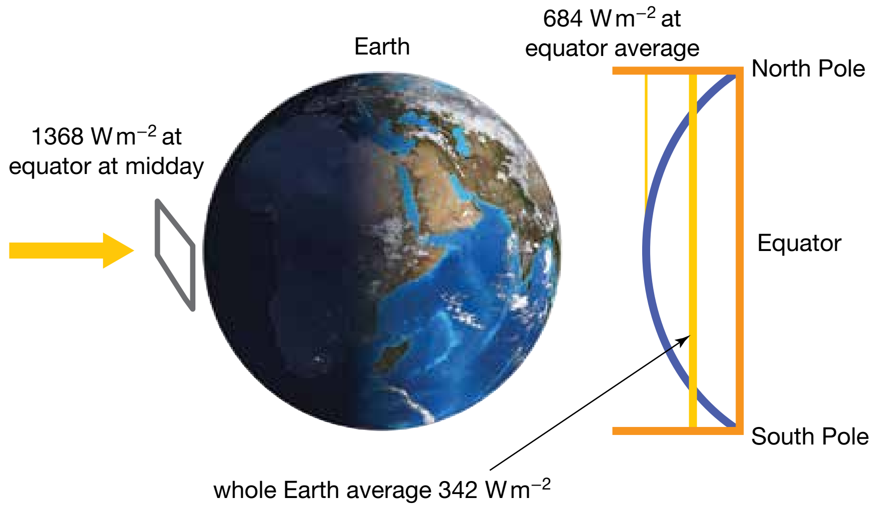
While a prisoner of war in World War I, Milutin Milankovic postulated several types of changes in the Earth's movement around the Sun that could affect the amount of solar radiation the Earth receives and its distribution. These changes can affect climate on a time span of many thousands of years and possibly explain the occurrence of ice ages. Some of the types of changes include:

- variation in the elliptical shape of the Earth's orbit with a cycle time of about 413 000 years
- precession of the Earth's axis of rotation; like any spinning top, the axis itself rotates, once every 26 000 years
- the tilt of the axis also ranges from 22° to 24.5° every 41 000 years.

All these changes are due to gravitational interactions in the solar system between the Earth, the Sun and other planets. It is thought that these factors may explain a long-term cooling trend the Earth has been in over the last 6000 years. From the slowness with which these changes occur, none can explain the unprecedented global warming in recent decades.

How hot is the Earth?

With the Stefan–Boltzmann relationship from chapter 2, it is possible to use the amount of energy the Earth radiates into space to calculate the temperature of the Earth as observed from space.



At the Earth's equator at midday, the light intensity from the Sun is 1368 W m^{-2}. The average over night and day and from pole to pole is 342 W m^{-2}.

How much energy does the Earth get from the Sun?

The Sun is directly overhead the equator at midday on the equinox. At this place and time, the solar radiation is about 1368 W m^{-2}. But because the Earth turns, producing night and day, this value has to be halved. Also, the Earth is curved with the North and South Poles receiving much less light than the equator over a full year. This requires the number to be halved again. So the average solar radiation across the Earth is 342 W m^{-2} as shown in the figure above. About 100 W m^{-2} of this radiation is reflected straight back into space by the white surfaces of clouds and ice sheets. This leaves 242 W m^{-2} to heat up the Earth.

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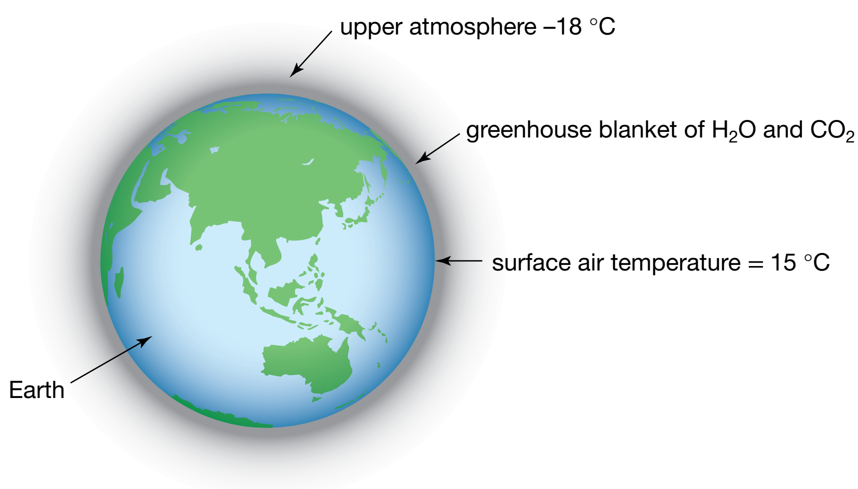
At what temperature would an object need to be to radiate 242 W m^{-2}?

In the previous chapter, the Stefan–Boltzmann relationship, $P \propto T^4$, was described. It enables the absolute temperature of an object to be determined if you know how much energy it is radiating. For the 242 W m^{-2} that the Earth radiates, this gives a temperature of 255.6 K, that is, –18 °C. This seems wrong. The Earth is not that cold! What causes the difference between this calculated temperature (which is the temperature of the Earth observed from space) and the temperature we observe at the surface? The explanation is that we ignored the greenhouse gases in the atmosphere.

The average global surface air temperature since the last ice age has been about +15 °C. This means that the greenhouse gases of water vapour (H_2O), carbon dioxide (CO_2) and others have been a blanket that has provided an extra 33 °C of warmth.



The necessary temperature (–18 °C) for the Earth to radiate 242 W m^{-2} actually occurs at an altitude of about 5 km above the surface. So the Earth's surface is warmed by a 5 km thick blanket!

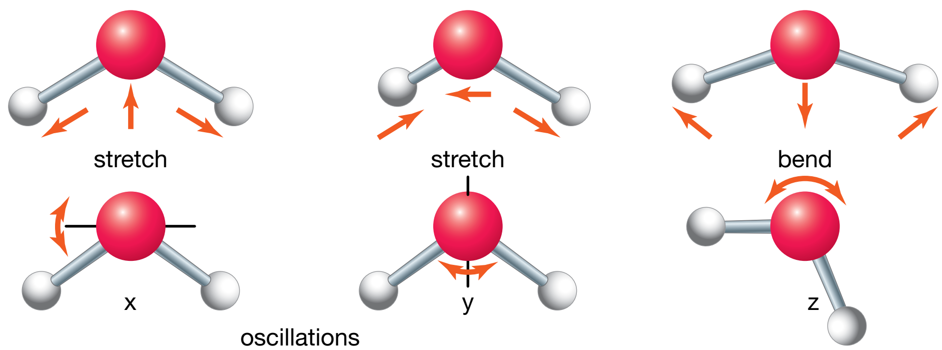
How do water vapour and carbon dioxide act as a blanket to trap heat?

If you shine a broad spectrum of light through a gas, some colours will be absorbed. The colours absorbed are specific to the substance, which means each substance produces its own unique pattern of absorption bands. These absorption bands are like fingerprints and can be used to identify molecules. The light in the absorption band has been absorbed by the molecule and then subsequently re-emitted, but in a random direction. This means the spectrum of light from the source will have gaps where absorption has occurred. The light from the other parts of the spectrum passes through the gas without a change in direction.

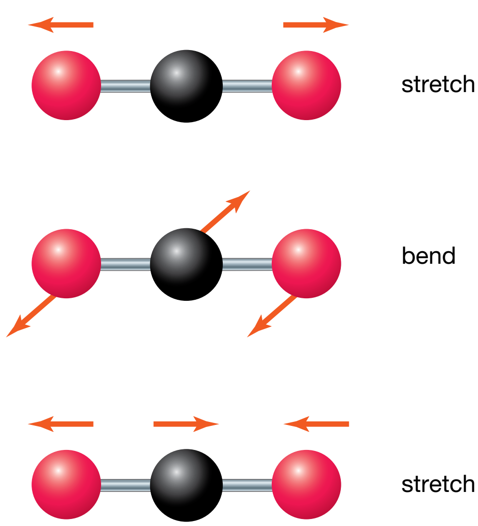
Ultraviolet light has more energy than visible light, which has more energy than infra-red, but none of them are energetic enough to break up molecules. These three types of radiation have only enough energy to stretch, twist and spin molecules. Molecules with two atoms such as nitrogen (N_2) and oxygen (O_2) have very strong bonds. When they absorb ultraviolet light, their bonds stretch. The energy of visible light and infra-red radiation is too low to affect such molecules. This means the two gases are transparent to visible light and infra-red.

Water vapour (H_2O) and carbon dioxide (CO_2) have three atoms in each molecule, so they are more flexible than N_2 and O_2. These molecules can bend, whereas atoms with only two molecules cannot. When H_2O and CO_2 absorb infra-red light, their bonds stretch and bend. Other molecules with more than two atoms, such as methane (CH_4), absorb infra-red radiation in the same way.

The diagrams below show the different ways water vapour and carbon dioxide molecules bend and stretch.



The water molecule has three different ways of stretching or bending, as well as oscillations about three axes.



The carbon dioxide molecule has three different ways of stretching.

The oxygen atoms at the ends of the bonds in carbon dioxide are heavier than the hydrogen atoms at the ends of the bonds in water, so the bonds in the two molecules stretch and bend differently. This means each molecule will absorb different parts of the infra-red spectrum. Consequently, water vapour and carbon dioxide contribute independently to the greenhouse effect.

Once a gas molecule has absorbed infra-red radiation coming from the Earth's surface, it re-emits the radiation, but

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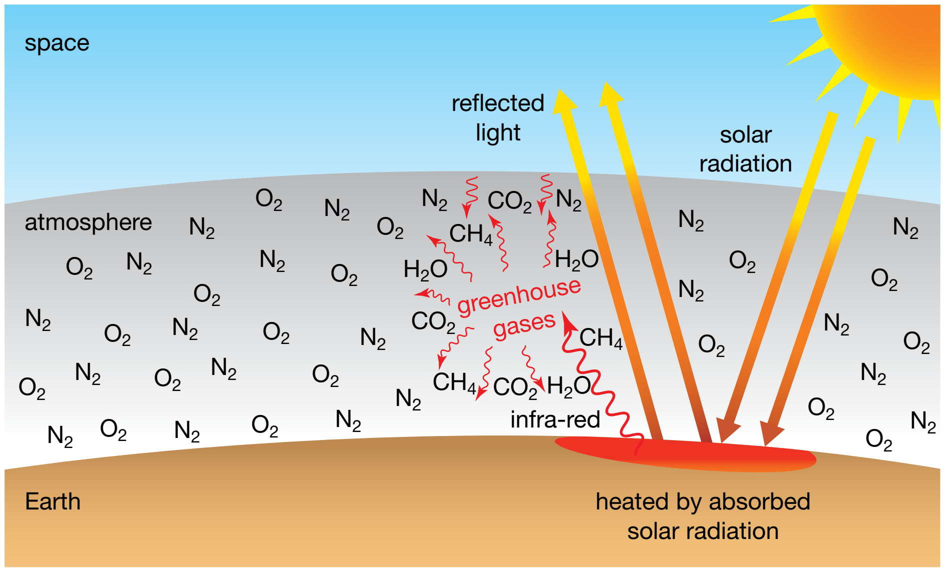
Solar radiation
Concept summary and practice questions

importantly in a random direction. So, for the gas as a whole, some radiation goes back down to the Earth to increase its temperature and some is directed towards the top of the atmosphere and out into space. However, other molecules further up in the atmosphere can absorb this radiation and re-emit more back to the Earth. The overall effect is that more than half of the radiation emitted by the gas comes back to the Earth's surface.



Infra-red radiation from the Earth's surface is absorbed by greenhouse gases and re-emitted in all directions.

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Enhanced greenhouse effect
Concept summary and practice questions

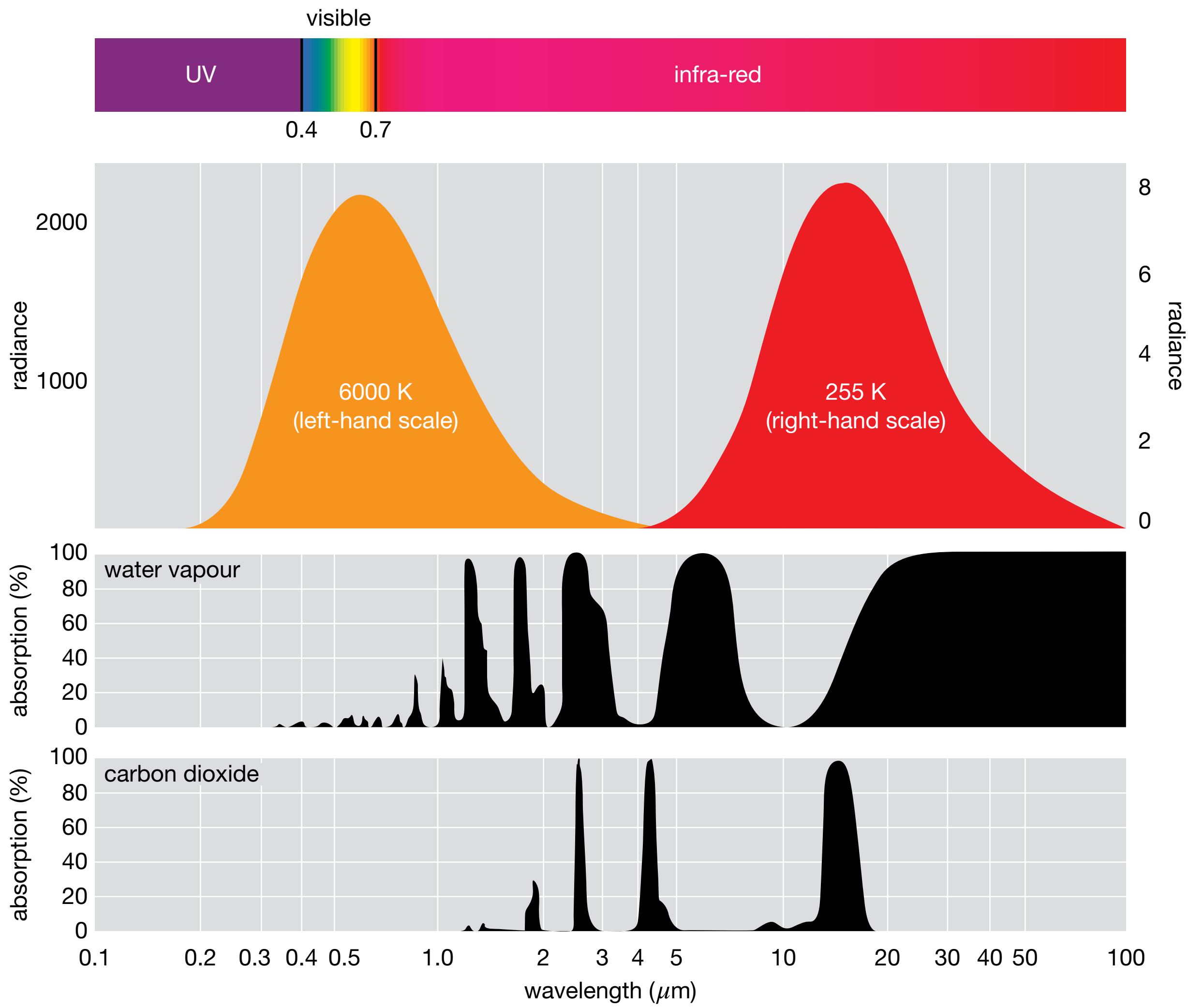
Human activities, such as the burning of fossil fuels (coal, oil and natural gas), agriculture and land clearing, are increasing the concentrations of greenhouse gases in the atmosphere. This increase is sometimes called the enhanced greenhouse effect.

Increased carbon dioxide concentration in the atmosphere means that more of the wavelengths that CO_2 absorbs will be re-emitted back to Earth, increasing the temperature of the Earth.

The next diagram shows:

- the spread of wavelengths radiated by the Sun at 6000 K (these are the wavelengths in sunlight)
- the spread of wavelengths radiated by the Earth at 255 K or –18 °C. *Note:* The scale on the left is for sunlight, while the scale on the right is for the Earth's radiation. The scales are markedly different.
- the absorption spectrum for water vapour
- the absorption spectrum for carbon dioxide.

It is worth clarifying the vertical scale on the absorption spectra. The spectra show that for some wavelengths 100% of the radiation is absorbed. This means that in a container holding only that gas, no radiation of that wavelength would pass through without interacting with a molecule. However, in the atmosphere with a mixture of gases, and with CO_2, H_2O and CH_4 at low concentrations, much of the radiation with these wavelengths has a good chance of passing through without ever hitting one of these molecules. The gases CO_2, H_2O and CH_4 make up a very small proportion of the atmosphere, so the infra-red radiation emitted from the Earth's surface has a good chance of reaching outer space without being absorbed. However, with increased emissions of CO_2 and CH_4, interactions are more likely to occur.



The energy spectra of the Sun (6000 K) and the Earth (255 K) with the absorption spectra of water vapour (H_2O) and carbon dioxide (CO_2)

Revision question 3.1

(a) Use the figures from the diagram above to determine the range of wavelengths emitted by the Earth that are absorbed by (i) CO_2 and (ii) H_2O.
(b) Which wavelengths emitted by the Earth are absorbed by CO_2 and not by H_2O?

Fossil fuel's fingerprints

Atoms with the same number of protons but different numbers of neutrons are called isotopes. Isotopes of an element have identical chemical behaviour because they have the same number of electrons. However, because different isotopes have different masses, their reactions may proceed at different speeds. Heavier isotopes generally react slower.

For example, carbon has two main isotopes: carbon-12 with six neutrons and carbon-13 with seven neutrons. The process of photosynthesis in plants turns carbon dioxide and water into carbohydrates. This reaction occurs more quickly with carbon-12 than it does with carbon-13. This means the proportion of carbon-13 in the plant is less than what was in the atmosphere at the time the plant was growing.

Over millions of years, dead plants are turned into fossil fuels, such as coal, oil and natural gas. When these fossil fuels are burnt, the carbon, which has relatively little carbon-13, is released back into the atmosphere. Tree rings and ice cores can be used to determine the ratio of carbon-13 to carbon-12 of the Earth's atmosphere going back thousands of years. These can then be compared to the current atmosphere.

The data shows that the ratio of carbon-13 to carbon-12 is much lower now than in the past. The ratio started to decline about 1850, around the time fossil fuel use began to increase. The low amount of carbon-13 in our atmosphere is evidence that the increased CO_2 is produced by humans using fossil fuels.

Revision question 3.2

(a) Which carbon dioxide molecule would move faster in the atmosphere: a lighter one with a carbon-12 atom or a heavier one with a carbon-13 atom?

(b) Which molecule do you think is more likely to dissolve in the ocean? Give a reason.

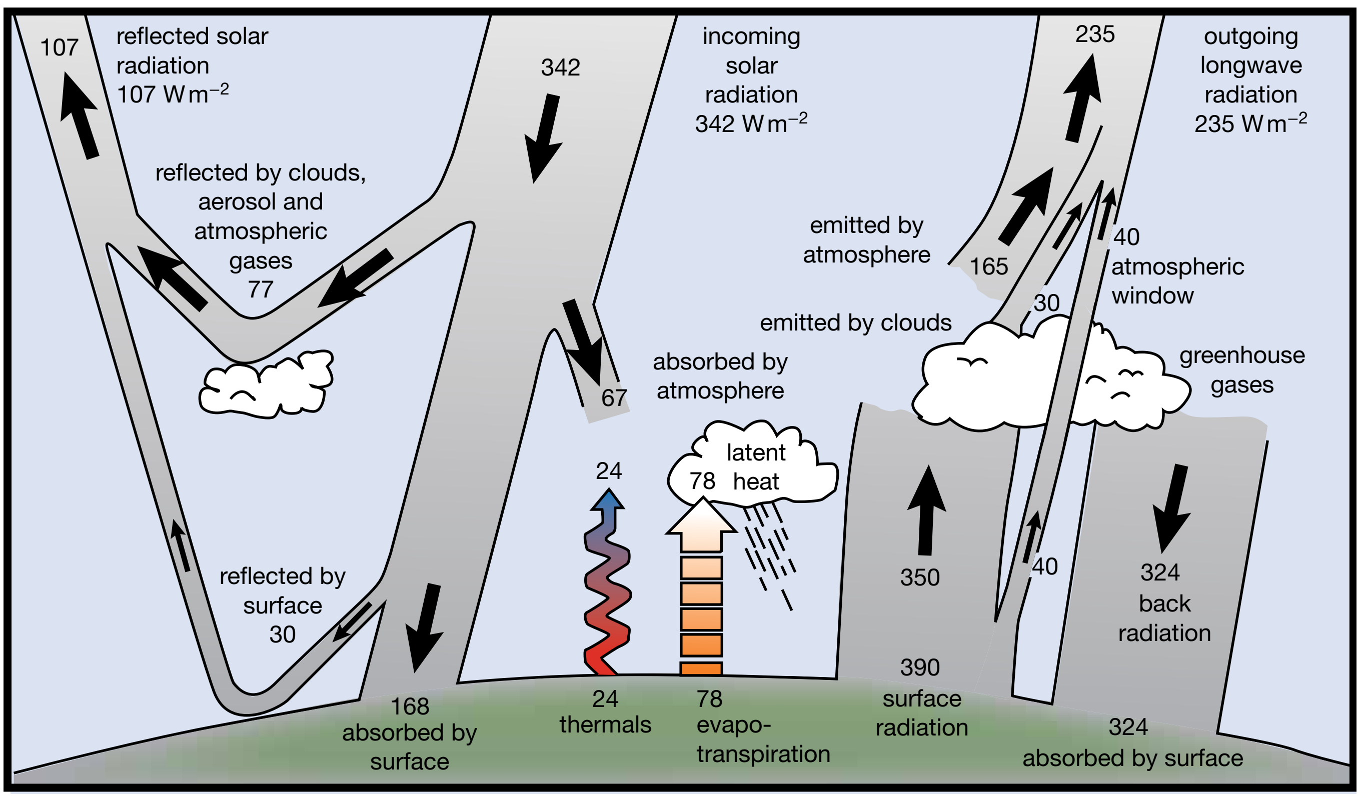
The Earth's energy budget

The Earth's energy budget is an accounting of the incoming energy from the Sun, where it goes in the atmosphere and at the surface, and how the outgoing energy leaves the Earth.

Note: This is called an energy budget, even though the numbers are measured in watts per square metre, which is actually the amount of energy passing through an area of one square metre every second.

The figure below shows all the different paths that energy takes from arriving at the Earth mainly as visible light to being emitted as longwave infra-red radiation or reflected straight back into space.

The Earth's energy budget from the International Panel on Climate Change (IPCC)



The numbers in the figure can be used to check the energy balance between energy coming in and energy going out, and not only of the whole Earth, but also of just the atmosphere, or just the Earth's surface. In each case, the energy coming in should equal the energy going out.

For example:
For the Earth as a whole:
Incoming energy = 342 $W m^{-2}$
Outgoing energy = 77 + 30 + 165 + 30 + 40 = 342 $W m^{-2}$

For the Earth's surface:
Incoming energy = 168 + 324 = 492 $W m^{-2}$
Outgoing energy = 24 + 78 + 350 + 40 = 492 $W m^{-2}$

Revision question 3.3

(a) From the figure for the Earth's energy budget, calculate the total incoming energy and total outgoing energy for the atmosphere and show that each equals 519 $W m^{-2}$.

(b) For each of the energy transfers in the figure for the Earth's energy budget, determine whether it occurs by conduction, convection, radiation or evaporation.

The table below provides a description and the contribution to the energy budget of most of the terms in the figure for the Earth's energy budget.

TABLE 3.1 Energy budget of the Earth by energy category

Energy category	Amount ($W m^{-2}$)	Description
Incoming solar radiation	342	Visible light with some infra-red and ultraviolet from the Sun
Outgoing longwave radiation	235	Infra-red radiation from many sources heading out to space
Reflected solar radiation	107	Visible light from two sources heading out to space
Reflected by clouds, etc.	77	Visible light reflected by clouds, aerosol and atmospheric gases
Atmosphere window	40	Infra-red radiation passing through the atmosphere because it is in the part of the spectrum that is not absorbed by the main greenhouse gases
Emitted by clouds	30	Infra-red radiation from clouds heading out to space
Latent heat	78	Energy used or released when there is a change of state
Back radiation	324	Infra-red radiation emitted downwards by Greenhouse gases in the atmosphere
Absorbed by surface	168, 324	Visible light, infra-red and ultraviolet radiation from two sources absorbed by the Earth's surface
Thermals	24	Rising currents of hot air
Evapotranspiration	78	Moisture in plants released as water vapour
Surface radiation	390	Infra-red radiation emitted by the Earth's surface into the atmosphere

Sample problem 3.1

Using the figure on page 37 for the Earth's energy budget from the IPCC, find the missing amount in the table below.

Energy category	Amount ($W m^{-2}$)	Description
Emitted by atmosphere	?	Infra-red radiation emitted upwards by greenhouse gases in the atmosphere

Solution: From the figure, the amount emitted is 165 ($W m^{-2}$).

Revision question 3.4

Using the figure on page 37 for the Earth's energy budget from the IPCC, find the missing amount in the table below.

Energy category	Amount ($W\,m^{-2}$)	Description
Reflected by surface	?	Visible light reflected by snow, land and sea ice
Absorbed by atmosphere	?	Incoming radiation that is absorbed by gases in the atmosphere

Feedback

In any complicated system with many interacting components, such as the Earth's climate, sometimes one part changes a second part, and a change in the second part can then change the first part. This is called feedback. A common audio example of feedback is when a person using a microphone walks in front of a loudspeaker. The microphone picks up the signal from the speaker, which is then amplified, fed back into the speaker, which is again picked up by the microphone, and so on, producing a loud high-pitched noise. This is called positive feedback. Negative feedback is also possible, for example, a 'governor' or control device is used in engines, where excess speed is used to reduce the input to keep the speed constant.

The climate has examples of both positive and negative feedback.

Positive feedback:

- Evaporation: Increasing sea temperatures leads to more evaporation of water, a greenhouse gas, which increases the temperature of the air and sea.

Negative feedback:

- Thermal radiation: Increasing surface temperature emits more infra-red radiation, which cools the Earth.

The risk of positive feedback is that there is a 'tipping point' beyond which the system can become unstoppable, as in the loudspeaker example above.

Another example of positive feedback in the Earth's climate is the physical quantity 'albedo'. Albedo is a measure of the proportion of incoming radiation that is reflected without being absorbed. It is usually expressed as a number between 0 and 1, with 1 being a perfect reflector and 0 a perfect absorber.

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TABLE 3.2 Albedo of different materials

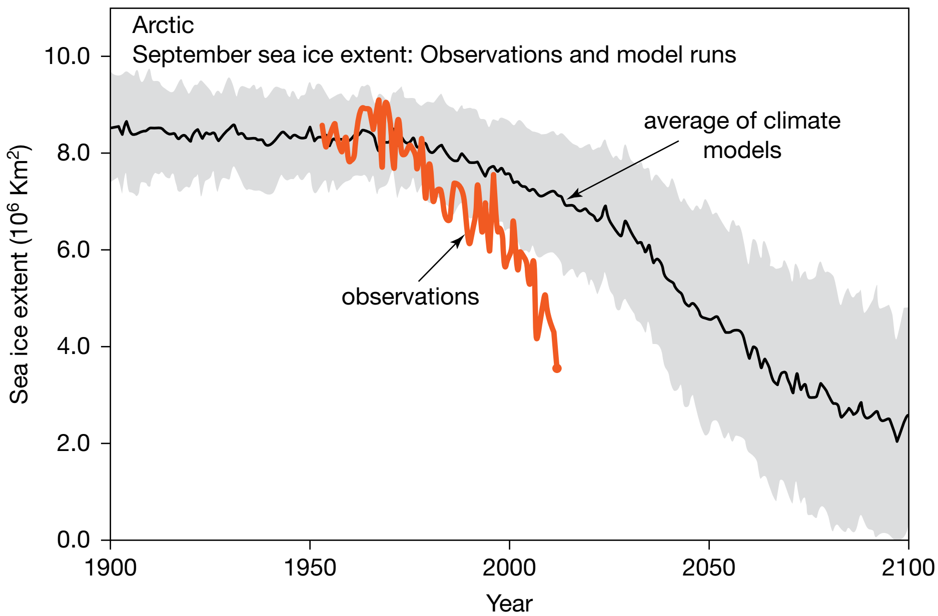
Material	Albedo
Water	0.08
Sea ice	0.5–0.7
Fresh snow	0.8–0.9
Clouds	0.4–0.8
Forest	0.1
Desert	0.3
Green grass	0.25

Revision question 3.5

(a) **Estimate the albedo of the following materials: (i) the asphalt road surface, (ii) crops, (iii) the roof of your house.**

(b) **Indicate whether each of the following is an example of positive or negative feedback. Explain your reasons.**
- **The release of methane from melting permafrost**
- **Effect of clouds**

The significance of albedo for the climate is the role it plays in determining the amount of sea ice in the Arctic. Sea ice is very reflective, but the water it is floating in is not. Increased air temperature leads to more sea ice melting, which means that more of the incoming radiation hits water rather than ice and is absorbed. This increased energy absorption then heats up the atmosphere, which leads to more sea ice melting, and so the feedback loop continues.



The extent of Arctic sea ice in September each year. The solid line shows the average of climate model predictions, the shaded area is the spread of the predictions from the different models.

Revision question 3.6

(a) **Why do you think the extent of Arctic sea ice in September is graphed?**
(b) **What factor about the sea ice other than its surface area could be important?**

Climate models

The scientific principles that underlie climate have been understood since the 19th century. They include:

- Newton's laws of motion that explain the movement of gases and liquids, such as the existence of high and low pressure regions, the formation of cyclones, the flow of ocean currents
- thermodynamics principles that explain heat transfer within the atmosphere, and also between the atmosphere, the oceans and the land
- gas laws and solubility in liquids from chemistry that explain the behaviour of gases within the atmosphere and their interactions with the oceans.

These principles are precisely known with mathematical relationships, some of which you will come across in this year's or next year's courses in Physics and Chemistry. The development of the computer meant that these principles and their mathematical relationships could be applied to the biggest problem on Earth, the Earth itself.

A climate model is an attempt to apply these relationships to the atmosphere of the whole Earth as well as the surface features of land, ice and sea. The model attempts to calculate aspects of the climate that are important to humans, such as rainfall and humidity, sea level rise, ocean acidity, wind strength and, of course, air temperature.

Climate models are also able to calculate future trends in these aspects of climate and then investigate the effect on these trends of changes such as reducing greenhouse gas emissions or aerosol use.

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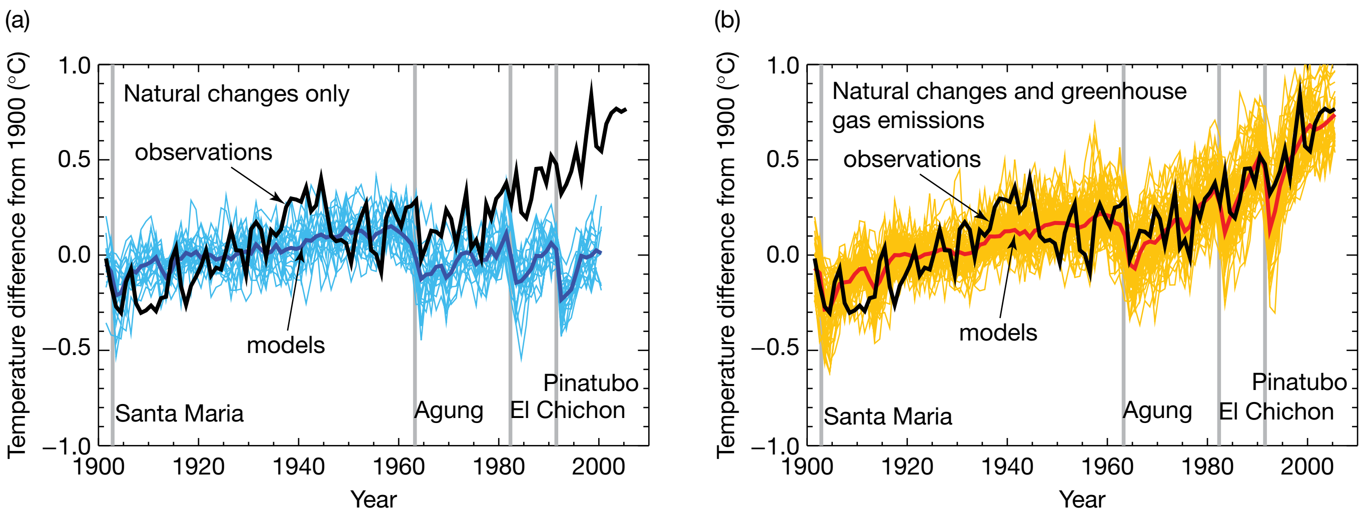
How to know if a climate model is accurate?

A climate model starts as hundreds of mathematical equations that describe all the physical and chemical interactions within the atmosphere, and between the atmosphere, the land, sea and ice. These equations are applied to a model of the Earth's atmosphere as it was at an earlier time, say 1900, to calculate the expected climate conditions for the next 100 years. These calculations are then compared with the actual climate conditions to see how close the climate model comes to reality.

If the model is out, then it is back to the drawing board to redesign the model. If the model is accurate, it can be used to calculate the future climate. Different countries and scientific organisations each produce their own climate models. The basic scientific principles are the same, but the models vary in their subtlety and complexity, and the available computing power.



Model comparisons against actual temperature from 1900 to 2000

Source: IPCC.

The solid black line in each graph above is the global average surface air temperature from 1900 until 2000. The models were run twice:

- The first run assumed the carbon dioxide concentration stayed constant at its value in 1900. This produced the blue graph on the left. The solid blue line is the average of all the different models.
- The second run included the actual carbon dioxide concentration over the century. This produced the red graph on the right. Again the solid red line is the average of all the different models.

The red line in the graph on the right is a close fit to the actual observed temperature change. It is apparent from comparing the two graphs that increased carbon dioxide concentration has led to an increase in the global temperature.

The close match of the red graph with the observations validates the design of the climate models and gives confidence about what the models might predict for the decades and centuries ahead. The models can also be used to investigate how long the Earth's atmosphere would take to respond to a significant reduction in CO_2 emissions.

With this information, governments can act together to bring about change. The models not only produce a global average, but also specific information for each region of the Earth. So local responses to climate change can be planned.

Revision question 3.7

Use the graphs above to answer the following questions.

(a) Pinatubo, El Chichon, Agung and Santa Maria are all volcanic eruptions.

   (i) What was the effect of the eruptions on the average global surface air temperature?

   (ii) Suggest a mechanism for this effect.

(b) There are some stretches of a number of years where the models and the actual temperature data differ significantly.

   (i) Identify those stretches of years.

   (ii) Thinking of the history of each of those years, is there a possibility that the collection of temperature data to obtain a global average may have been unreliable?

(c) Looking at the two graphs, when do you think the increased carbon dioxide concentrations started to affect the global average surface air temperature?

(d) The Earth's surface is made up of solid rock, liquid oceans and a gaseous atmosphere.

(i) Which do you think would be better to use to measure the temperature of the Earth's surface?

(ii) Why do you think the air temperature is used?

Climate models can be used to investigate the long-term effects of international agreements on controlling greenhouse emissions on surface air temperature, sea level rise and rainfall.

Investigating a simple climate model

The energy budget shown in the figure on page 37 has been converted into a rudimentary spreadsheet model of the climate, which you can use to investigate the effect of future scenarios such as:

- a decrease in sea ice, leading to a reduction in the amount of radiation reflected straight back into space
- increased atmospheric CO_2 concentration, leading to a lesser proportion of infra-red radiation from the atmosphere being emitted into space and more being emitted back to Earth.

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A simple climate change model
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Issues related to thermodynamics

You have studied many aspects of thermodynamics in the last three chapters that affect our lives in many ways, including:

- preparing food
- designing our homes, as well as heating and cooling them
- keeping our bodies at an even temperature
- selecting energy sources for our economy and, most important of all,
- understanding and addressing climate change.

It is therefore appropriate that you explore an issue in some depth, to identify the thermodynamic principles in use and to evaluate relevant public policy and social commentary for their scientific accuracy.

The Resources section of your eBookPLUS has an extensive list of possible topics to research, each with supporting documents and useful weblinks, as well as suggestions for how to present your findings.

Some possible topics for you to research are listed below.

- Compare domestic heating and cooling technologies. Are the brochures and advertising physically plausible?
- Investigate the design of energy efficient houses. How do building materials differ? Are star ratings reliable? Should design features such as double glazing and orientation in relation to the Sun be mandatory?
- Compare appliances by their technology, efficiency and emissions. Are the energy ratings useful?
- Research solar thermal technology. Is generating electricity by solar thermal technology a feasible alternative for Australia?
- Investigate geo-engineering solutions to tackle climate change. Are any of them feasible?
- Examine the treatments for hypothermia (body core temperature < 35 °C) and hyperthermia (body core temperature > 38 °C). How have they changed over time and how do they work?
- Compare different technologies for food preparation, e.g. microwave oven vs convection oven as well as different fuel options.

These broad topics may need to be narrowed down to focus on a specific aspect if the task is to be manageable.

Evaluating resources

When collecting information from the internet or elsewhere, it is important to determine how reliable and accurate the information is. Each item should be evaluated to see how useful it will be.

Some aspects worth considering are:

Reliability

- Relevant: Is the information central to your purpose?
- Up to date: When was the information produced? Has it been superseded by new information?
- Expertise: Is the information produced by someone with appropriate qualifications? Do they know what they are talking about?
- Source: Where did the author obtain their information?
- Audience: Who is the intended audience and is the resource suited to your purpose?
- Bias: Is there evidence of overstatement, selective quoting or other tricks designed to mislead?

Validity

- Accuracy: Are physics concepts correctly used?
- Argument: Is the argument logically sound and strong? Are deceptive strategies used, e.g. oversimplification or false choices?
- Analysis: Are physics relationships applied correctly?

Uncertainty

- Graphs: Are the graphs misleading?
- Data: Does the data lack precision? Is only selected data used?

Chapter review

Summary

- The Earth on average, over the day and across the globe, receives about 342 joules of energy every second in each square metre.
- About 100 joules of this energy the Earth receives is reflected back into space by ice, snow and clouds.
- Without greenhouse gases in the atmosphere, the surface temperature of the Earth would be –18 °C.
- Most of the radiation emitted by the Earth is infra-red radiation.
- The main greenhouse gases are water vapour (H_2O) and carbon dioxide (CO_2), with methane (CH_4) making a small contribution along with other molecules with more than two atoms.
- The relative flexibility of the greenhouse gas molecules allows them to absorb the infra-red radiation emitted by the Earth's surface. After absorbing the infra-red radiation, the greenhouse gases re-emit it in all directions; some upwards out into space, but most back down to the Earth to heat the surface.
- Some of the wavelengths absorbed by the greenhouse gases are common to each, but each particular gas absorbs some wavelengths that are unique to that gas.
- The energy that comes to the Earth from the Sun is balanced by the energy the Earth radiates back into space.
- The energy from the Sun is absorbed by the atmosphere, the land surface and the oceans. The energy absorbed by the land and sea is transferred by conduction, convection, radiation and evaporation to the atmosphere. Some of this energy returns to the Earth's surface after being emitted by the greenhouse gases and increases the surface temperature.
- Climate models are based on the scientific principles of motion, thermodynamics and the chemistry of gases and liquids.
- Climate model calculations are very consistent with the historical record.
- Climate model calculations show that the increase in global average surface air temperature in recent decades is explained by the increased atmospheric CO_2 concentration.
- The albedo of a surface is the proportion of incoming radiation that is reflected with no change in wavelength.
- Feedback mechanisms are processes in complex systems where the output from the system can affect an input to the system. The feedback can be either positive or negative. Both types occur in the Earth's atmosphere.

Questions

1. Why doesn't all of the radiation from the Sun that enters the Earth's atmosphere reach the surface?
2. List the features of the Earth that influence its climate.
3. Describe the properties of water that cause the variation in climate over the Earth's surface.
4. What is the enhanced greenhouse effect and why is it a threat to life on Earth?
5. Is the majority of the heating of the Earth's atmosphere due to the transfer of radiant energy from the Sun or from the Earth's surface?
6. Why do the atmosphere and surface of the Earth emit infra-red radiation?
7. Why does water take much longer to increase in temperature due to exposure to sunlight than the same mass of soil in an identical container?
8. Why does air cool as it rises even though it is getting closer to the Sun?
9. The intensity of the Sun's radiation on the Earth's surface at latitudes of 60° is about half of that near the equator. Give two reasons for this difference.
10. Use the Earth's energy budget illustrated in the figure on page 37 to show that the total amount of energy entering the atmosphere is equal to the total amount of energy leaving it.
11. Why is so little heat transferred from the Earth's surface to its atmosphere by conduction?
12. All of the energy transferred from the Earth's surface and atmosphere into space is transferred by radiation. Why is there no transfer by conduction or convection?
13. In the tropical regions of the Earth, more radiant energy is received from space than is lost. At the poles, more radiant energy is lost than is received. This would suggest that average temperatures in the tropics should be continually increasing while the average temperatures at the poles should be continually decreasing. Explain why this doesn't happen.
14. Although the IPCC graphs on page 41 show that long-term global warming is occurring, the temperature increase is not steady. What factors make the increase so erratic?
15. What is the major cause of the greenhouse effect?
    A. Gases in the atmosphere absorb heat from the Earth's surface.
    B. Gases in the ozone layer absorb heat from the Earth's surface.

C. Gases in the ozone layer absorb heat from the Sun.
D. Gases in the atmosphere absorb heat from the Sun.

16. It has been falsely argued that since the bulk of the greenhouse effect is caused by water, the other greenhouse gases are insignificant. Use the absorption spectra of CO_2 to show that this is not the case.
17. Indicate whether each of the following is an example of positive or negative feedback and explain why.
    - Carbon cycle: Carbon atoms in CO_2 are absorbed by plants, which are either eaten as food or used as fuel, which produce CO_2.
    - Warmer oceans absorb less CO_2.
18. What are the similarities and differences between the energy from the Sun that is absorbed by the Earth and the energy the Earth radiates into space?
19. Why can the low carbon-13 to carbon-12 ratio in our atmosphere be described as fossil fuels' fingerprints?
20. The specific heat capacity of water is over four times that of sand.
    (a) What effect does this have on the heating and cooling of water and sand?
    (b) Explain why, on a hot day, sand is too hot to stand on in bare feet while the water in the sea can be too cold for some people.
    (c) Why is the temperature of the sand of an inland desert almost always greater than that of the sand on a beach at the same latitude?
21. At night, still water cools by conduction, convection, radiation and evaporation. However, during the day, convection takes no part in its warming. Why not?
22. When the Sun is directly overhead, each square metre of the Earth's surface receives 1368 J of radiant energy each second. On a typical winter's weekday, Victoria consumes about 4500 MW of electrical energy. What area of solar collectors (of 15 per cent efficiency) would be needed to provide energy at the same rate while the Sun is directly overhead?
23. Estimate the quantity of radiant energy that would fall on your body if you were to lie in the afternoon sun on the beach for 30 minutes. Assume that each square metre is receiving radiant energy at the rate of 1200 W. Explain any additional assumptions that you have made in making your estimate.

More of a challenge

24. The table below compares the specific heat capacities as well as reflection and absorption properties of water and dry sand.

Property	Water	Dry sand
Specific heat capacity (J kg^{-1} K^{-1})	4200	820
Reflectivity (%)	3	15
Depth to which 50% of the radiant energy is absorbed	11 m	1 mm

When the Sun is directly overhead, each square metre of the Earth's surface receives radiant energy at the rate of 1368 W. Assuming that all of the energy that is not reflected is absorbed, what average temperature increase would be expected during a period of 1 hour in:
(a) water to a depth of 11 m
(b) sand to a depth of 1 mm?

The density of water is 1000 kg m^{-3} while the density of dry sand is 2400 kg m^{-3}.

25. On a warm sunny day, the Sun's radiation melts very little snow on the slopes of an alpine ski resort. Why?

CHAPTER

4 Current electricity

REMEMBER

Before beginning this chapter, you should be able to:

- identify a range of common components of simple electric circuits
- recognise the circuit symbols for common components of simple electric circuits
- connect components into simple circuits following a circuit diagram.

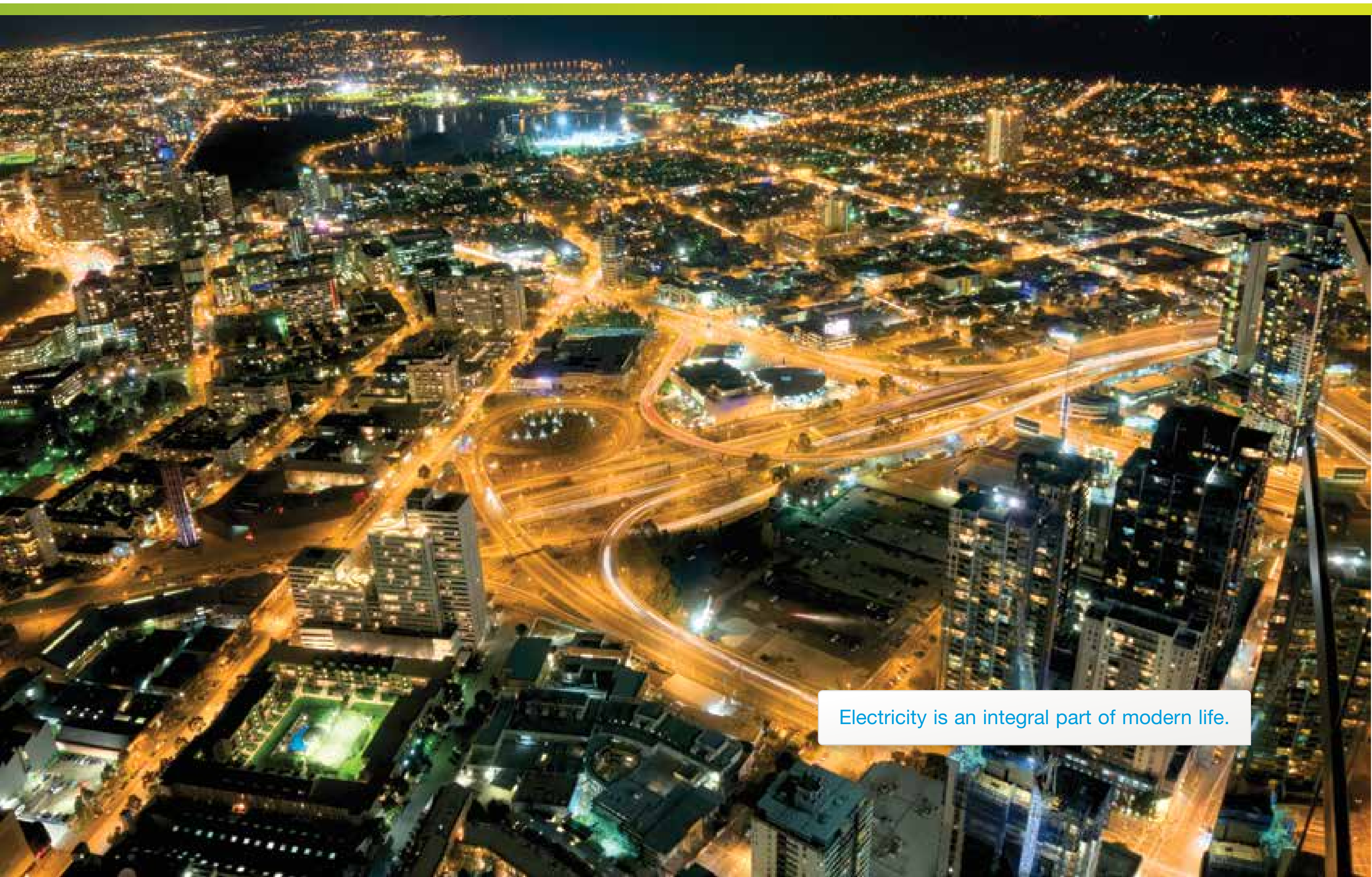
KEY IDEAS

After completing this chapter, you should be able to:

- apply the concepts of charge (Q), electric current (I), potential difference or voltage drop (V), energy (E) and power (P) to electric circuits
- compare different models of electric current and potential difference
- use the following mathematical relationships to analyse electric circuits:

$$I = \frac{Q}{t} \qquad V = \frac{E}{Q} \qquad E = VIt \qquad P = \frac{E}{t} = VI$$

- define the resistance of a circuit element
- state and apply Ohm's Law $V = IR$ for ohmic devices at a constant temperature
- use a V versus I graph to calculate the resistance of a circuit element
- investigate electric circuits comprising resistors, diodes and other non-ohmic devices
- present data obtained from electric circuit investigations in tables and graphs.



Electricity is an integral part of modern life.

Electric circuits

An electric **circuit** is a closed loop of moving electric charge. A simple circuit can be made up of a source of energy, such as a battery, **conductors** such as wires, and some kind of **load** where energy is transformed from electrical energy into other forms, such as heat, sound, light and movement by devices such as toasters, speakers, lamps and motors. A **switch** stops or allows the flow of electricity in the circuit. To convert the electrical energy into other forms of energy, loads resist the movement of charge.

An electric **circuit** is a closed loop of moving electric charge.

In an electric circuit, the **conductor** can be the wire connecting the circuit elements.

A **load** is a device where electrical energy is converted into other forms to perform tasks such as heating or lighting.

A **switch** stops or allows the flow of electricity through a circuit.

For a circuit to be useful, it must have a load in it. A load is a device where electrical energy is converted into other forms to perform a task such as heating something, or providing light, sound or mechanical energy from a motor. A load is anything that is doing a job.

To convert electrical energy into other forms of energy, loads resist the flow of current through them. This transforms some or all the potential energy stored in the current.

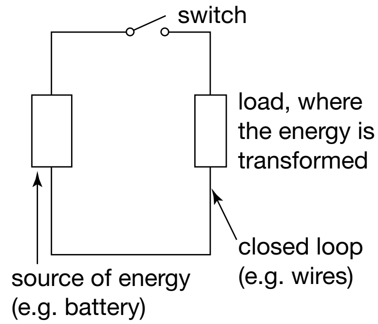


Diagram of an electric circuit

Back to basics

Electric charge

Electric charge is a basic property of matter. It occurs in two states: positive (+) charge and negative (–) charge.

Electric charge is a basic property of matter. Matter is all the substance that surrounds us — solid, liquid and gas.

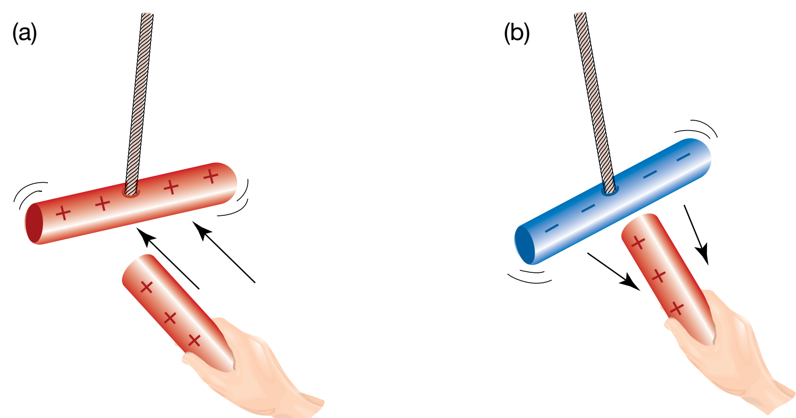
You will have experienced a small electric shock when you touched a metal rail after walking across carpet. This type of phenomenon has been observed for thousands of years. Objects such as glass, gemstones, tree resin and amber can become 'electrified' by friction when they are rubbed with materials such as animal fur and fabrics to produce a spark. Indeed the word 'electricity' comes from the Ancient Greek word for amber.

Experiments in the early 1700s showed that:

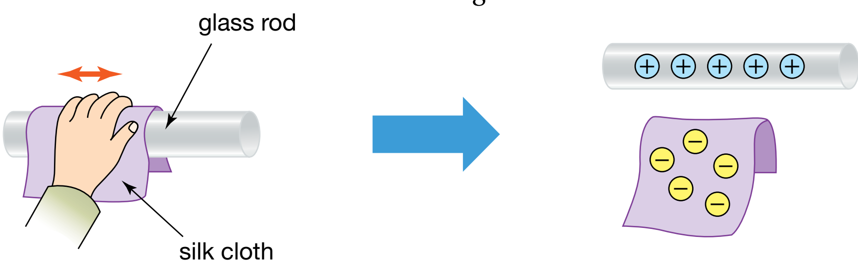
- both the object and the material became 'electrified' or 'charged'
- when charged objects were brought near each other, for some objects there was a force of attraction, while for others it was a force of repulsion.

An **electrostatic force** is the force between two stationary charged objects.

It was quickly observed that like-charged objects repelled each other while unlike-charged objects attracted each other. Charged objects exert a force on each other. The force between two stationary charged objects is called an **electrostatic force**.



(a) Two positively charged objects repel each other. (b) Oppositely charged objects attract each other.



The charge developed by glass rubbed with silk was arbitrarily assigned as positive charge and resin rubbed with flannel was deemed to have negative charge. It was also found that when the glass acquired an amount of positive charge, the silk acquired an equal amount of negative charge.

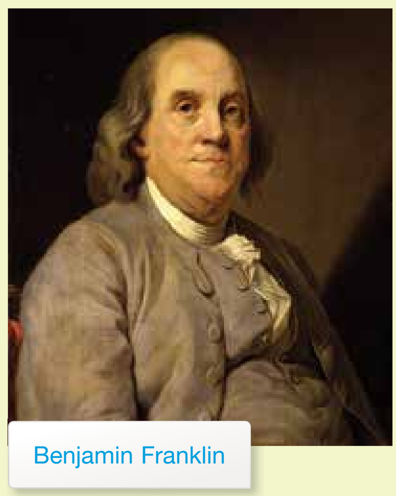
Possible explanations for these observations abounded, but further experiments could not determine the correct theory. In the mid-1700s Benjamin Franklin suggested that positively charged fluid was transferred from the silk to the glass. This made the silk negative and the glass positive, although a negatively charged fluid was equally plausible. Franklin's status as an eminent scientist ensured that the existence of a positive fluid was accepted and all developments in electrical engineering for the next 150 years were based on this convention. By 1897, when JJ Thomson demonstrated that the negatively charged electron was responsible for electricity, it was too late to change the convention and all the associated labelling of meters.

Electric charge is conserved — it can be neither created nor destroyed. A **neutral** object carries an equal amount of positive and negative charge.

A **neutral** object carries an equal amount of positive and negative charge.

AS A MATTER OF FACT

Benjamin Franklin (1706–1790), an American political leader, inventor and scientist, introduced the concepts of positive and negative electricity. His research on lightning, including discharges obtained with a kite, helped to establish its electrical nature. He advocated the use of lightning rods as protective devices for buildings. Franklin was almost killed one day when he was trying to electrocute a turkey with a condenser, a device used to store charge. (Members of genteel society at the time thought it was acceptable to see how big an animal they could electrocute.)



Benjamin Franklin

REMEMBER THIS

All matter is made up of atoms. Atoms in turn are made up of smaller particles called protons, neutrons and electrons. Protons and neutrons are found in the nucleus while the electrons move in well-defined regions called orbits or shells.

Protons and electrons possess a characteristic known as charge. Protons are positively charged and electrons are negatively charged. The magnitude of the charge of a proton is equal to that of an electron. Negative and positive charges neutralise each other. Neutrons have no electric charge.

Most of the mass of the atom is concentrated in its nucleus. Protons and neutrons have approximately the same mass (1.67×10^{-27} kg) which is about 1800 times the mass of an electron (9.11×10^{-31} kg).

The atomic number of an atom is equal to the number of protons in its nucleus; the mass number is equal to the total number of protons and neutrons.

Elements are substances whose atoms all have the same atomic number. Metals are a category of element whose outer electrons are so loosely bound to the nucleus that they are effectively free to move easily through the material. Normally this movement is random.

Conductors and insulators

In an **electric insulator** the electrons are bound tightly to the nucleus and are not free to travel through the material.

An **ion** is a charged particle.

Some materials are made up of atoms which are bound together in such a way that all their electrons are bound tightly to the nucleus and are not free to travel through the material. Such substances are termed **electric insulators**. Examples of insulators include glass, plastics and non-metals.

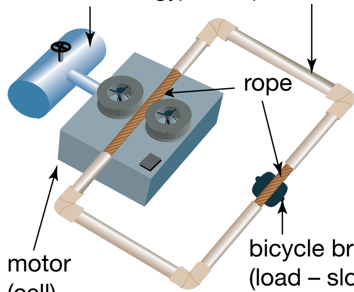
Materials where charge can travel freely are called electrical conductors. Examples include metals that have loosely bound electrons, and salt water in which charged particles, such as **ions**, are free to move.

Modelling an electric circuit

A **model** uses objects and phenomena that we can see and understand or have experienced to explain things that we cannot see.

One way to understand something we can't see is to use a **model**. A good scientific model uses objects and phenomena that we can see and understand or have experienced to explain things that we cannot see.

To understand what happens in basic electric circuits, imagine a machine consisting of a motor that makes a rope move through a pipe. The rope fills the pipe and there is very little friction between the pipe and the rope. (The pipe is teflon-coated to reduce friction.) The motor has a supply of fuel, and the faster the rope moves, the faster the fuel is used up. The motor gives energy to the rope, using two wheels that rotate to move the rope through the pipe. The purpose of the motor is to supply energy to places along the pipe, just as a battery is used to provide energy to the load in a circuit.



A model of an electric circuit

In a basic circuit, such as a globe or a resistor connected to a battery, most of the energy is transformed into thermal energy. (The filament in a globe gets so hot that it emits light.)

To model a load, imagine a set of bicycle brakes that grip the rope. Friction between the rope and the brakes produces thermal energy and slows down the rope. If you've ever gripped a moving rope, or slid down a rope, you'll have some idea of the thermal energy produced. The harder the rope is gripped, the more energy is transformed at the brakes and the more slowly the rope moves.

An **electric cell** supplies energy to a circuit from chemical reactions; it can be modelled by a motor with a supply of fuel.

A **battery** is composed of two or more cells in series in a single unit.

The motor with its supply of fuel is a model of an **electric cell**. If there are two or more cells (motors) in series in a single unit, the unit is called a **battery** and more energy is available to the load. The energy is transferred to the brakes, which represent a load. Little energy is transformed in the pipe because of the small amount of friction between the rope and the pipe. The moving rope represents the movement of electrons around the circuit.

This model demonstrates how energy is transformed in a circuit. Energy is supplied to the circuit by the cell (the motor) from chemical reactions, and is transformed into other forms in the load. Note that the transformation is virtually instantaneous. It is caused by the movement of the charge carriers (the rope) through the load. The charge carriers that received the energy do not have to get to the load before the transformation takes place.

Current

Electric current is the movement of charged particles from one place to another.

A **charge carrier** is a charged particle moving in a conductor.

Electric current is the movement of charged particles from one place to another. The charged particles may be electrons in a metal conductor or ions in a salt solution. Charged particles that move in a conductor can also be referred to as '**charge carriers**'.

There are many examples of electric currents. Lightning strikes are large currents. Nerve impulses that control muscle movement are examples of small currents. Charge flows in household and automotive electrical devices such as light globes and heaters. Both positive and negative charges flow in cells, in batteries and in the ionised gases of fluorescent lights. The solar wind is an enormous flow of protons, electrons and ions being blasted away from the Sun.

studyon

Unit 1 | AOS 2 | Topic 1 | Concept 1

Electric current and charge
Concept summary and practice questions

Not all moving charges constitute a current. There must be a net movement of charge in one direction for a current to exist. In a piece of metal conductor, electrons are constantly moving in random directions, but there is no net movement in one direction and no current. A stream of water represents a movement of millions of coulombs of charge as the protons and electrons of the water molecules move. There is no electrical current in this case, because equal numbers of positive and negative charge are moving in the same direction.

For there to be a current in a circuit such as in the upper figure on page 47, there must be a complete conducting pathway around the circuit and a device to make the charged particles move. When the switch in the circuit is open, the pathway is broken and the current stops almost immediately.

Conventional current

Conventional current is defined as the movement of positive charges from the positive terminal of a cell through the conductor to the negative terminal.

Electron current is the term used when dealing with the mechanisms for the movement of electrons.

By the time the battery was invented by Alessandro Volta in 1800, it was accepted that electric current was the movement of positive charge. It was assumed that positive charges left the positive terminal of the battery and travelled through a conductor to the negative terminal. This is called **conventional current.**

In reality, the charge carriers in a metal conductor are electrons moving from the negative terminal towards the positive terminal of the battery. The effect is essentially the same as positive charges moving in the opposite direction.

When dealing with the mechanisms for the movement of electrons, the term '**electron current**' is used.

Direct current

Direct current (DC) refers to circuits where the net flow of charge is in one direction only.

Direct current (DC) refers to circuits where the net flow of charge is in one direction only. The current provided by a battery is direct current, which usually flows at a steady rate.

Alternating current

Alternating current (AC) refers to circuits where the charge carriers move backwards and forwards periodically.

Alternating current (AC) refers to circuits where the charge carriers move backwards and forwards periodically. The electricity obtained from household power points is alternating current.

The rope model described previously helps to explain direct current and alternating current. In a direct current circuit the current (rope) moves in one direction only. The current moves at a steady rate when a cell is used. In an alternating current circuit the current periodically changes direction (the rope is pulled backwards and forwards through the pipe). In terms of the rope model, energy is still transferred at the brakes (load) even though the rope where the energy is supplied never reaches the brakes.

Electric current is a measure of the rate of flow of charge around a circuit. It can be expressed as:

$$I = \frac{Q}{t}$$

where I is the current and Q is the quantity of charge flowing past a point in the circuit in a time interval t.

The **ampere** is the unit of current.

The **coulomb** is the unit of electric charge.

The unit of current is the **ampere** (A). It is named in honour of the French physicist André-Marie Ampère (1775–1836).

The unit for charge is the **coulomb** (C), named after the French physicist Charles-Augustin de Coulomb (1736–1806).

One coulomb of charge is equal to the amount of charge carried by 6.24×10^{18} electrons. The charge carried by a single electron is equal to -1.602×10^{-19} C.

One ampere is the current in a conductor when 1 coulomb of charge passes a point in the conductor every second.

The charge possessed by an electron is the smallest free charge possible. All other charges are whole-number multiples of this value. This so-called elementary charge is equal in magnitude to the charge of a proton. The charge of an electron is negative, whereas the charge of a proton is positive.

André-Marie Ampère

AS A MATTER OF FACT

Charges smaller than that carried by the electron are understood to exist, but they are not free to move as a current. Particles such as neutrons and protons are composed of quarks, with one-third of the charge of an electron, but these are never found alone.

Sample problem 4.1

What is the current in a conductor if 10 coulombs of charge pass a point in 5.0 seconds?

Solution:

$$Q = 10 \text{ C}$$
$$t = 5.0 \text{ s}$$
$$I = \frac{Q}{t} = \frac{10 \text{ C}}{5.0 \text{ s}} = 2.0 \text{ C s}^{-1} = 2.0 \text{ A}$$

Sample problem 4.2

How much charge passes through a load if a current of 3.0 A flows for 5 minutes and 20 seconds?

Solution:

$$I = \frac{Q}{t}$$

or $Q = It$

$$I = 3.0 \text{ A}$$
$$t = 5 \text{ minutes and 20 seconds} = 320 \text{ s}$$
$$Q = 3.0 \text{ A} \times 320 \text{ s} = 960 \text{ C} = 9.6 \times 10^2 \text{ C}$$

Revision question 4.1

What is the current passing through a conductor if 15 coulombs of charge pass a point in 3.0 seconds?

Revision question 4.2

For how long must a current of 2.5 amperes flow to make 7.5 coulombs of charge pass a point in a circuit?

In real circuits, currents of the order of 10^{-3} A are common. To describe these currents, the milliampere (mA) is used. One milliampere is equal to 1×10^{-3} ampere.

To convert from amperes to milliamperes, multiply by 1000 or by 10^3. To convert from milliamperes to amperes, divide by 1000 or multiply by 10^{-3}.

Sample problem 4.3

Convert 450 mA to amperes.

Solution:

$$\frac{450\ \text{mA}}{1000} = 0.450\ \text{A}$$

So 450 mA is equal to 0.450 A.

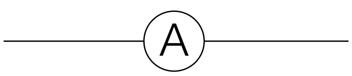
An **ammeter** is a device used to measure current.

Measuring electric current

Electric current is measured with a device called an **ammeter**. This must be placed directly in the circuit so that all the charges being measured pass through it. This is known as placing the ammeter in series with the circuit.

Ammeters are designed so that they do not significantly affect the size of the current by their presence. Their resistance to the flow of current must be negligible.

The circuit diagram symbol for an ammeter is shown at left.



The circuit diagram symbol for an ammeter

Most school laboratories now use digital multimeters. These can measure voltage drop and resistance as well as current. Each quantity has a few settings to allow measurement of a large range of values. Labels on multimeters may vary, but those given below are most common.

The black or common socket, labelled 'COM', is connected to the part of the circuit that is closer to the black or negative terminal of the power supply. The red socket, labelled 'VΩmA', is used for measuring small currents and is connected to the part of the circuit that is closer to the red or positive terminal of the power supply. The red socket, labelled '10A MAX' or similar, is used for measuring large currents, see warning below. The dial has a few settings, first choose the setting for current, labelled 'A', with the largest value. If you want more accuracy in your measurement, turn the dial to a smaller setting. If the display shows just the digit '1', the current you are trying to measure exceeds the range of that setting and you need to go back to a higher setting.

A digital multimeter, which can measure current, voltage drop and resistance

WARNING: While for most quantities, multimeters are quite tolerant of values beyond a chosen setting, care must be taken when measuring current. Multimeters have a fuse that can blow if the current exceeds the rated value. For this reason, they have two red sockets. One socket is for exclusive use when measuring currents in the range 200 mA to 10A. This is labelled '10A MAX'. (Some multimeters may be able to measure up to 20 A.) The other red socket is for currents less than 200 mA as well as the other quantities of voltage and resistance.

If you are using a needle type ammeter, the instructions above generally apply.

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Interactivity
The hydraulic model of current
int-0053
eLesson
The hydraulic model of current
eles-0029
Weblink
Calculating an electron's drift velocity

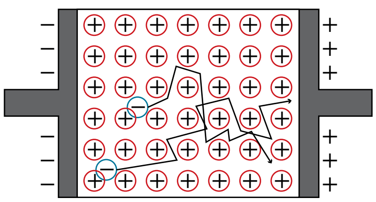
The hydraulic model of current

Most circuits have metal conductors, which means that the charge carriers will be electrons.

Metal conductors can be considered to be a three-dimensional arrangement of atoms which have one or more of their electrons loosely bound. These electrons are so loosely bound that they tend to drift easily among the atom. Metals are good conductors of both heat and electricity because of the ease with which these electrons are able to move, transferring energy as they go. Diagrammatically, the atoms are represented as positive ions (atoms that have lost an electron and have a net positive charge) in a 'sea' of free electrons.

When the ends of a conductor are connected to a battery, the free electrons drift towards the positive terminal. The electrons are attracted by the positive terminal and indeed accelerate, but constantly bump into atoms, so on average they just drift along.

The flow of electrons through a metallic conductor can be modelled by the flow of water through a pipe.



The motion of free electrons through a metal. *Note:* Only two of the free electrons have been shown.

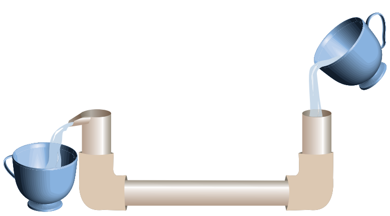
Electrons cannot be destroyed, nor, in a closed circuit, can they build up at a point. Therefore, if electrons are forced into one end of a conductor, an equal number will be forced out the other end. This is rather like pouring a cupful of water into one end of a full pipe. It forces a cupful of water to come out the other end.

Note that when water is put in one end it is not the same water that comes out the other end, because the pipe was already full of water.

How rapidly do electrons travel through a conductor?

The speed of electrons through the conductor depends on the cross-sectional area of the conductor, the number of electrons that are free to move, the electron charge and the size of the current.

For example, if a current of 10 A passes through a copper wire of cross-sectional area 1 mm^2, the electron speed is 0.16 mm s^{-1} or 1.6×10^{-4} m s^{-1}. This speed is known as the drift velocity (since the electrons are drifting through the wire), and is quite small.



The hydraulic model for current flow. One cupful of water in one end of the pipe means one cupful out the other end.

Sample problem 4.4

How long will it take an electron to travel from a car's battery to a rear light globe if it has a drift velocity of 1.0×10^{-4} m s^{-1} and there is 2.5 m of metal to pass through? (Electrons travel from the negative terminal of the battery through the car body towards the circuit elements.)

Solution: The drift velocity equals the distance travelled divided by the time taken to travel the distance. Therefore, the time taken equals the distance travelled divided by the drift velocity.

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

$$= \frac{2.5\,\text{m}}{1.0 \times 10^{-4}\,\text{m s}^{-1}}$$

$$= 2.5 \times 10^{4}\,\text{s}$$

This is almost 7 hours!

Voltage

A battery is a source of energy that enables electrons to move around a circuit. Inside the battery a chemical reaction separates electrons, leaving one terminal short of electrons and therefore with an excess of positive charge. The other battery terminal has an excess of electrons and so is the negative terminal.

Batteries are rated by their voltage (V). This is a measure of the amount of energy the battery gives to the separated charges. Energy (E) is measured in joules; charge (Q) is measured in coulombs. So a 9 volt battery gives 9 joules of energy to each coulomb of charge. This is summarised in the equation:

$$V = \frac{E}{Q} \text{ or } E = VQ$$

Sample problem 4.5

(a) How much energy does a 1.5 V battery give to 0.5 coulombs of charge?
(b) The charge on an electron is 1.6×10^{-19} coulombs. How much energy does each electron have as it leaves a 1.5 V battery?

Solution: (a) Using $E = VQ$

$$= 1.5 \times 0.5$$

$$= 0.75 \text{ joules}$$

(b) Using $E = VQ$

$$= 1.5 \times 1.6 \times 10^{-19}$$

$$= 2.4 \times 10^{-19} \text{ joules}$$

If the voltage had been only 1 volt, the answer would have been 1.6×10^{-19} joules.

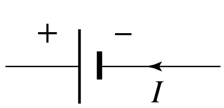
Note: In many technologies, such as X-ray machines and particle accelerators, the energy of electrons needs to be determined. The number 1.6×10^{-19} joules is inconvenient, so another energy unit is used. It is the called the 'electron volt', abbreviated eV, where 1 eV = 1.6×10^{-19} joules.

Revision question 4.3

A mobile phone battery has a voltage of 3.7 V. During its lifetime, 4000 coulomb of charge leave the battery. How much energy did the battery originally hold?

The electrons at the negative terminal of a battery are attracted to the positive terminal, but the chemical reaction keeps them apart. The only way for the electrons to get to the positive terminal is through a closed circuit. The energy the electrons gain from the chemical reaction is transferred in the closed circuit as the electrons go through devices such as light globes, toasters and motors.

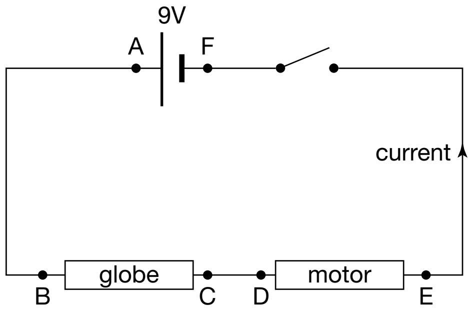
Once back at the positive terminal, the chemical reaction in the battery transfers the electrons across to the negative terminal, and then the electrons move around the circuit again.

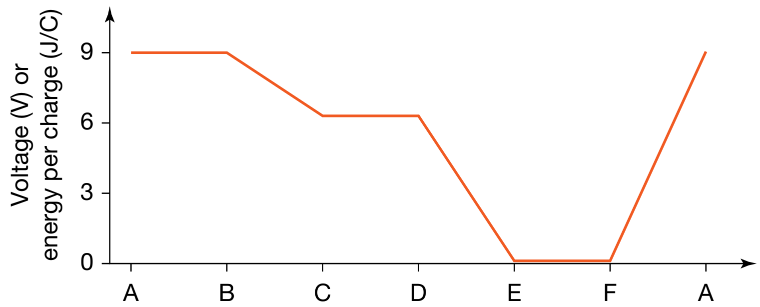


The circuit symbol for a battery showing direction of conventional current

The conventional point of view

Looking from the perspective of conventional current, that is, positive charge carriers, the current would go in the opposite direction. In the circuit that follows, positive charges at A, the positive terminal, would leave with energy and arrive at F with no energy. The graph below shows the energy held by one coulomb of charge, that is, the voltage, as the charge moves around the circuit from A to F.





At the positive terminal, A, the coulomb of charge has 9 joules of energy; its voltage is 9 V. The wire, AB, from the battery to the globe is a good conductor, so no energy is lost and the voltage is still at 9 V. In the globe, as the current goes from B to C, the coulomb of charge loses 3 joules of energy and now has a voltage of 6 V at C. The conducting wire from C to D has no effect, so the coulomb of charge arrives at the motor, DE, with 6 joules of energy. This energy is used up in the motor so that at E the voltage is 0 V. The charge then moves on to F, the negative terminal, where the battery re-energises the charge to go around again.

Voltage is also called the electric potential. Using the hydraulic model, at A the charge is like water in a high dam that has gravitational potential energy that can be released when the dam opens. The charge at A has an electric potential of 9 V or 9 joules for every coulomb, which can be released when a switch is closed.

Measuring potential difference or voltage drop

A **voltmeter** is a device used to measure potential difference.

The **potential difference** or **voltage drop** is the amount of electrical potential energy, in joules, lost by each coulomb of charge in a given part of a circuit.

The difference in voltage between any two points in the circuit can be measured with a **voltmeter**. This is called the **potential difference** or **voltage drop**. The voltmeter must be connected across a part of the circuit. If the voltmeter was connected to points A and B in the circuit above, it would display zero, as there is no difference in the potential or voltage between those two points. If instead it was connected across the globe at BC, it would show a voltage drop of 3 V (9 – 6 = 3 V). This means that in the globe 3 joules of electrical energy are lost by each coulomb of charge and transformed by the globe into light and heat.

Voltmeters are designed so that they do not significantly affect the size of the current passing through the circuit element. For this reason, the resistance of the voltmeter must be much higher than the resistance of the circuit elements involved. Resistance will be discussed later in this chapter. The circuit diagram symbol for a voltmeter is shown below left.

As discussed in the ammeter section, most school laboratories now use digital multimeters, which can generally measure both AC and DC voltages. To measure DC voltages, use one of the settings near the 'V' with a bar beside it.

The black or common socket, labelled 'COM', is connected to the part of the circuit that is closer to the black or negative terminal of the power supply. The red socket, labelled 'VΩmA', is used for measuring voltages and is connected to the part of the circuit closer to the red or positive terminal of the power supply. The other red socket, labelled '10A MAX' is only for large currents. The dial has a range of

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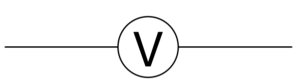
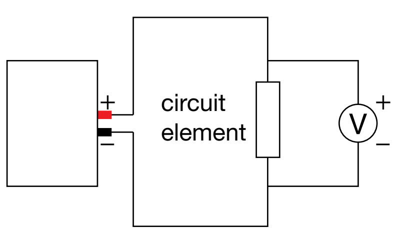


The circuit diagram symbol for a voltmeter



Connecting a voltmeter into a circuit

settings; when first connecting the multimeter, choose the setting with the largest value. If you want more accuracy in your measurement, turn the dial to a smaller setting. If the display shows just the digit '1', the voltage you are trying to measure exceeds the range of that setting and you need to go back to a higher setting.

Energy transformed by a circuit

Electric circuits transform electrical energy into other forms of energy. Since the potential difference is a measure of the loss in electrical potential energy by each coulomb of charge, the amount of energy (E) transformed by a charge (Q) passing through a load can be expressed as:

$$E = QV$$

$$\text{since } V = \frac{E}{Q}$$

where V is the potential difference across the load.

The amount of charge passing through a load in a time interval t can be expressed as:

$$Q = It$$

Thus $$E = VIt$$

where I is the current.

Sample problem 4.6

What is the potential difference across a heater element if 3.6×10^4 J of heat energy are produced when a current of 5.0 A flows for 30 s?

Solution:

$$E = 3.6 \times 10^4 \text{ J}$$
$$I = 5.0 \text{ A}$$
$$t = 30 \text{ s}$$
$$V = ?$$
$$E = VIt$$
$$\text{or } V = \frac{E}{It}$$
$$= \frac{3.6 \times 10^4 \text{ J}}{5.0 \text{ A} \times 30 \text{ s}}$$
$$= 240 V$$

Revision question 4.4

What is the potential difference across a light globe if 1.44×10^3 J of heat is produced when a current of 2.0 A flows for 1.0 minute?

Power delivered by a circuit

Power is the rate of doing work, or the rate at which energy is transformed from one form to another.

In practice, it is the rate at which energy is transformed in an electrical load that determines its effect. The brightness of an incandescent light globe is determined by the rate at which electrical potential energy is transformed into the internal energy of the filament.

Power is the rate of doing work, or the rate at which energy is transformed from one form to another. Power is equal to the amount of energy transformed

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Unit 1 | AOS 2 | Topic 1 | Concept 3

Energy and power
Concept summary and practice questions

per second, or the amount of energy transformed divided by the time it took to do it. It can therefore be expressed as:

$$P = \frac{E}{t}$$

where P is the power delivered when an amount of energy E is transformed in a time interval t.

The SI unit of power is the watt (W).
1 watt = 1 joule per second = 1 J s^{-1}

$$E = VIt \text{ and } P = \frac{E}{t}$$

Therefore $P = \frac{VIt}{t}$

$$\Rightarrow P = VI$$

This is a particularly useful formula because the potential difference V and electric current I can be easily measured in a circuit.

Sample problem 4.7

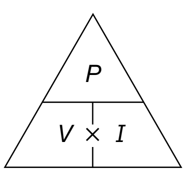
What is the power rating of an electric heater if a current of 5.0 A flows through it when there is a voltage drop of 240 V across the heating element?

Solution:

$I = 5.0$ A
$V = 240$ V
$P = VI$
$= 240 \text{ V} \times 5.0 \text{ A}$
$= 1200$ W
or 1.2 kW

Revision question 4.5

What is the power rating of a CD player if it draws a current of 100 mA and is powered by four 1.5 V cells in series?



Power formula triangle

1 kilowatt = 1×10^3 watts

When converting from watts to kilowatts, divide by 1000.
When converting from kilowatts to watts, multiply by 1000.

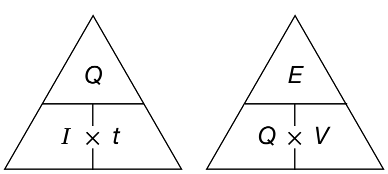
Transposing formulae

If you have trouble transposing formulae to solve a question, you could use the triangle above left.

Cover the pronumeral you want to be the subject, for example I. What is visible in the triangle shows what that pronumeral equals. In this example,

$$I = \frac{P}{V}.$$

This method can also be used for any formula of the form $x = yz$. For example, $Q = It$ and $E = QV$.



Variants of the power formula triangle

Sample problem 4.8

How much energy is supplied by a mobile phone battery rated at 3.7 V and 1200 mAh? 'mAh' stands for milliamp hours, which means that the battery would last for one hour supplying a current of 1200 mA or two hours at 600 mA.

Solution:

$V = 3.7\text{ V}$

$I = 1200\text{ mA} = 1.2\text{ A},$

$t = 60 \times 60 = 3600\text{ s}.$

The energy produced is given by $E = VIt$, so

$$E = 3.7 \times 1.2 \times 3600$$
$$= 16\text{ kJ}$$

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Investigation 4.1:
Energy transferred by an electric current
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Revision question 4.6

A 3.7 V mobile phone battery has an energy capacity of 14 000 joules. In a talk mode test, the battery lasted for 6 hours. What was the average current?

Providing energy for the circuit

Electromotive force is a measure of the energy supplied to a circuit for each coulomb of charge passing through the power supply.

The purpose of 'plug-in' power supplies, batteries or cells is to provide energy for the circuit. Such devices are said to provide an **electromotive force** or emf. The term electromotive force is misleading since it does not refer to a 'force', measured in newtons. It is a measure of the energy supplied to the circuit for each coulomb of charge passing through the power supply. The circuit symbol for emf is ε.

The unit of emf is the volt (V) because it is a measure of energy per coulomb. A power supply has an emf of X volts if it provides the circuit with X joules of energy for every coulomb of charge passing through the power supply.

The rate at which an emf source supplies energy to a circuit is the product of the emf and current. The amount of energy (E) supplied to the charge passing through the power supply is equal to the amount of energy given to each coulomb, or emf (ε), multiplied by the amount of charge (Q) passing through the power supply:

$$E = \varepsilon Q$$

This can be rewritten as:

$$E = \varepsilon It$$

since $Q = It$ and t is the time interval during which energy is transferred.

The power delivered to the charge passing through the power supply can therefore be expressed as:

$$I = \frac{E}{t}$$

$$\Rightarrow P = \varepsilon I.$$

This is the formula used to determine the rate at which a source of emf supplies energy to a circuit.

Sample problem 4.9

A 12 V car battery has a current of 2.5 A passing through it. At what rate is it supplying energy to the car's circuits?

Solution:

$\varepsilon = 12\text{ V}$

$I = 2.5\text{ A}$

$$P = EI$$
$$= 12\text{ V} \times 2.5\text{ A}$$
$$= 30\text{ W}$$

The **resistance**, *R*, of a substance is defined as the ratio of voltage drop, *V*, across it to the current, *I*, flowing through it.

Georg Simon Ohm

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The current-versus-voltage characteristics of a light globe
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Resistance

The **resistance**, *R*, of a substance is defined as the ratio of the voltage drop, *V*, across it to the current, *I*, flowing through it.

$$R = \frac{V}{I}$$

The resistance of a device is a measure of how difficult it is for a current to pass through it. The higher the value of resistance, the harder it is for the current to pass through the device.

The SI unit of resistance is the ohm (symbol Ω). It is the resistance of a conductor in which a current of one ampere results from the application of a constant voltage drop of one volt across its ends.

$$1\ \Omega = 1\ \text{V A}^{-1}$$

The ohm is named in honour of Georg Simon Ohm (1787–1854), a German physicist who investigated the effects of different materials in electric circuits.

PHYSICS IN FOCUS

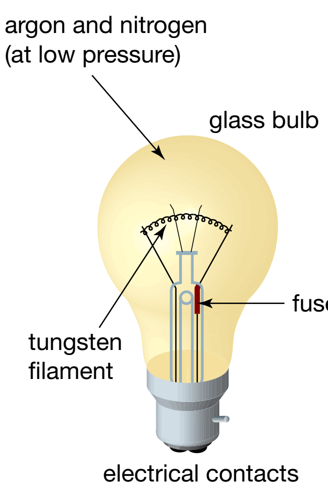
The lie detector

The lie detector, or polygraph, is a meter which measures the resistance of skin. The resistance of skin is greatly reduced by the presence of moisture. When people are under stress, as they may be when telling lies, they sweat more. The subsequent change in resistance is detected by the polygraph and is regarded as an indication that the person *may* be telling a lie.

The resistance, of a material depends on its temperature. In general, the resistance of a metal conductor increases with temperature. Usually, the increases will not be significant over small temperature ranges and most problems in this book ignore any temperature and resistance changes that might occur. Resistance does not depend on the voltage drop across the substance nor the current through it.

One example of the effect of a change in temperature on resistance can be seen in the tungsten filament of an ordinary light globe.

When operating normally, the filament reaches a temperature of 2500 °C. The globe is filled with inert gases to prevent the filament from burning or oxidising. Tungsten is used because it has a high melting point. The filament is coiled to increase the length, and it has a very small cross-sectional area so that the resistance of the filament is increased. As the temperature of the filament increases, its resistance increases due to an increase in tungsten's resistivity.



A 240-volt, 60-watt globe

Resistors

In many electrical devices, **resistors** are used to control the current flowing through, and the voltage drop across, parts of the circuits. Resistors have constant resistances ranging from less than one ohm to millions of ohms. There are three main types of resistors. 'Composition' resistors are usually made of the semiconductor carbon. The wire wound resistor consists of a coil of fine wire made of a resistance alloy such as nichrome. The third type is the metal film resistor, which consists of a glass or pottery tube coated with a thin film of metal. A laser trims the resistor to its correct value.

A **resistor** is used to control the current flowing through, and the voltage drop across, parts of a circuit.

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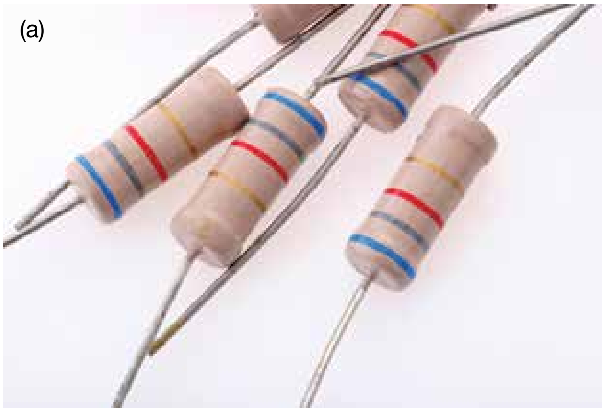
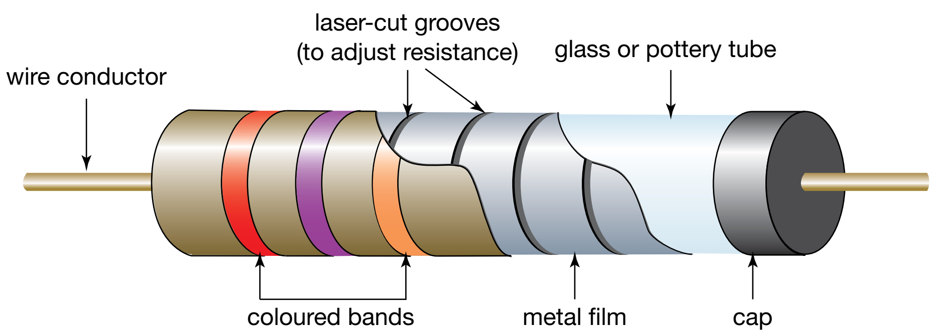
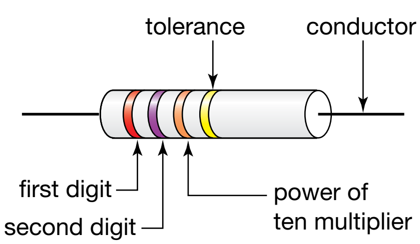


Examples of (a) carbon resistors and (b) a coiled wire resistor

Some large resistors have their resistance printed on them. Others have a colour code to indicate their resistance, as shown in the table and figure below. The resistor has four coloured bands on it. The first two bands represent the first two digits in the value of resistance. The next band represents the power of ten by which the two digits are multiplied. The fourth band is the manufacturing tolerance.



Example of a metal film resistor



A resistor, showing the coloured bands

TABLE 4.1 The resistor colour code

Colour	Digit	Multiplier	Tolerance
Black	0	10^0 or 1	
Brown	1	10^1	
Red	2	10^2	±2%
Orange	3	10^3	
Yellow	4	10^4	
Green	5	10^5	
Blue	6	10^6	
Violet	7	10^7	
Grey	8	10^8	
White	9	10^9	
Gold		10^{-1}	±5%
Silver		10^{-2}	±10%
No colour			±20%

Sample problem 4.10

What is the resistance of the following resistors if their coloured bands are:
(a) red, violet, orange and gold
(b) brown, black, red and silver?

Solution: (a) Red = 2, violet = 7, so the first two digits are 27.

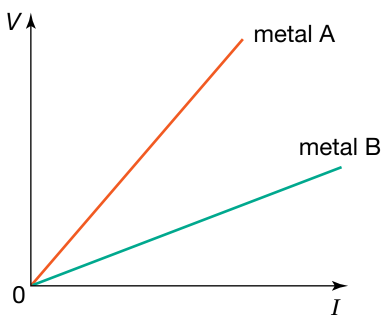
The third band is orange, which means multiply the first two digits by 10^3. So the resistance is 27 000 Ω, or 27 kΩ.

The fourth band is gold, which means there is a tolerance of 5%. This means that the true value is 27 000 Ω ± 1350 Ω (5% of 27 000 Ω).

(b) Brown and black give 10. Red means multiply by 10^2, so the resistance is 1.0×10^3 Ω, and the tolerance is 10%.

When holding a resistor to read its value, keep the gold or silver band on the right and read the colours from the left.

Ohm's Law



Graphs of *V* versus *I* for two different metal wires

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Ohm's Law app

Georg Ohm established experimentally that the current *I* in a metal wire is proportional to the voltage drop *V* applied to its ends.

$$I \propto V$$

When he plotted his results on a graph of *V* versus *I*, he obtained a straight line.

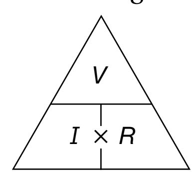
The equation of the line is known as Ohm's Law and can be written:

$$V = IR$$

where *R* is numerically equal to the constant gradient of the line. This is known as the resistance of the metal conductor to the flow of current through it. Remember that the SI unit of resistance is the ohm.

If you have trouble transposing equations, you can use the triangle method for Ohm's Law: simply cover the quantity you wish to calculate, and the triangle indicates what to do.

For example, if you are given the voltage drop and the current and you wish to find the resistance, cover *R*, and the triangle shows that $R = \frac{V}{I}$.



Triangle for Ohm's Law

Sample problem 4.11

A transistor radio uses a 6 V battery and draws a current of 300 mA. What is the resistance of the radio?

Solution: From Ohm's Law: $R = \frac{V}{I}$

so $R = \frac{6\ V}{0.3\ A}$ (since 300 mA = 0.3 A)

$= 20\ \Omega.$

Remember, the voltage drop must be expressed in volts and current must be expressed in amperes.

Note that the equation used for defining resistance is $R = \frac{V}{I}$. This is not Ohm's Law unless *R* is constant. The *V* versus *I* graph is not a straight line for a metallic conductor unless the temperature is constant.

An **ohmic device** is one for which, under constant physical conditions such as temperature, the resistance is constant for all currents that pass through it.

A **non-ohmic device** is one for which the resistance is different for different currents passing through it.

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Unit 1	**Resistance: ohmic and non-ohmic**
AOS 2	Concept summary and practice questions
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Unit 1	**Diodes and LEDs**
AOS 2	Concept summary and practice questions
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A **diode** is a device that allows current to pass through it in one direction.

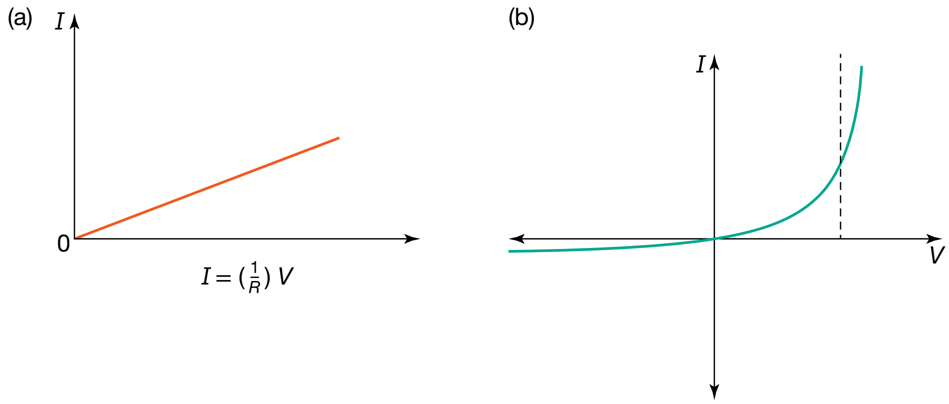
A **light-emitting diode (LED)** is a small semiconductor diode that emits light when a current passes through it.

A **thermistor** is a device that has a resistance which changes with a change in temperature.

Ohmic and non-ohmic devices

An **ohmic device** is one for which, under constant physical conditions such as temperature, the resistance is constant for all currents that pass through it.

A **non-ohmic device** is one for which the resistance is different for different currents passing through it.



The I versus V graphs for (a) an ohmic resistor and (b) a diode, which is a non-ohmic device

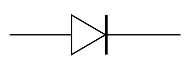
The graph beside the section on Ohm's Law has voltage on the y-axis and current on the x-axis. The graph is drawn this way so that the gradient of lines for the metals A and B gave the resistance of each. However, the size of the current in a circuit depends on the magnitude of the voltage; that is, the voltage is the independent variable and the current is the dependent variable. The accepted convention graphs the independent variable on the x-axis and the dependent variable on the y-axis. So in graph (a) above the gradient equals $\frac{1}{R}$.

Non-ohmic devices

Many non-ohmic devices are made from elements that are semiconductors. They are not insulators as they conduct electricity, but not as well as metals. Common semiconductor elements are silicon and germanium, which are in Group 14 of the periodic table. Many new semiconductor devices are compounds of Group 13 and Group 15 elements such as gallium arsenide.

The conducting properties of silicon and germanium can be substantially changed by adding a very small quantity of either a Group 13 element or a Group 15 element. This is called doping and affects the movement of electrons in the material.

A **diode** is formed by joining two differently doped materials together. A diode allows current to flow through it in only one direction. This effect can be seen in the current–voltage graph for a diode in graph (b), where a small positive voltage produces a current, while a large negative or reverse voltage produces negligible current.



Circuit symbol for a diode

Light-emitting diodes (LEDs) are diodes that give off light when they conduct. They are usually made from gallium arsenide. Gallium nitride is used in blue LEDs.

Thermistors are made from a mixture of semiconductors so they can conduct electricity in both directions. They differ from metal conductors, whose resistance increases with temperature, as in thermistors an increase in temperature increases the number of electrons available to move and the resistance decreases.

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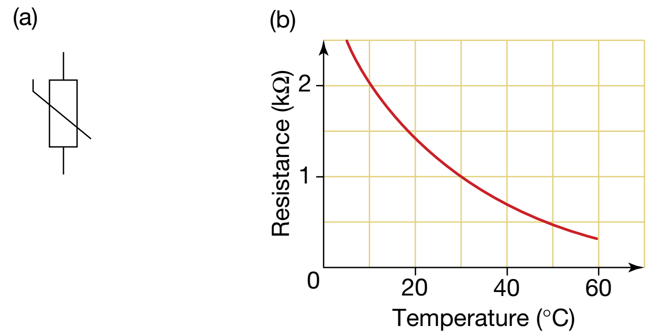
Unit 1 | AOS 2 | Topic 1 | Concept 7

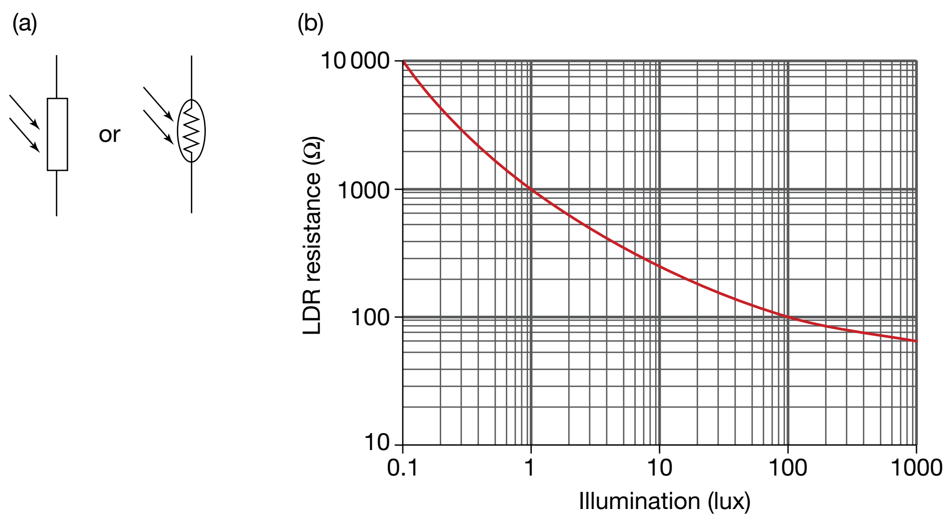
Thermistors and LDRs
Concept summary and practice questions



(a) Circuit symbol for a thermistor; (b) resistance-versus-temperature graph for a thermistor

A **light-dependent resistor (LDR)** is a device that has a resistance which varies with the amount of light falling on it.

Light-dependent resistors (LDRs) are like thermistors, except they respond to light. The resistance of an LDR decreases as the intensity of light shining on it increases. The axes in the graph below for an LDR have different scales to the other graphs. As you move from the origin, each number is 10 times the previous one. This enables more data to fit in a small space.



(a) Circuit symbols for an LDR; (b) resistance-versus-light intensity graph for an LDR

Heating effects of currents

Whenever a current passes through a conductor, thermal energy is produced. This is due to the fact that the mobile charged particles, for example electrons, make repeated collisions with the atoms of the conductor, causing them to vibrate more and producing an increase in the temperature of the material.

This temperature increase is not related to the direction of the current. A current in a conductor always generates thermal energy, regardless of which direction the current flows. Examples of devices that make use of this energy include radiators, electric kettles, toasters, stoves, incandescent lamps and fuses.

AS A MATTER OF FACT

Nichrome is a heat-resistant alloy used in electrical heating elements. Its composition is variable, but is usually around 62% nickel, 15% chromium and 23% iron.

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Unit 1 | AOS 2 | Topic 1 | Concept 5

Power, energy and resistance
Concept summary and practice questions

Power and resistance

The rate at which energy is dissipated by any part of an electric circuit can be expressed as:

$$P = VI$$

where

P = power

I = current

V = voltage drop.

This relationship can be used, along with the definition of resistance, $R = \frac{V}{I}$, to deduce two different formulae describing the relationship between power and resistance:

$$P = VI = (IR)I$$

Thus $P = I^2R$.

$$P = VI = V\left(\frac{V}{R}\right) \quad [1]$$

Thus $P = \frac{V^2}{R}$. [2]

You now have three different ways of determining the rate at which energy is transferred as charge flows through a voltage drop in an electric circuit:

$$P = VI \qquad P = I^2R \qquad P = \frac{V^2}{R}.$$

In addition, the quantity of energy transferred, E, can be determined using:

$$E = VIt = I^2Rt = \frac{V^2t}{R}.$$

These formulae indicate that in conducting wires with low resistance, very little energy is dissipated. If the resistance, R, is small, and the voltage drop, V, is small, the rate of energy transfer is also small.

Sample problem 4.12

A portable radio has a total resistance of 18 Ω and uses a 6.0 V battery consisting of four 1.5 V cells in series. At what rate does the radio transform electrical energy?

Solution:

$$P = \frac{V^2}{R}$$

$$= \frac{(6.0\ \text{V})^2}{18\ \Omega}$$

$$= 2.0\ \text{W}$$

Sample problem 4.13

A pop-up toaster is labelled '240 V, 800 W'.

(a) What is the normal operating current of the toaster?

(b) What is the total resistance of the toaster while it is operating?

Solution: (a) $P = VI$

$$\Rightarrow I = \frac{P}{V}$$

$$= \frac{800\ \text{W}}{240\ \text{V}}$$

$$= 3.3\ \text{A}$$

(b) $P = \frac{V^2}{R}$

$$\Rightarrow R = \frac{V^2}{P}$$

$$= \frac{(240\ \text{V})^2}{800\ \text{W}}$$

$$= 72\ \Omega$$

Revision question 4.7

A microwave oven is labelled '240 V, 600 W'.

(a) What is the normal operating current of the microwave oven?

(b) What is the total resistance of the microwave oven when it is operating?

Chapter review

studyon
Unit 1
AOS 2
Topic 1
Current electricity
Sit Topic test

Summary

- An electric circuit is a complete conducting path containing an energy supply and a load.
- Current is the rate of flow of charge. Direct current always flows in one direction. Alternating current periodically reverses its direction in a circuit.
- Conventional current is defined as flowing from the positive to the negative terminal of a supply, even though the charge is usually carried by electrons travelling in the opposite direction.
- Electric current is measured with an ammeter.
- The potential difference across part of an electric circuit is a measure of the electrical potential energy lost by charge carriers. This can be expressed as

$$V = \frac{E}{Q}.$$

- Potential difference is measured using a voltmeter.
- The electromotive force (emf) of a power supply is a measure of the amount of energy supplied to the circuit for each coulomb of charge passing through that supply.
- Resistance is the opposition provided by a substance to the flow of current through it.
- Ohm's Law states the current flowing in a metal wire varies directly with the voltage drop across the conductor and inversely with the resistance of the conductor. The graph of voltage drop versus current at a constant temperature is a straight line.
- The amount of energy transformed in a device during a given time interval can be calculated using the equation $E = VIt$.
- Power is the rate at which work is done, or at which energy is transformed from one form into another.
- The power delivered to a device in an electric circuit can be calculated using the equation $P = VI$.
- Non-ohmic devices such as LDRs, LEDs, diodes and thermistors do not obey Ohm's Law.

Questions

Electric circuits

1. Imagine you are an electron. Describe your journey around the closed circuit of a torch, beginning at the negative terminal of a cell.

Current

2. State the difference between conventional current and electron current.
3. What is the difference between direct current and alternating current?
4. Name three devices which produce a steady direct current.
5. A steady direct current of 2.5 A flows in a wire connected to a battery for 15 seconds. How much charge enters or leaves the battery in this time?
6. Convert 45 mA to amperes.
7. Convert 2.3×10^{-4} A to milliamperes.
8. Convert 450 μA to amperes ($1 \mu\text{A} = 1 \times 10^{-6}$ A).
9. Is current used up in a light globe? Explain your answer.
10. A car light globe has a current of 3.5 A flowing through it. How much charge passes through it in 20 minutes?
11. What is the current flowing through an extension cord if 15 C of charge passes through it in 50 seconds?
12. The drift velocity is directly proportional to the current in the conductor. If electrons have a drift velocity of 1.6×10^{-4} m s^{-1} for a current of 10 A in a certain conductor, what would be their velocity if the current was 5.0 A?

Potential difference

13. What is the emf of a battery that gives 1.05 J of energy to 0.70 C of charge which passes through it?
14. Copy and complete the following table.

Potential difference	Energy	Charge
? V	32 J	9.6 C
? V	4.0 J	670 mC
9.0 V	? J	3.5 C
12 V	? J	85 mC
4.5 V	12 J	? C
240 V	7.5 kJ	? C

15. How much electrical potential energy will 5.7 μC of charge transfer if it passes through a voltage drop of 6.0 V?
16. A 6.0 V source supplies 3.6×10^{-4} J of energy to a quantity of charge. Determine the quantity of charge in coulombs and microcoulombs.

Energy and power in circuits

17. Calculate the current drawn by:
    (a) a 60 W light globe connected to a 240 V source
    (b) a 40 W globe with a voltage drop of 12 V across it
    (c) a 6.0 V, 6.3 W globe when operating normally
    (d) a 1200 W, 240 V toaster when operating normally.

18. The element of a heater has a voltage drop of 240 V across it.
(a) What does this mean?
(b) How much energy is transformed into thermal energy in the element if 25 C of charge flow through it?

19. How much energy is transformed by a rear window demister circuit if it draws 2.0 A of current from a 12 V battery for 30 minutes?

20. What is the power rating of the car demister described in question 19?

21. How long will it take a 600 W microwave oven to transform 5.4×10^4 J of energy?

22. What is the power rating of an electric radiator if it draws a current of 10 A when connected to a 240 V AC household circuit?

23. An electric jug is connected to a 240 V supply and draws a current of 3.3 A. How long would it take to transfer 3.2×10^4 J of energy to its contents?

Providing energy for the circuit

24. What is the emf of a battery that provides 9.0 J of energy to 6.0 C of charge?

Resistance

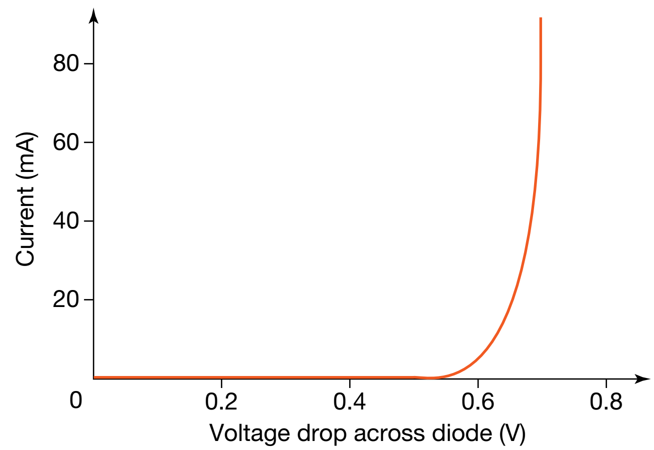
25. How much energy is provided by a 6.0 V battery if a current of 3.0 A passes through it for 1.0 minute?

26. Copy and complete the following table.

Potential difference	Current	Resistance
?	8.0 A	4.0 Ω
?	22 mA	2.2 kΩ
12 V	?	6.0 Ω
240 V	?	8.0×10^4 Ω
9.0 V	6.0 A	?
1.5 V	45 mA	?

27. What are the resistances and tolerances of resistors with the following colour codes:
(a) orange, white, black, gold
(b) green, blue, orange, silver
(c) violet, green, yellow, gold?

28. The figure below shows the current versus voltage characteristic for an electronic device.
(a) Is this device ohmic or non-ohmic? Justify your answer.
(b) What is the current through the device when the voltage drop across it is 0.5 V?
(c) What is the resistance of the device when the voltage drop across it is 0.5 V?
(d) Estimate the voltage drop across the device, and its resistance, when it draws a current of 20 mA.



29. At what rate is thermal energy being transferred to a wire if it has a resistance of 5.0 Ω and carries a current of 0.30 A?

30. Calculate the resistance of the following globes if their ratings are:
(a) 240 V, 60 W
(b) 6.0 V, 6.3 W
(c) 12 V, 40 W.

31. What is the power rating of an electric jug if it has a resistance of 48 Ω when hot and is connected to a 240 V supply?

Thermistors

32. A thermistor has the characteristic curve shown below.

(a) What is the resistance of the thermistor at the following temperatures?

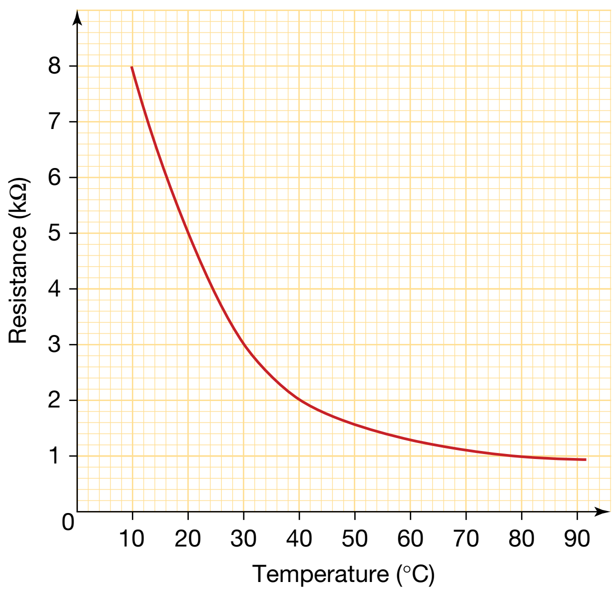
 (i) 20 °C

 (ii) 80 °C

(b) What is the temperature when the thermistor has the following resistances?

 (i) 4 kΩ

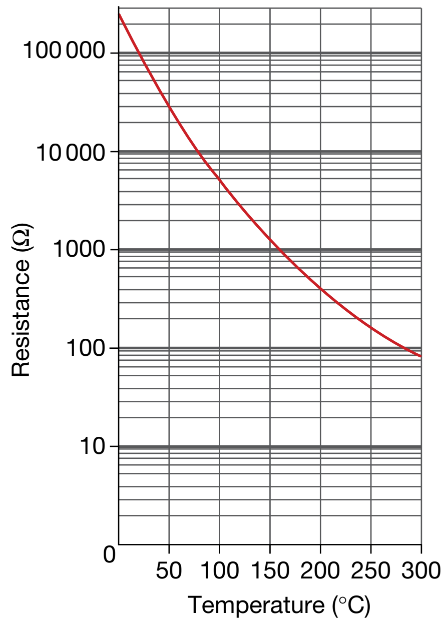
 (ii) 1.5 kΩ



33. A temperature sensing system in an oven uses a thermistor with the characteristics shown in the figure below.

(a) What is the resistance of the thermistor when the temperature in the oven is 100 °C?

(b) What is the temperature in the oven when the resistance of the thermistor is 400 Ω?



CHAPTER

5 Circuit analysis

REMEMBER

Before beginning this chapter, you should be able to:

- identify a range of common components of simple electric circuits
- recognise the circuit symbols for common components of simple electric circuits
- connect components into simple circuits following a circuit diagram.

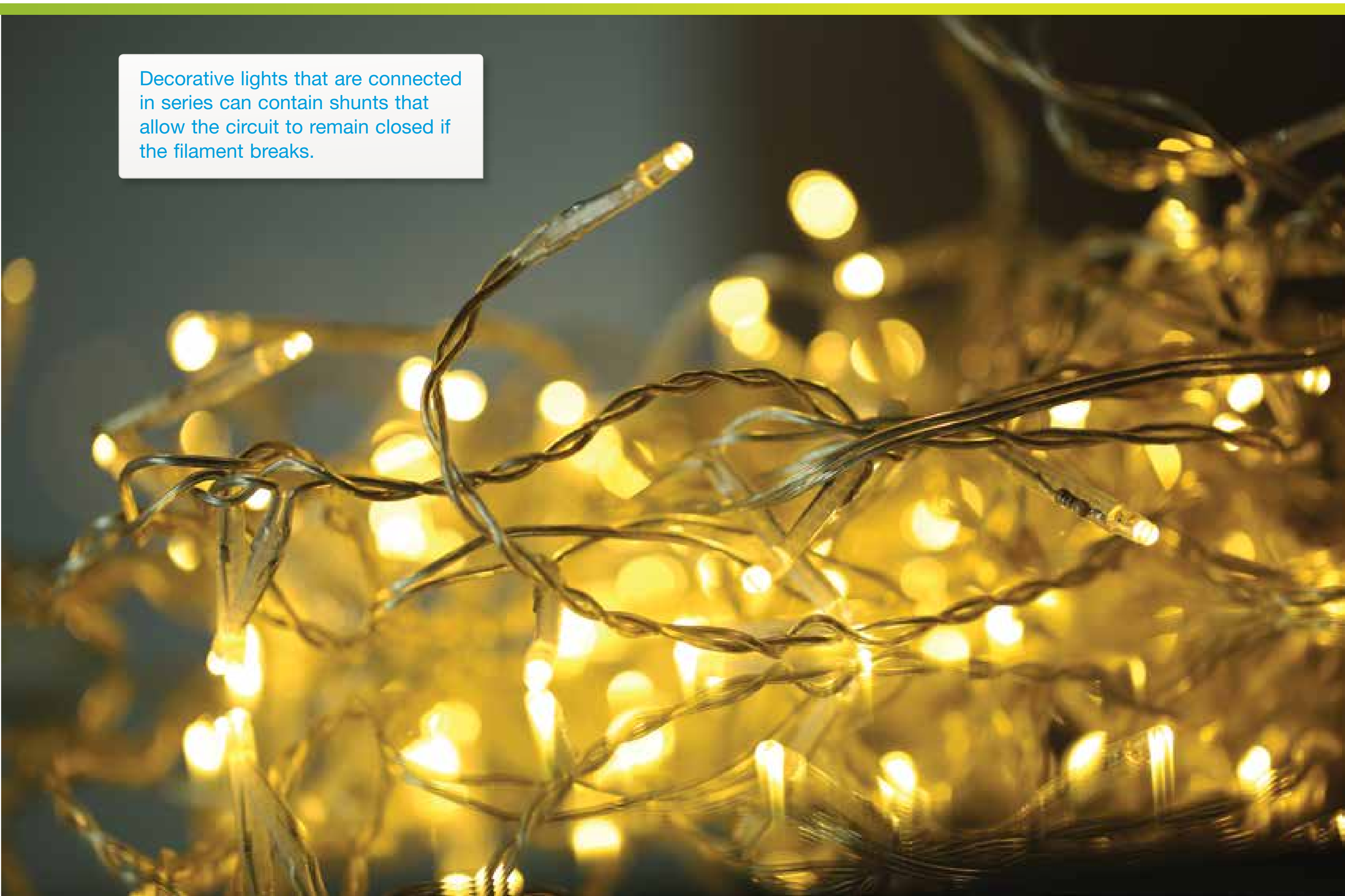
KEY IDEAS

After completing this chapter, you should be able to:

- use the principles of conservation of charge and conservation of energy to analyse current and voltage in series and parallel circuits
- model resistance in series and parallel circuits using voltage-versus-current graphs
- find the effective resistance of series arrangements using the relationship

  $R_T = R_1 + R_2 + \ldots + R_n$
- find the effective resistance of parallel arrangements using the relationship

  $$\frac{1}{R_T} = \frac{1}{R_1} + \frac{1}{R_2} + \ldots + \frac{1}{R_n}$$
- present data obtained from electric circuit investigations in tables and graphs
- describe energy changes in transducers
- analyse voltage divider circuits using transducers such as LDRs and thermistors.



Decorative lights that are connected in series can contain shunts that allow the circuit to remain closed if the filament breaks.

What happens in an electric circuit?

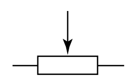
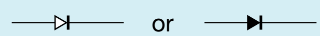
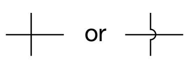
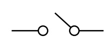
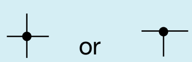
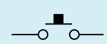
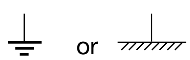
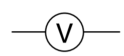
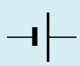
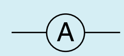
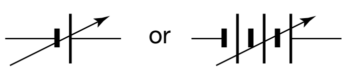
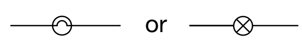
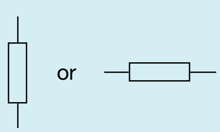
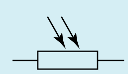
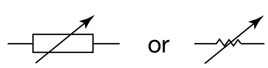
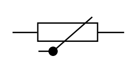
In chapter 4, an electric circuit was described as a number of electrical conductors connected together to form a conducting path. A circuit can contain one or more sources of emf (electromotive force) to provide energy to the circuit. If the conductors form a continuous closed path through which a current can circulate, the circuit is said to be a closed circuit. If there is a break in the path so that charge cannot flow, for example at a switch, the circuit is said to be an open circuit.

In many simple electric circuits, electrical energy is used for heating one or more loads. The temperature increase in a load occurs because the charge carriers make repeated collisions with the atoms in the load. This increases the internal energy of the load and its temperature rises. The electrical energy transformed in the load originally came from some source of emf, for example a battery, laboratory power pack or power point in the home. Examples of this type of circuit include a torch (where the conductor in the filament gets so hot that it emits light), a toaster plugged into a power point and a car demister circuit.

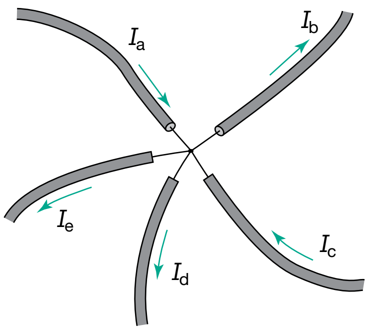
Circuit diagrams

A circuit diagram shows schematically the devices used in constructing an electrical circuit. The table below shows the symbols commonly used in drawing circuits.

TABLE 5.1 Symbols used in circuit diagrams

Circuit component	Symbol	Circuit component	Symbol
Connection between conductors	•	Resistor with sliding contact to give a variable resistance	
Terminal	○	Semiconductor diode*	
Conductors not connected*		Single pole switch (open)	
Conductors connected*		Button switch (open)	
Earth*		Voltmeter	
Battery		Ammeter	
Variable power supply*		Incandescent lamp*	
Resistor		Light-dependent resistor (LDR)	
Variable resistor*		Heat-dependent resistor (thermistor)	

*The first of the two alternative symbols is used in this book.



Five wires soldered at a junction

Circuit rules

Accounting for electrons

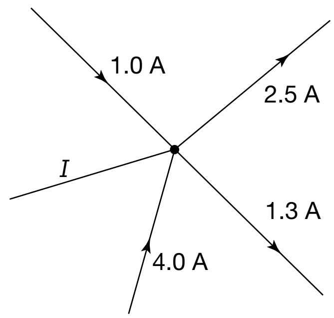
Electric charge is conserved. At any point in a conductor, the amount of charge (usually electrons) flowing into that point must equal the amount of charge flowing out of that point. Electrons do not build up at a point in a conductor, nor will they magically disappear. You don't get traffic jams in electric circuits.

The sum of the currents flowing into a junction is equal in magnitude to the sum of the currents flowing out of that junction: $I_{in} = I_{out}$.

In the figure at left, $I_a + I_c = I_b + I_d + I_e$.

Sample problem 5.1

Calculate the magnitude and direction of the unknown current in the figure at right, showing currents meeting at a junction.



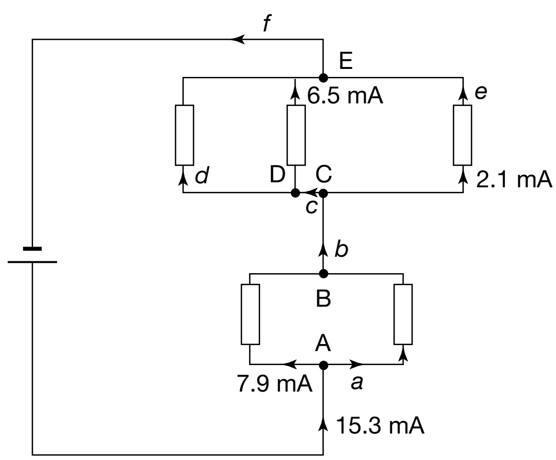
Solution: Currents flowing into the junction equal $1.0 + 4.0 = 5.0$ A.

Currents flowing out of the junction equal $2.5 + 1.3 = 3.8$ A.

Therefore the unknown current must be $5.0 - 3.8 = 1.2$ A out of the junction.

Sample problem 5.2

Find the values of currents *a*, *b*, *c*, *d*, *e* and *f* as marked in the figure below.



Solution: At junction A,

$$I_{in} = I_{out}$$
$$\Rightarrow 15.3 = 7.9 + a$$
$$\Rightarrow a = 7.4 \text{ mA}.$$

At junction B,

$$I_{in} = I_{out}$$
$$\Rightarrow 7.9 + 7.4 = b$$
$$\Rightarrow b = 15.3 \text{ mA}.$$

At junction C,

$$I_{in} = I_{out}$$
$$\Rightarrow 15.3 = c + 2.1$$
$$\Rightarrow c = 13.2 \text{ mA}.$$

At junction D,

$$I_{in} = I_{out}$$
$$\Rightarrow c = d + 6.5$$
$$\Rightarrow 13.2 = d + 6.5$$
$$\Rightarrow d = 6.7 \text{ mA}.$$

At the resistor,

$e = 2.1$ mA, as $I_{in} = I_{out}$ for the resistor.

At junction E,

$$I_{in} = I_{out}$$
$$\Rightarrow d + 6.5 + e = f$$
$$\Rightarrow 6.7 + 6.5 + 2.1 = f$$
$$\Rightarrow f = 15.3 \text{ mA}.$$

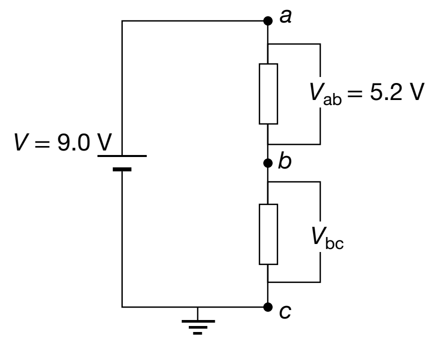
Conservation of electrical energy

Around a circuit electrical energy must be conserved. This can be stated as:

In any closed loop of a circuit, the sum of the voltage drops must equal the sum of the emfs in that loop.

Sample problem 5.3

Calculate the unknown voltage drop V_{bc} in the figure on the right.



Solution:

$$V = \text{the sum of the voltage drops}$$
$$V = 9.0\ \text{V}$$
$$\Rightarrow 9.0\ \text{V} = 5.2\ \text{V} + V_{bc}$$
$$\Rightarrow V_{bc} = 3.8\ \text{V}$$

Series and parallel circuits

Devices connected in **series** are joined together one after the other.

Devices connected in **parallel** are joined together so that one end of each device is joined at a common point and the other end of each device is joined at another common point.

There are two ways in which circuit elements can be connected. These are called in **series** and in **parallel**.

When devices are connected in series, they are joined together one after the other. There is only one path for the current to take.

When devices are connected in parallel, they are joined together so that there is more than one path for the current to flow through.

Many devices can be connected in series and parallel. These include resistors and cells.

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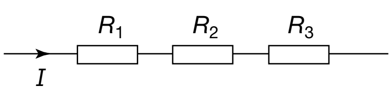
Series circuits
Concept summary and practice questions

Resistors in series

When a number of resistors are placed in series, some basic rules can be derived.

There is only one path for the current to flow through. Therefore in the figure below left, the current in R_1 equals the current in R_2 and in R_3. I_1 refers to the current in R_1; I_2 to the current in R_2 etc. Similarly V_1 is the voltage drop across R_1; V_2 is the voltage drop across R_2 etc.



Resistors connected in series

$$I = I_1 = I_2 = I_3$$

Since $V = I R$,

$$V_1 = I R_1$$
$$V_2 = I R_2$$
$$V_3 = I R_3.$$

The total voltage drop, V_T, across resistors in series is equal to the sum of the voltage drops across each individual resistor.

$$V_T = V_1 + V_2 + V_3$$
$$\Rightarrow V_T = I R_1 + I R_2 + I R_3$$
$$\Rightarrow V_T = I (R_1 + R_2 + R_3)$$

Since $V_T = I R_T$ (where R_T is the effective resistance of all three resistors), the effective resistance offered by resistors in series is found by obtaining the sum of the individual resistances:

$$R_T = R_1 + R_2 + R_3.$$

This means that the effective resistance of a circuit is increased by adding an extra resistor in series with the others. The resistance of a series circuit is greater than that for any individual resistor.

Sample problem 5.4

Find the effective resistance of a circuit comprising three resistors, having resistance values of 15 Ω, 25 Ω and 34 Ω, connected in series.

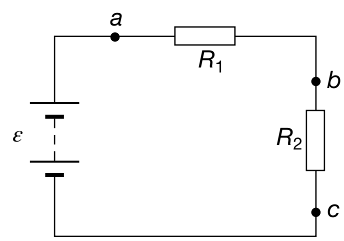
Solution:

$$R_T = R_1 + R_2 + R_3$$
$$= 15\ \Omega + 25\ \Omega + 34\ \Omega$$
$$= 74\ \Omega$$

Sample problem 5.5

In the series circuit shown in the figure on the right, the emf of the power supply is 100 V, the current at point *a*, I_a, equals 1.0 A, and the value of R_2 is 60 Ω. Find the following quantities:

(a) the current at point *b*
(b) the voltage drop across R_2
(c) the voltage drop across R_1
(d) the value of R_1.



Solution:

(a) The current is the same at all points of a series circuit. Therefore the current at point *b*, I_b, is 1.0 A.

(b) $V_2 = IR_2$
$= 1.0\ \text{A} \times 60\ \Omega$
$= 60\ \text{V}$

(c) $\varepsilon = V_1 + V_2$
$\Rightarrow 100\ \text{V} = V_1 + 60\ \text{V}$
$V_1 = 40\ \text{V}$

(d) $V_1 = IR_1$
$40\ \text{V} = 1.0\ \text{A} \times R_1$
$R_1 = 40\ \Omega$

Revision question 5.1

Find the effective resistance of three resistors in series if they have the following values: 1.2 kΩ, 5.6 kΩ and 7.1 kΩ.

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Unit 1 | AOS 2 | Topic 2 | Concept 2

Parallel circuits
Concept summary and practice questions

Resistors in parallel

In a parallel branch of a circuit, there is more than one path for the current to flow through.

The total current flowing into the parallel section of a circuit equals the sum of the individual currents flowing through each resistor.

$$I_T = I_1 + I_2 + I_3$$

As can be seen in the following figure, the left-hand sides of all the resistors are connected to point A, so they are all at the same voltage. This means that all charges on that side of the resistors have the same amount of electrical potential energy. Similarly, the right-hand sides of the resistors are connected to point B, therefore they also are at the same voltage. This means that each resistor in a parallel section of a circuit has the same voltage drop across it.

$$V_T = V_1 = V_2 = V_3$$

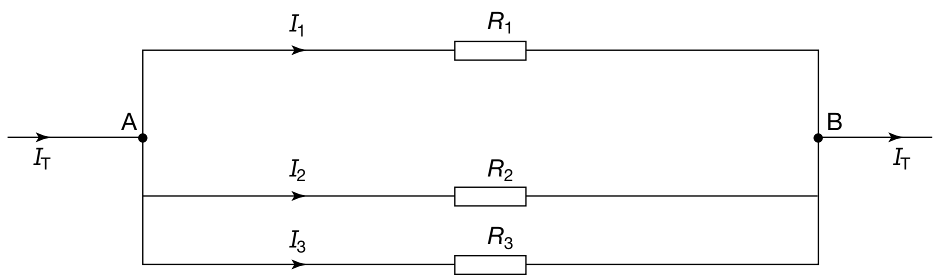
In a parallel section of a circuit, the total current equals the sum of the individual currents, and the voltage drops across each resistor are the same. It is possible to derive an expression for the effective resistance, R_T, of a parallel section of a circuit.

$$I_T = I_1 + I_2 + I_3$$

$$\Rightarrow \frac{V}{R_T} = \frac{V}{R_1} + \frac{V}{R_2} + \frac{V}{R_3}$$

(since $I = \frac{V}{R}$ for each resistor and the whole section of the circuit)

$$\Rightarrow \frac{1}{R_T} = \frac{1}{R_1} + \frac{1}{R_2} + \frac{1}{R_3} \text{(dividing both sides by } V\text{)}$$



A parallel branch of a circuit

This means that the reciprocal of the effective resistance is equal to the sum of the reciprocals of the individual resistances. The effective resistance is less than the smallest individual resistance. The more resistors there are added in parallel, the more paths there are for the current to flow through, and the easier it is for the current to flow through the parallel section.

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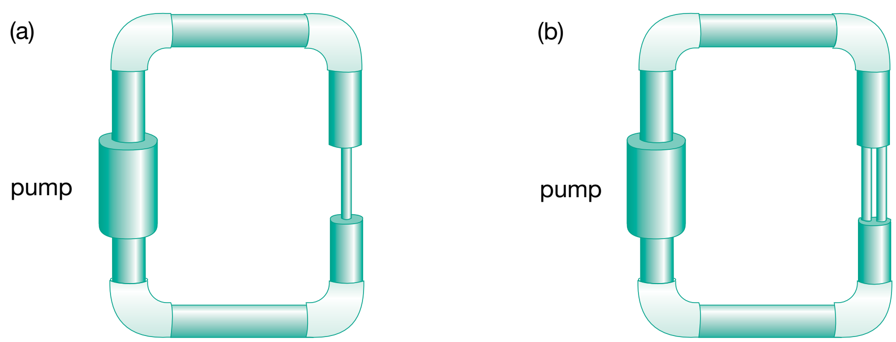
Weblinks
DC circuit water analogy
Simple electric circuits

Modelling resistors in parallel

One way to help understand this concept is to use the hydraulic model. Current is represented by water flowing in a pipe. Resistors are represented as thin pipes. The thinner the pipe, the greater the resistance and therefore less water can flow in the circuit. A conductor is represented by a large pipe through which water flows easily. The source of emf is represented by a pump that supplies energy to the circuit.

If there is only one thin pipe, it limits the flow of water. Adding another thin pipe beside the first allows more water to flow. The total resistance offered by the two thin pipes in parallel is less than that offered by an individual thin pipe.



The hydraulic model for resistors in parallel showing (a) a circuit with one 'resistor' and (b) a second 'resistor' added in parallel, which allows more current to flow and reduces the effective resistance

Sample problem 5.6

What is the effective resistance of three resistors connected in parallel if they have resistance values of 5.0 Ω, 10 Ω and 20 Ω respectively?

Solution:

$$\frac{1}{R_T} = \frac{1}{R_1} + \frac{1}{R_2} + \frac{1}{R_3}$$

$$\frac{1}{R_T} = \frac{1}{5.0\,\Omega} + \frac{1}{10\,\Omega} + \frac{1}{20\,\Omega}$$

$$\Rightarrow \frac{1}{R_T} = \frac{4}{20\,\Omega} + \frac{2}{20\,\Omega} + \frac{1}{20\,\Omega}$$

$$\Rightarrow \frac{1}{R_T} = \frac{7}{20\,\Omega}$$

$$\Rightarrow R_T = \frac{20\,\Omega}{7} = 2.9\,\Omega$$

Note that the effective resistance of a set of resistors connected in parallel is always less than the value of the smallest resistor used. Adding resistors in parallel increases the number of paths for current to flow through, so more current can flow and the resistance is reduced.

If there are n resistors of equal value, R, the effective resistance will be $\frac{R}{n}$.

$$R_T = \frac{R}{n}$$

Sample problem 5.7

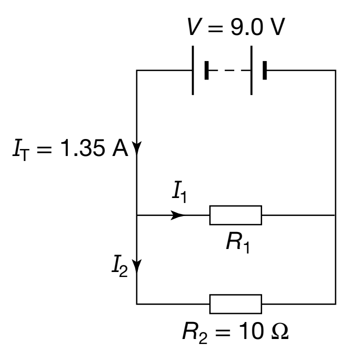
Consider the parallel circuit shown in the figure below.

The emf of the power supply is 9.0 V, R_2 has a resistance of 10 Ω, and the current flowing through the power supply is 1.35 A. Find the following quantities:

(a) the voltage drop across R_1 and R_2
(b) I_2, the current flowing through R_2
(c) I_1, the current flowing through R_1
(d) the resistance of R_1
(e) the effective resistance of the circuit.

Solution:

(a) For a parallel circuit, $V_1 = V_2$, which in this case is 9.0 V.



(b) $$I_2 = \frac{V}{R_2}$$

$$\Rightarrow I_2 = \frac{9.0\text{ V}}{10\ \Omega} = 0.90\text{ A}$$

(c) $$I_T = I_1 + I_2$$

$$\Rightarrow I_1 = I_T - I_2$$
$$= 1.35\text{ A} - 0.9\text{ A}$$
$$= 0.45\text{ A}$$

(d) $$R_1 = \frac{V}{I_1}$$

$$\Rightarrow R_1 = \frac{9.0\text{ V}}{0.45\text{ A}}$$

$$\Rightarrow R_1 = 20\ \Omega$$

(e) $$\frac{1}{R_T} = \frac{1}{R_1} + \frac{1}{R_2}$$

$$\Rightarrow \frac{1}{R_T} = \frac{1}{10\ \Omega} + \frac{1}{20\ \Omega}$$

$$\Rightarrow \frac{1}{R_T} = \frac{3}{20\ \Omega}$$

$$\Rightarrow R_T = \frac{20\ \Omega}{3}$$

$$= 6.7\ \Omega$$

Sample problem 5.8

Find the effective resistance when a 10 Ω resistor is placed in parallel with a 10 kΩ resistor.

Solution:

$$\frac{1}{R_T} = \frac{1}{R_1} + \frac{1}{R_2}$$

$$= \frac{1}{10\ \Omega} + \frac{1}{10\,000\ \Omega}$$

$$= \frac{1000}{10\,000\ \Omega} + \frac{1}{10\,000\ \Omega}$$

$$= \frac{1001}{10\,000\ \Omega}$$

$$\Rightarrow R_T = \frac{10\,000\ \Omega}{1001}$$

$$= 9.99\ \Omega$$

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Revision question 5.2

Find the effective resistance of two resistors in parallel if they have resistance values of 1.2 kΩ and 4.8 kΩ.

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Digital docs
Investigation 5.1: Series circuits
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Investigation 5.2: Parallel circuits
doc-16178

Note: Adding a large resistance in parallel with a small resistance slightly reduces the effective resistance of that part of a circuit.

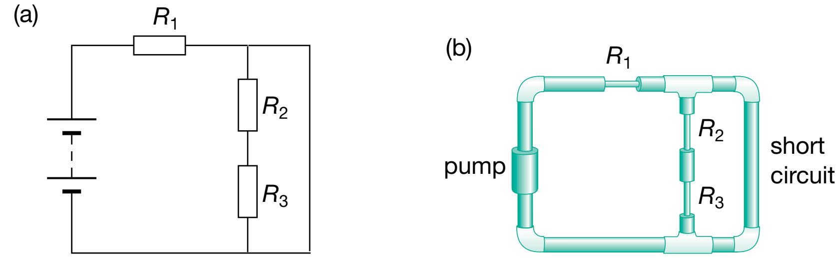
Parallel circuits are used extensively. Australian households are wired in parallel with an AC voltage of 230 V. This is equivalent to a DC voltage of 230 V, and all the formulae that have been presented so far can be used for analysing AC circuits.

The advantage of having parallel circuits is that all appliances have the same voltage across them and the appliances can be switched on independently. If appliances were connected in series, they would all be on or off at the same time; and they would share the voltage between them, so no appliance would receive the full voltage. This would present problems when designing the devices, as it would not be known what voltage to allow for.

Car lights, front and rear, are wired in parallel for the same reason. If one lamp 'blows', the other lamps will continue functioning normally.

Short circuits

A short circuit occurs in a circuit when a conductor of negligible resistance is placed in parallel with a circuit element. This element may be a resistor or a globe. The result of a short circuit is that virtually all the current flows through the conductor and practically none flows through the circuit element. Because there is effectively no voltage drop across the wire, there is also no voltage drop across the circuit element, and no current flows through it. Think of what would happen in the hydraulic model if a conducting pipe were placed beside a thin pipe. This situation is represented in both ways in the figures below.

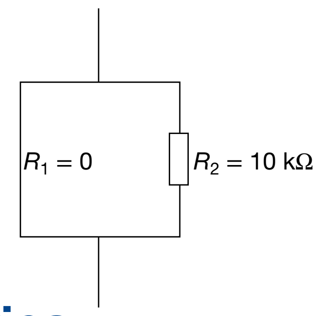


(a) Circuit diagram showing a short circuit (b) Hydraulic model of a short circuit

In this case, the current through the power supply passes through R_1, but then flows through the short circuit, effectively avoiding R_2 and R_3.

Sample problem 5.9

The figure below shows a 10 kΩ resistor which has been short circuited with a conductor of 0 Ω resistance. Calculate the effective resistance of this arrangement.



Solution:

$$\frac{1}{R_T} = \frac{1}{R_1} + \frac{1}{R_2}$$

$$= \frac{1}{0\,\Omega} + \frac{1}{10\,000\,\Omega}$$

$$= \infty$$

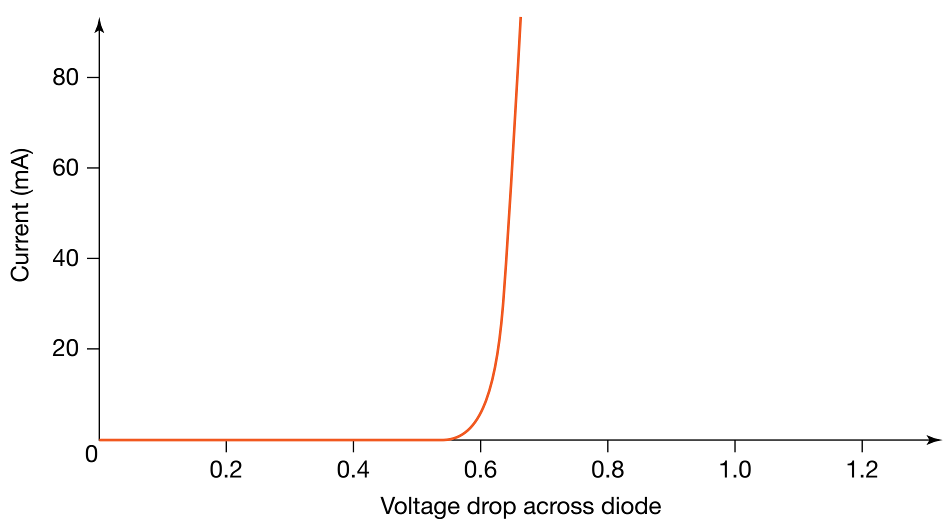
$$\Rightarrow R_T = 0\,\Omega$$

Non-ohmic devices in series and parallel

Non-ohmic devices do not obey Ohm's Law. Their current-versus-voltage characteristics can be presented graphically.

The value of $\frac{V}{I}$ is not constant for non-ohmic devices.

The rules for series and parallel circuits still apply when analysing circuits containing non-ohmic devices. Devices in series have the same current and share the voltage. Devices in parallel have the same voltage and the current is shared between them. The actual values of the voltage or current are obtained from the *V–I* graphs for the devices.



V–I characteristic for a silicon diode

Sample problem 5.10

The figure below shows the current-versus-voltage graph for two electrical devices.

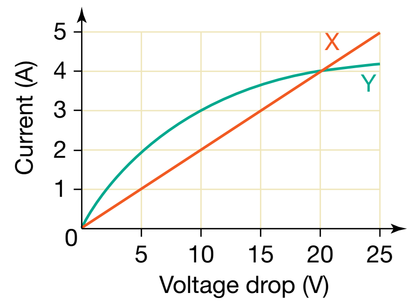
If X and Y are in parallel, and the current through X is 2.0 A, calculate:

(a) the voltage across Y

(b) the current through Y.

Solution: (a) As X and Y are in parallel, the voltage across X equals the voltage across Y. From the graph, when the current through X is 2.0 A, the voltage is 10 V, so the voltage across Y is 10 V also.

(b) When the voltage across Y is 10 V, the current through Y is seen to be 3.0 A.



Power in circuits

Recall that the power being used in a circuit element is the product of the voltage drop across it and the current through it: $P = VI$. The total power being provided to a circuit is the sum of the power being used in, or 'dissipated by', the individual elements in that circuit. It does not matter if the elements are connected in series or in parallel.

$$P_T = P_1 + P_2 + P_3 = \ldots$$

Sample problem 5.11

A household electrical circuit is wired in parallel. Find the total current flowing in the circuit if the following appliances are being used: a 600 W microwave oven, a 450 W toaster and a 1000 W electric kettle. Household circuits provide a voltage drop of 230 V across each appliance.

Solution: The total power being used in the circuit is 600 + 450 + 1000 = 2050 W.

$$I_T = \frac{P_T}{V} = \frac{2050\text{ W}}{230\text{ V}} = 8.91\text{ A}$$

Revision question 5.3

Find the total current flowing through a household circuit when the following devices are being used: a 400 W computer, a 200 W DVD player, a 500 W television and a 60 W lamp.

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Careers in electrical engineering

The voltage divider

The **voltage divider** is used to reduce, or divide, a voltage to a value needed for a part of the circuit.

The **voltage divider** is an example of resistors in series. It is used to divide or reduce a voltage to a value needed for a part of the circuit. A voltage divider is used in many control circuits, for example, turning on the heating in a house when the temperature drops.

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Unit 1 | AOS 2 | Topic 2 | Concept 3

Voltage dividers
Concept summary and practice questions

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Voltage dividers
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The voltage divider has an input voltage, V_{in}, and an output voltage, V_{out}. A general voltage divider is shown in the figure at right.

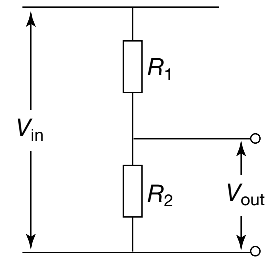
The current I flowing through R_1 and R_2 is the same, since R_1 and R_2 are in series.

$$V_{in} = I(R_1 + R_2)$$

$$\Rightarrow I = \frac{V_{in}}{R_1 + R_2}$$

$$V_{out} = IR_2$$

$$\Rightarrow V_{out} = \frac{V_{in}}{R_1 + R_2} \times R_2$$



A general voltage divider

This can be rewritten as:

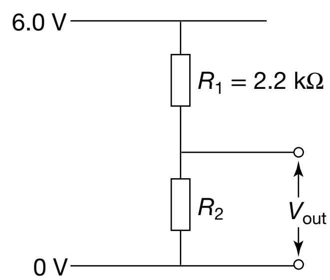
$$V_{out} = \left[\frac{R_2}{R_1 + R_2}\right] V_{in}, \text{ or more generally,}$$

$$V_{out} = \left[\frac{\text{resistance across which } V_{out} \text{ is taken}}{\text{sum of all resistances}}\right] V_{in} = \frac{R_{out}}{R_{total}} V_{in}.$$

If R_1 and R_2 are equal in value, the voltage will be divided equally across both resistors. If R_1 is much greater than R_2, then most of the voltage drop will be across R_1.

Sample problem 5.12

Calculate the value of the unknown resistor in the voltage divider shown in the figure below, if the output voltage is required to be 4.0 V.



Solution:

$$V_{out} = \frac{R_2 V_{in}}{R_1 + R_2}$$

$$\Rightarrow 4.0\text{ V} = \frac{6.0\text{ V} \times R_2}{2.2\text{ k}\Omega + R_2}$$

$$\Rightarrow 8.8\text{ k}\Omega\text{V} + 4.0\text{ V } R_2 = 6.0\text{ V } R_2$$

$$\Rightarrow 2.0\text{ V } R_2 = 8.8\text{ k}\Omega\text{V}$$

$$\Rightarrow R_2 = 4.4\text{ k}\Omega$$

Revision question 5.4

Calculate the value of the unknown resistor in the voltage divider in sample problem 5.12 if the output voltage is to be 1.5 V.

Transducers and sensors

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Unit 1 | AOS 2 | Topic 2 | Concept 4

Transducers and sensors
Concept summary and practice questions

Transducers are devices that convert energy from one form to another. They can be affected by, or can affect, the environment. The word *transducer* comes from the Latin for 'to lead across'. Table 5.2 following has a range of transducers and their energy conversions.

Sensors are a subset of transducers where the energy conversion is to electrical, that is, to a variation in voltage. Some sensors generate the voltage directly, for example piezoelectric devices. Other sensors whose resistance changes, such as LDRs and thermistors, use a voltage divider circuit.

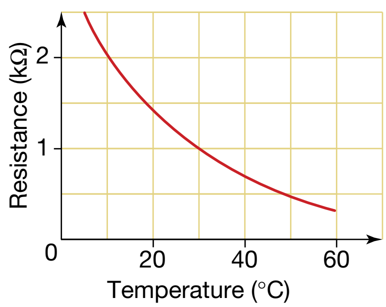
TABLE 5.2 Examples of transducers

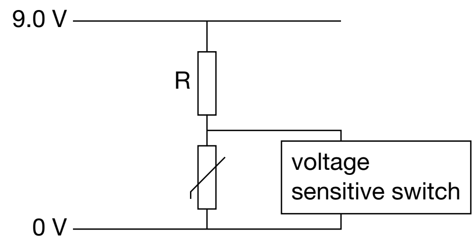
Transducer	Energy conversion From	Energy conversion To
Solar cell	Light	Electrical
Loudspeaker	Electrical	Sound
Microphone	Sound	Electrical
LED	Electrical	Light
Antenna	Electromagnetic	Electrical
Thermocouple	Heat energy (temp. difference)	Electrical
Peltier cooler	Electrical	Heat energy (temp. difference)
Piezoelectric gas lighter*	Stored mechanical energy due to pressure	Electrical

*The piezoelectric effect is also used in strain gauges to measure the stress in construction materials and in the accelerometers found in video game controllers and guidance systems.

Sample problem 5.13

The resistance of a thermistor changes with temperature as shown in the graph below left. In the voltage divider circuit shown, the thermistor is one of the two resistors; the other is a resistor with a fixed resistance value.





As the temperature drops, the resistance of the thermistor increases. As the thermistor's resistance increases, its share of the voltage from the power supply also increases, while that of the fixed value resistor will decrease.

A voltage sensitive switch is placed across the thermistor. It is built to turn on a heater when the voltage across the thermistor is greater than 6 V. Your task as the circuit designer is to determine the resistance value required for the fixed value resistor to turn on the heater at 19 °C.

Solution: From the graph, at 19 °C the thermistor has a resistance of 1.5 kΩ (1500 Ω). Substituting into the voltage divider equation gives:

$$V_{out} = \left[\frac{R_2}{R_1 + R_2}\right] V_{in}$$

$$6\text{V} = \left[\frac{1.5\,\text{k}\Omega}{R + 1.5\,\text{k}\Omega}\right] \times 9\text{V}$$

Solving for R gives:

$$6 \times (R + 1500) = 1500 \times 9.0\text{ V}$$
$$6R + 9000 = 13\,500$$
$$6R = 4500$$
$$R = 750\ \Omega$$

Sample problem 5.14

To reduce the heating bill from the heater in sample problem 5.13, it is decided that the heater should be turned on when the temperature is below 18 °C. Should the value of the fixed value resistor be increased or decreased? Explain.

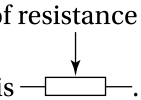
Solution: The voltage to turn on the switch will still be 6 V, so the voltage across the two resistors will be unchanged. The ratio of their resistance values will therefore also be the same. From the previous graph, it can be seen that at 18 °C the thermistor's resistance will be greater than it was at 19 °C. So to keep the ratio the same, R must increase.

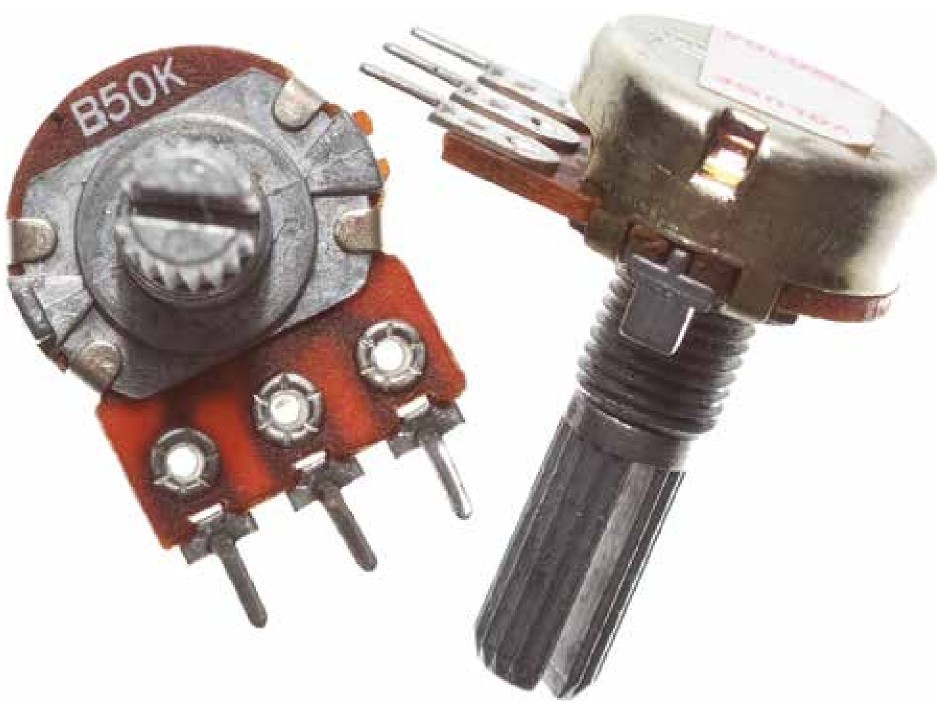
This can also be explained using current. As the resistance of the thermistor is higher at the lower temperature, there will be less current through both resistors. As the voltage drop across R is to remain the same, its resistance will need to be greater ($V = IR$).

Revision question 5.5

The thermistor and voltage sensitive switch from sample problem 5.13 are to be used for a cooling system. The cooling system is to turn on when the temperature is greater than 24 °C. To which resistor, the thermistor or the fixed resistor, should the voltage sensitive switch be connected so that the voltage is greater than 6 V for temperatures greater than 24 °C? Explain. What should be the value of the fixed resistor?

Potentiometers

A potentiometer, called a 'pot' for short, is a variable voltage divider. It consists of a fixed resistor, usually a length of wire, with a contact that can slide up and down, varying the amount of resistance in each arm of the voltage divider. The symbol for a potentiometer is . Potentiometers are commonly used as controls in radio equipment, either as a slide control or in a rotary form. They are also the basis of joysticks in game controls.



Chapter review

Summary

- An electric circuit is a closed conducting path containing a source of emf.
- In a series circuit the components are placed one after the other. There is only one path for the charge carriers to flow through.
- In a series circuit the current is the same at all points; the sum of the potential drops is equal to the emf of the circuit.
- The effective resistance of resistors placed in series is equal to the sum of the individual resistances.
- In a parallel circuit, there is more than one path for the current to flow through.
- Resistors in parallel have the same potential difference across them; the current in each resistor adds up to the total current flowing into the parallel branch.
- In a parallel arrangement of resistors, the reciprocal of the effective resistance is equal to the sum of the reciprocals of the individual resistances:

$$\frac{1}{R_T} = \frac{1}{R_1} + \frac{1}{R_2}$$

- A short circuit occurs when a conductor of negligible resistance is placed in parallel with a circuit element and stops current from flowing through it.
- Circuits containing non-ohmic devices can be analysed using the rules for series and parallel circuits with their voltage–current characteristic graphs.
- The total power used in a circuit equals the sum of the powers used in individual devices.
- A voltage divider is used to reduce an input voltage to some required value.
- A voltage divider consists of two or more resistors arranged in series to produce a smaller voltage at its output.
- The output of a voltage divider can be calculated using the equation:

$$V_{out} = \left[\frac{R_2}{R_1 + R_2}\right] V_{in}$$

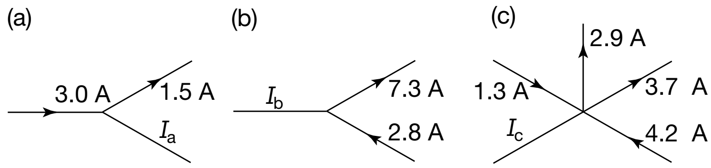
- A transducer is a device that can be affected by, or affects, the environment.

Questions

Circuit rules

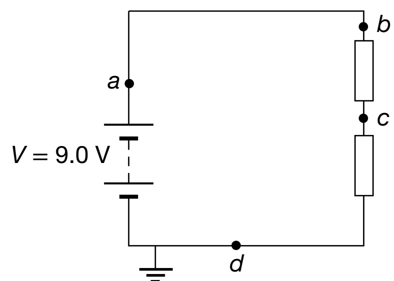
1. Explain what is meant by the following terms, as they relate to electric circuits.
   (a) junction
   (b) open circuit
   (c) voltage drop
   (d) series
   (e) parallel
   (f) short circuit

2. Find the unknown current at each of the junctions in the figure below. State the direction of the current in each case.



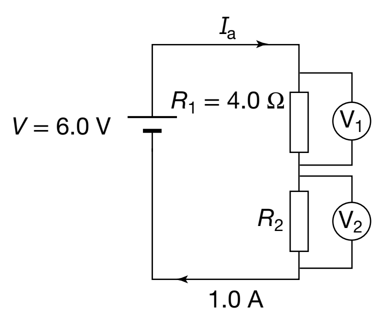
Series and parallel circuits

3. Find the voltage at the points *a*, *b*, *c* and *d* in the figure below, given that V_{bc} is 5.0 V.

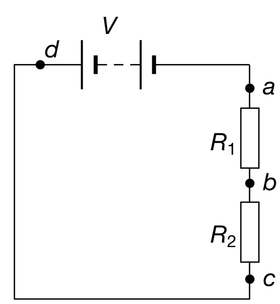


4. Find the effective resistance of the following sets of resistors if they are connected in series:
   (a) 2.7 Ω, 9.8 Ω
   (b) 12 Ω, 20 Ω, 30 Ω
   (c) 1.2 kΩ, 3.2 kΩ, 11 kΩ.

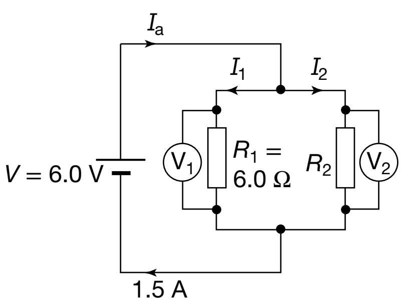
5. Find the unknown quantities in the series circuit shown in the following figure.



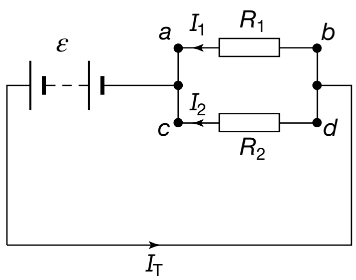
6. In the series circuit shown in the figure at right, $V_{ab} = 20$ V, $R_2 = 30$ Ω, and $I_a = 2.0$ A. Find values for the following:
   (a) I_b
   (b) V_{bc}
   (c) R_1
   (d) R_T
   (e) E.



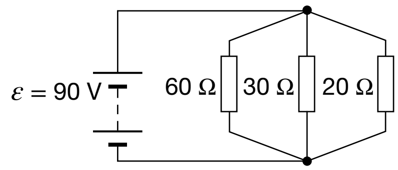
7. A 20 Ω resistor and a 30 Ω resistor are connected in series in a circuit with a 100 V power supply.
   (a) What is the effective resistance of the circuit?
   (b) What current flows through the circuit?
   (c) Calculate the voltage drop across each resistor.
   (d) Sketch a diagram of this circuit, showing where you would place an ammeter to measure the current in the circuit and a voltmeter to measure the voltage across the 30 Ω resistor.
8. Three resistors of 3.0 Ω, 5.0 Ω and 4.0 Ω are connected in series across a 12 V battery.
   (a) What is the effective resistance of the three resistors?
   (b) What current flows in the circuit?
   (c) What is the voltage drop across each resistor?
   (d) What is the total voltage drop across the circuit?
9. Consider two people connected in series with a 25 V source across them. The first person, R_1, has a resistance of 1000 Ω and the second person, R_2, has a resistance of 1500 Ω.
   (a) Determine the current through each person.
   (b) What is the voltage drop across each person?
10. Find the effective resistance when the following resistors are connected in parallel:
   (a) 30 Ω, 20 Ω
   (b) 5.0 Ω, 10 Ω, 30 Ω
   (c) 15 Ω, 60 Ω, 60 Ω
   (d) 20 Ω, 50 Ω, 80 Ω.
11. Find the unknown quantities in the parallel circuit shown in the figure below.



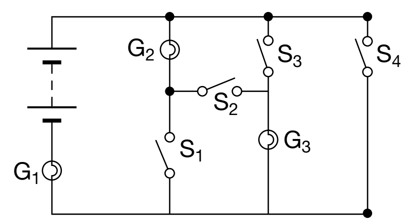
12. In the parallel circuit shown in the figure below, $I_1 = 0.20$ A, $R_1 = 60$ Ω and $I_T = 0.50$ A. Find values for the following:
   (a) V_{ab}
   (b) V_{cd}
   (c) ε
   (d) I_2
   (e) R_2.



13. Two 10 Ω resistors are connected in parallel across the terminals of a 15 V battery.
   (a) What is the effective resistance of the circuit?
   (b) What current flows in the circuit?
   (c) What is the current through each resistor?
14. Three resistors of 60 Ω, 30 Ω and 20 Ω are connected in parallel across a 90 V power source as shown in the following figure.



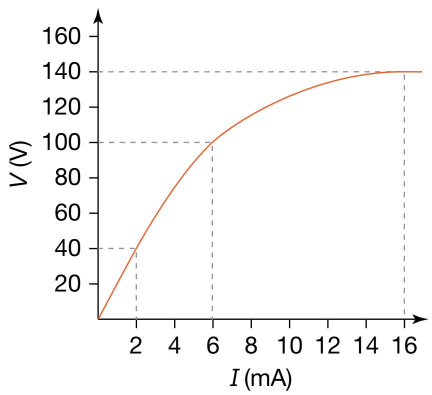
   (a) Calculate the effective resistance of the circuit.
   (b) Find the current flowing through the source.
   (c) What is the current flowing through each resistor?
15. A 6.0 Ω resistor, an 18 Ω resistor and a 9.0 Ω resistor are connected in parallel across a 36 V power supply.
   (a) What current flows through each resistor?
   (b) What total current flows in the circuit?
   (c) What is the effective resistance of the circuit?
16. The figure below shows an arrangement of switches and globes connected to a source of emf.



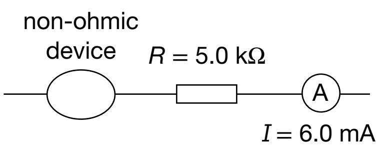
   Which globes would light up if the following sets of switches are closed:
   (a) switch S_2 only
   (b) switch S_3 only
   (c) switches S_3 and S_4 only?
17. Prove mathematically that the resistance of a short-circuited resistor branch is zero.

Non-ohmic devices in series and parallel

18. The voltage-versus-current characteristic graph for a non-ohmic device is shown in the figure on top of the following page.
   (a) What is the device's current when the voltage drop across it is 100 V?
   (b) What is the voltage drop across the device when the current through it is 16 mA?
   (c) What is the resistance of the device when it carries a current of 16 mA?

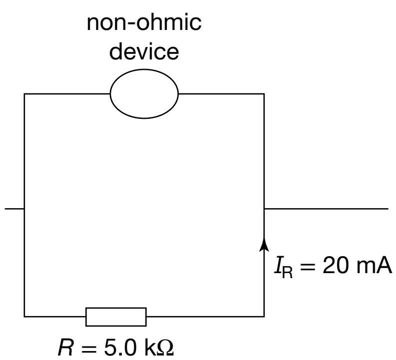


19. The device described in question 18 is placed in series with a 5.0 kΩ resistor and a voltage drop is applied across the combination. This arrangement is shown in the following figure.



The current in the resistor is measured to be 6.0 mA.
(a) What is the voltage drop across the resistor?
(b) What is the current in the device?
(c) What is the voltage drop across the device?
(d) What is the total voltage drop across the device and the resistor?

20. The device described in question 18 is now placed in parallel with a 5.0 kΩ resistor and a new voltage is applied across the combination. This arrangement is shown in the following figure.



The current in the resistor is measured to be 20 mA.
(a) Calculate the voltage drop across the resistor.
(b) What is the voltage drop across the device?
(c) What is the current in the device?
(d) What is the total current in the circuit?

Power in circuits

21. Three resistors of value 25 Ω, 15 Ω and 10 Ω are connected in series to a 10 V power supply.
(a) Calculate the current in the circuit.
(b) What is the voltage drop across each resistor?
(c) At what rate is energy being transformed in each resistor?
(d) What is the total power rating of the circuit?

22. Repeat question 21 with the resistors being connected in parallel.

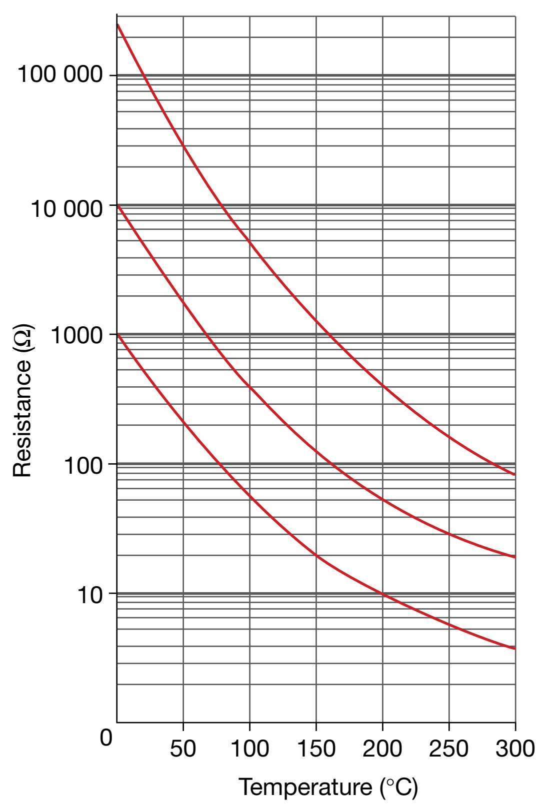
23. Two students are discussing how to produce more power in a circuit.
'$P = VI$,' says Tom. 'Since $V = IR$, $P = I^2R$. This shows that power is proportional to resistance. Therefore, if I want more power from a supply I should use a bigger resistance.'
'I don't agree,' says Henrietta. 'It is true that $P = VI$, but Ohm's Law gives $I = \frac{V}{R}$. This means that $P = \frac{V^2}{R}$, in which case power is proportional to the inverse of resistance. If I want to draw more power from a supply, I would use a smaller resistance.'
Which student is correct, and under what circumstances is he/she correct?

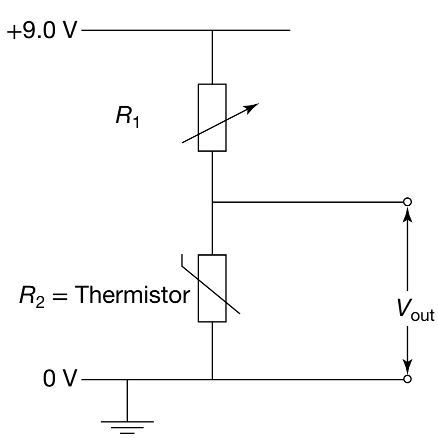
24. Design a dimmer switch circuit for a light. Does the circuit consume more power when the light is bright or dull? Justify your answer.

25. Some lighting circuits are controlled by two switches in different locations. Design a circuit to show how this could be achieved in a DC circuit.

Transducers and voltage dividers

26. A thermistor has the temperature–resistance characteristic shown by the bottom curve in the graph below. It is placed in the voltage divider shown in the following circuit diagram.

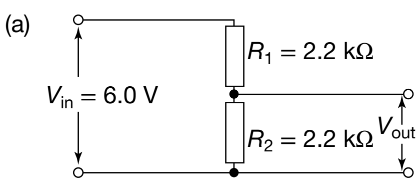




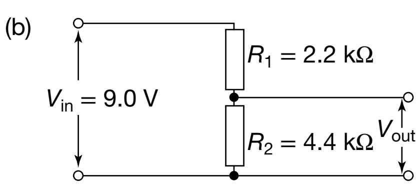
(a) What is the resistance of the thermistor when the temperature is 150 °C?
(b) What is the value of the variable resistor if the temperature is 200 °C and V_{out} is 6 V?

27. The thermistor in question 26 is replaced with one that has the temperature–resistance characteristic shown by the top curve in the graph.
(a) What is the resistance of the thermistor when the temperature is 200 °C?
(b) Calculate the value of the variable resistor in the voltage divider if the temperature is 100 °C and the output voltage is 4.5 V.

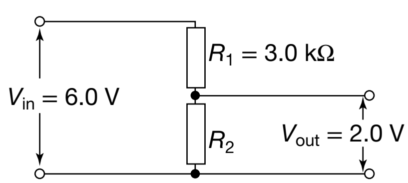
28. (a) Find the output voltage for the voltage divider shown in circuit (a) below.



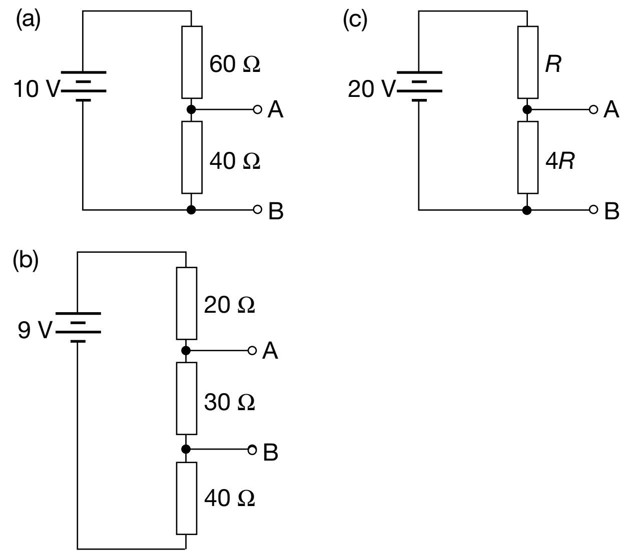
(b) What is the output voltage of circuit (b) below if a load of resistance 4.4 kΩ is connected across the output terminals of the voltage divider?



29. Find the value of R_2 in the voltage divider in the following figure which would give an output voltage of 2.0 V.

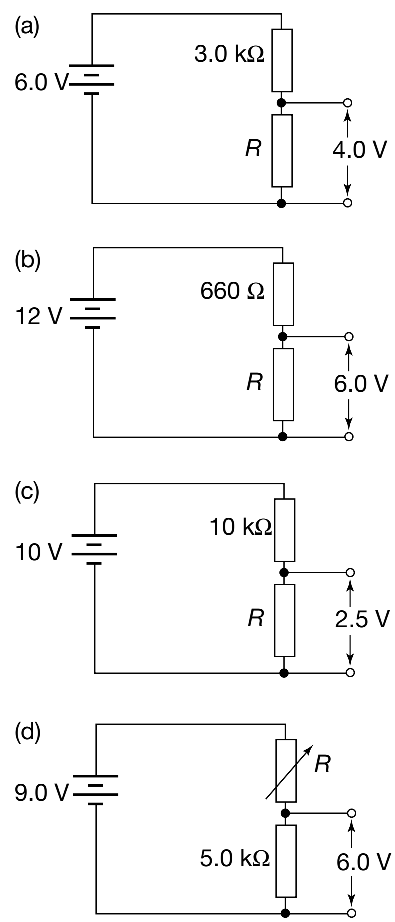


30. Find the voltage drop between A and B in each of the following voltage divider circuits.



31. What happens to the voltage drop across a variable resistor in a two-element voltage divider when its resistance decreases and the other resistance is unchanged?

32. Find the value of the unknown resistor in the voltage dividers shown.



CHAPTER

6 Using electricity

REMEMBER

Before beginning this chapter, you should be able to:

- identify a range of common components of simple electric circuits
- recognise the circuit symbols for common components of simple electric circuits
- describe the operation of simple series and parallel circuits
- connect components into simple circuits following a circuit diagram.

KEY IDEAS

After completing this chapter, you should be able to:

- model simple electrical devices as simple direct current (DC) circuits
- model household (AC) systems as simple direct current (DC) circuits
- describe the operation of household electrical circuits and such components as circuit breakers, fuses and residual current devices (RCDs)
- convert quantities of energy to kilowatt-hours (kW-h)
- identify the causes, effects and treatment of electric shocks to humans in the context of household use of electricity
- present data obtained from electric circuit investigations in tables and graphs
- assess risk in the use of electrical equipment.

Hybrid cars combine electric drives with combustion engines to reduce reliance on petrol and increase efficiency. The black box on the right houses the electric generator.

Electricity in the real world

In this chapter you will see how the basic rules for series and parallel circuits can be applied to household use of electricity. The safe use of electricity will also be discussed, as well as the effects of electric shocks on the human body.

Parallel circuits are usually preferred over series circuits, because each device in a parallel circuit can be turned on and off independently. Devices in parallel circuits also have the same voltage drop. In series circuits, on the other hand, the devices have the same current flowing through them and the voltage is shared across the circuit. If one device is switched off, all the devices go off.

study on

Unit 1	**Household electricity** Concept summary and practice questions
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Household use of electricity

Houses connected to the main electrical grid are supplied with an AC voltage of 230 V rms at a frequency of 50 Hz. The term '230 V rms' means that the AC voltage produces the same heating effect when applied across a conductor as would a DC voltage of 230 V applied across the same conductor. The actual value of the voltage oscillates between +325 V and –325 V. 'Root mean square' (rms) refers to the mathematical process by which the equivalent DC voltage is calculated. 'A frequency of 50 Hz' means that the full cycle is completed 50 times each second. The voltage supplied is sinusoidal in nature.

Frequency is a measure of how many times per second an event happens.

Period is the amount of time one cycle or event takes, measured in seconds.

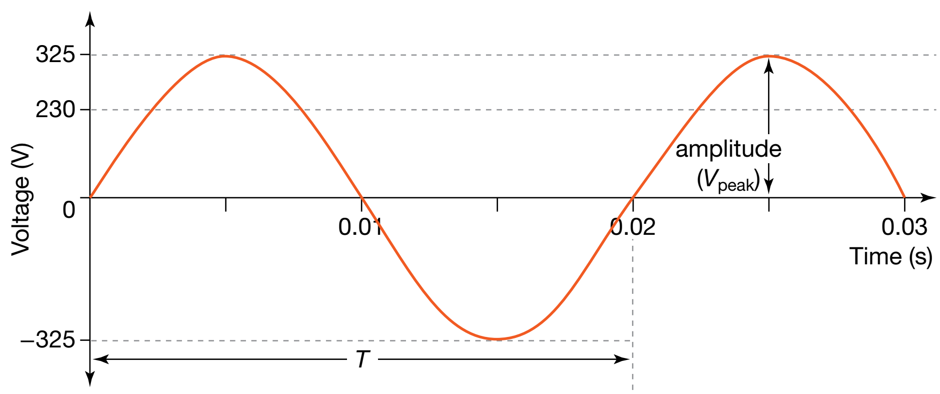
Frequency (f) is a measure of how many times per second an event happens. The unit for frequency is the hertz (Hz). One hertz means one cycle or event per second. **Period** (T) is the amount of time one cycle or event takes, measured in seconds. Period is the reciprocal of frequency.

$$T = \frac{1}{f}$$

or

$$f = \frac{1}{T}$$

A frequency of 50 Hz means that the period is 0.02 s, as shown below.



The variation of voltage with time for a supply of 230 V rms, 50 Hz

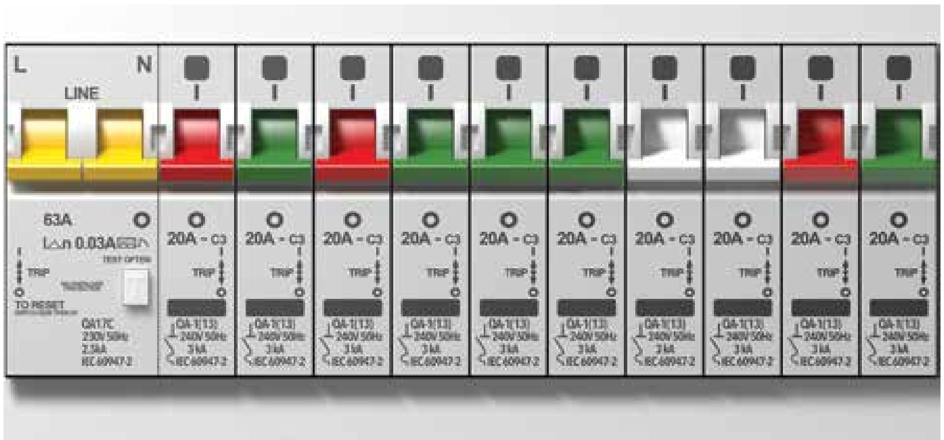
Electricity is fed into the home through underground cables or overhead lines. It enters the house through a switchboard. This contains a mains switch which can cut off the supply of electricity to the house. There is also a meter that measures the amount of electrical energy transformed in the house. From the meter, the electricity enters a fuse box or circuit breaker box where it is divided among a number of parallel circuits. The role of fuses and circuit breakers is dealt with later in this chapter.

The structure of household circuits differs from the structure of DC circuits studied in chapters 4 and 5. Household circuits make use of the earth to complete the circuit. The **active wire** in a circuit is connected to the 230 V rms

The **active wire** in a circuit is connected to the 240 V rms supply at the switchboard.

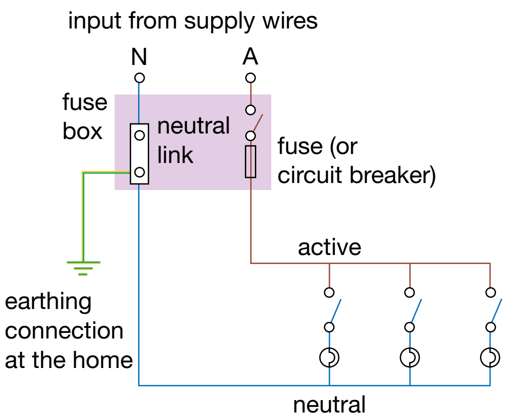
supply at the switchboard. Its voltage oscillates periodically between +340 V and –340 V relative to a reference voltage called 'earth'. The earth is defined as having a voltage of 0 V. The **neutral wire** is connected to the neutral link at the switchboard, which is connected to the earth through the supply wires and via a metal rod driven into the ground at the switchboard. The neutral wire is always at 0 V. The voltage drop between the active and the neutral wire oscillates between +340 V and –340 V.

The **neutral wire** in a circuit is connected to the neutral link at the switchboard, which is connected to the earth.



A typical household circuit breaker. All the switches are in the off position. When the switches are turned up, the current flows. If the circuit is broken, the switches will flick down to the off position.

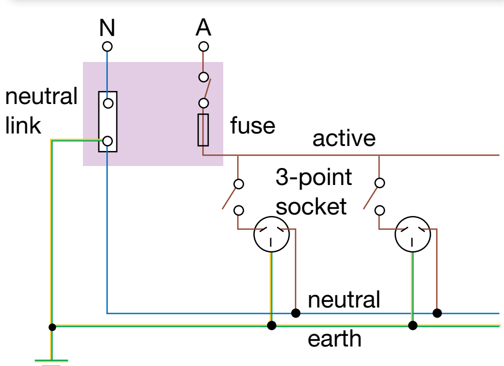
When an appliance is connected between the active wire and the neutral wire, current flows backwards and forwards between the active and neutral wires through the device, supplying it with energy.



A typical household lighting circuit

Conventional current flows from a high voltage to a low voltage. When the active wire is positive, the current flows from the active to the neutral wire and so to the earth. When the active wire is negative, the neutral wire at 0 V will have the higher voltage, and the current will flow from the neutral to the active wire.

In lighting circuits, only the active and neutral wires are used if there are no metal fittings. The current oscillates through the filaments of the globes, transforming energy. If metal fittings are used, they must be earthed. A typical lighting circuit is shown in the figure at left.

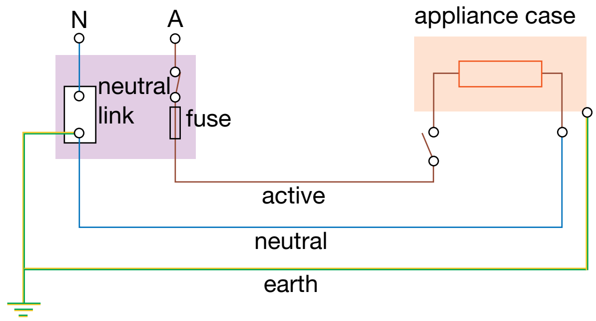


A typical power circuit

The **earth wire** is used in power circuits as a safety device; it connects the case of the appliance being used to the earth.

In power circuits, a third wire is used. This is called the **earth wire**. It connects the case of the appliance being used to the earth as a safety device. Its function is discussed in the section on safety later in this chapter. Otherwise, a power circuit operates in exactly the same way as a lighting circuit, with the current oscillating between the active and neutral wires through the appliance. The figure at left shows how 3-point power sockets are connected in a typical power circuit.

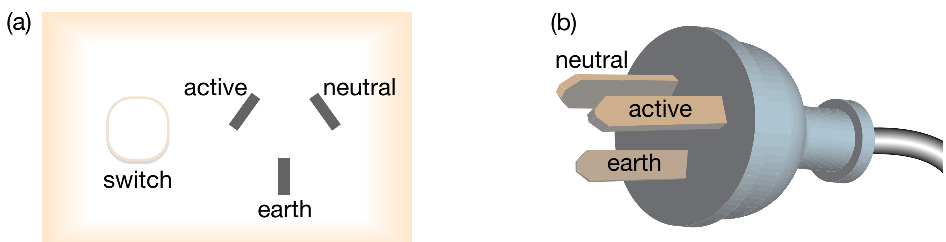
The figure below shows the connection of the earth wire to the case of an appliance.



The connection of the earth wire to the case of an appliance

Note that in both the lighting and power circuits the switch is in the wire connecting the device to the active wire. A switch in the neutral wire would also turn off the device, but the functional parts of the device would be 'live'. That is, the functional parts (e.g. the heating element of a toaster) would still be directly attached to the active wire.

If you were to touch anything in contact with the active wire while you were in contact with the ground, there would be a voltage drop across you and a potentially lethal current could flow through you. For this reason, if ever it is necessary to tamper with the functional parts of an electrical device, it must be unplugged first. The 3-point socket may have been wrongly wired, and it is not worth taking the risk.



(a) A 3-point socket. The top left point is the active, the top right point is the neutral, and the bottom point is the earth connection. The switch is connected in the active wire. Also shown (b) is the wiring arrangement of a typical 3-point appliance plug. Note that the active pin is inserted into the active socket.

Different-coloured insulating plastic is used to distinguish the three wires from each other. In the modern system, the active wire is brown, the neutral wire is blue and the earth wire is striped green and yellow. In the old system, red was used for the active, black for the neutral, and green for the earth wires.

Power ratings

The total power used in an electrical circuit, be it series or parallel, is the sum of the power used by each device in the circuit. Electrical appliances or devices are given a power rating, which is usually printed on them.

Sample problem 6.1

A toaster is rated at 1400 W, 230 V.
(a) What current does the toaster draw when operating normally?
(b) What is the resistance of the toaster element when hot?

Solution: (a) $P = VI$, so $I = \frac{P}{V}$

$$\Rightarrow I = \frac{1400 \text{ W}}{230 \text{ V}}$$

$$\Rightarrow I = 6.09 \text{ A}$$

(b) $V = IR$

$$\Rightarrow R = \frac{V}{I}$$

$$\Rightarrow R = \frac{230 \text{ V}}{6.1 \text{ A}}$$

$$\Rightarrow R = 37.8 \ \Omega$$

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Operating costs of electrical appliances

Revision question 6.1

A compact fluorescent light globe is rated at 15 W, 230 V.
(a) Calculate the current through the globe when it is operating normally.
(b) Calculate the resistance of the globe when it is operating normally.

Paying for electricity

The meter on a household switchboard is used to measure how much electrical energy has been consumed on the premises. The amount of electrical energy used in a household can be determined by multiplying the rate of power transformation by the time. Since power is equal to the voltage drop multiplied by current, and the voltage drop across a household is 230 V, the meter on the switchboard records the total current that has passed through the premises over a certain period of time. This amount is converted into the amount of energy 'consumed' or transformed.

The unit used for measuring energy in this case is the **kilowatt-hour** (kW-h). This is the amount of energy transformed by a 1000 W appliance when used for one hour.

A **kilowatt-hour** (kW-h) is the amount of energy transformed by a 1000 W appliance when used for one hour.

Sample problem 6.2

How many joules does one kilowatt-hour represent?

Solution: Energy = power × time.

1 h = 3600 s, 1 kW = 1000 W.

Therefore 1 kW-h = 1000 W × 3600 s, or 3.6×10^6 J, or 3.6 MJ.

The cost to consumers of 1 kW-h of electrical energy can be found on electricity accounts. Find out what 1 kW-h of electrical energy costs in your household. To calculate the cost of running a particular appliance, two methods can be used. In the first, calculate the energy in kilowatt-hours by multiplying the power rating of the appliance, in kilowatts, by the number of hours that it was used for.

The second method is used if the power rating is unknown. Calculate the energy consumed in joules, using the formula $E = VIt$, where E is the energy consumed, V is the voltage drop across the device, I is the current flowing through the device and t is the time in seconds. The amount of energy is then converted into kilowatt-hours by dividing by 3.6×10^6.

To calculate the cost, use the formula:

$$\text{cost} = \text{energy} \times \text{rate}.$$

Sample problem 6.3

A television draws 0.37 A of current when connected to a 230 V supply.

(a) What is the power rating of the television?

(b) How much energy does the television consume if it is operated for 5 hours a day for 4 weeks?

(c) What is the cost of running the TV for this period of time if the consumer is charged at a rate of 16.381 cents per kilowatt-hour?

Solution:

(a)
$$P = VI$$
$$P = 230\text{ V} \times 0.37\text{ A}$$
$$= 85\text{ W}$$

(b)
$$\text{energy} = \text{power} \times \text{time}$$
$$\text{time} = 28\text{ days} \times 5\text{ hours per day} = 140\text{ h}$$
$$\text{power} = 85\text{ W}$$
$$\text{So energy} = 85\text{ W} \times 140\text{ h}$$
$$= 12\,000\text{ W-h}$$
$$= 12\text{ kW-h}$$

(c)
$$\text{cost} = \text{energy} \times \text{rate}$$
$$= 12\text{ kW-h} \times 16.381\text{ cents}$$
$$= 197\text{ cents or \$1.97}$$

Revision question 6.2

A home sound system consumes 2.4 W of electric power when it is on standby and connected to a 230 V supply.

(a) Calculate the current that flows through the system when it is on standby.

(b) Calculate the energy consumed by the system if it is left on standby for one week.

(c) Calculate the cost of leaving the system on standby for one week if electricity is priced at 12 c per kW-h.

A shocking experience

An **electric shock** is a violent disturbance of the nervous system caused by an electrical discharge or current through the body.

There are various factors that contribute to the severity of an electric shock. The first of these is the size of the voltage involved. Also, the human body is far more sensitive to alternating current than direct current. Voltages as low as 32 V AC and 115 V DC can be fatal.

It is not the voltage alone that causes damage to the human body. When you slide across a car seat, you can generate a voltage of several thousand volts. When you get out of the car and touch the ground, you are discharged and experience a shock, but with no serious consequences. The voltage drop across a person is one factor in determining the seriousness of an electric shock, but clearly other factors are involved.

The following information refers to shocks involving alternating currents with a frequency of 50 Hz.

An **electric shock** is a violent disturbance of the nervous system caused by an electrical discharge or current through the body.

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Unit 1 | AOS 2 | Topic 3 | Concept 3

Electric shock
Concept summary and practice questions

Resistance of the human body

One contributing factor to the severity of an electric shock is the resistance of the human body. The interior of the body is a good conductor of electricity. The tissues and fluids beneath the skin conduct electricity due to the presence of ions in the fluids.

The skin provides the main resistance to the flow of electricity in the body. The resistance of the skin ranges in value from $10^6\ \Omega$ for dry skin, to 1500 Ω for a person with wet hands, and about 500 Ω for a person sitting in a bath. This is a good reason for keeping electrical appliances away from water in the bathroom; tap water is also a reasonably good conductor.

Resistance to current flow is offered by the skin up to about 600 V, at which point the skin is punctured and offers little resistance to current flow. Breaks or cuts in the skin also reduce the resistance of the skin.

One of the main reasons for the high resistance of skin is the poor contact that is made between the skin and the electrical source. Water improves the contact. In hospitals, a conducting gel is used when a good electrical contact is required, for example when using an electrocardiogram.

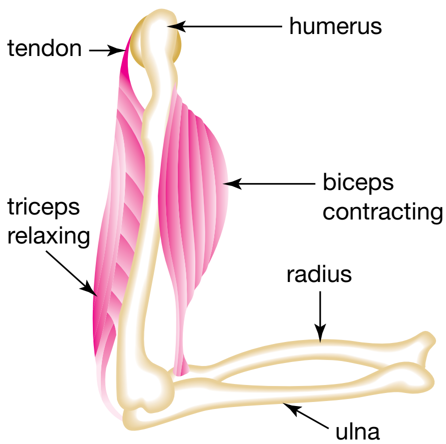

Diagram showing the biceps and triceps in the human arm

The effect of current

The most important factor to be considered in respect to the severity of an electric shock is the amount of current flowing through the body. This is important because impulses within the nervous system are themselves electrical in nature.

Even very small currents passing along nerves make muscles contract. Skeletal muscles (muscles attached to the bones) work in pairs. To raise your forearm, for example, the biceps muscle contracts and the triceps muscle relaxes. To lower your forearm, the biceps muscle relaxes and the triceps muscle contracts. This arrangement of muscles is shown in the figure at left.

One effect of passing a small current through the body is to make muscles contract. Another effect stimulates the nerves that send pain signals to the brain, causing the painful sensations associated with shocks.

AS A MATTER OF FACT

You may have heard of someone who received an electric shock being 'thrown across the room.' This is not due to any explosion, but to the violent contraction of the person's muscles.

A current of 9 mA AC across the chest causes shock. A current of twice that amount causes difficulty in breathing. A current of 20 mA causes muscles to become paralysed: they contract and stay contracted. A person unfortunate enough to touch a live conductor with the palm of their hand will grip onto the conductor and not be able to let go. Lazy electricians, if unsure whether a wire is live, may bring the back of the hand towards the wire. Any shock they receive will contract the muscles so that the hand is pulled away from the wire. This procedure is definitely not recommended.

A current as low as 25 mA through the trunk of the body can cause **fibrillation**. This is the disorganised rapid contraction of separate parts of the heart so that it pumps no blood, and death soon follows. Sometimes fibrillation subsides when the external voltage is removed.

Fibrillation is the disorganised, rapid contraction of separate parts of the heart so that it pumps no blood; death may follow.

PHYSICS IN FOCUS

Heart starter

Defibrillation is a medical intervention technique carried out on victims of heart attack. If the cardiac monitor shows that fibrillation is occurring, a current of 20 A at 3000 V is passed through the heart for about 5 ms. This produces a major contraction of all the muscles in the heart, which usually jolts them back into the proper rhythm. The shock is applied above and below the heart via two large electrodes called paddles. Conducting gel is used to make good contact with the body. It is important that the operator and other staff are well insulated from the patient.

The effect of current path

The third factor affecting the severity of an electric shock is the path of the current through the body. Respiratory arrest generally requires the current to pass through the back of the head. Ten milliamps of current through the forearm muscles make them contract sufficiently to hold the victim to any live conductor he or she is gripping. The most dangerous pathway for current is through the trunk of the body.

Time of exposure

The final factor contributing to the severity of a shock is the time of exposure to the current. The longer the current flows through the body, the greater the damage to tissue will be. Table 6.1 shows what effects current size and time duration have on the heart.

TABLE 6.1 Electric shock current-versus-time parameters

Current (mA)	Time (ms)	Effect
50	10–200	Usually no dangerous effect
50	>4000	Fibrillation possible
100	10–100	Usually no dangerous effect
100	>600	Fibrillation possible
500	>40	Fibrillation possible

In the event of a shock

Electrocution is death brought about by an electrical shock.

The first priority, when helping a victim of electric shock, is to make sure that the victim is not still connected to the electrical source. If the person is still connected, and you grab them, you could be electrocuted too. (**Electrocution** is death brought about by an electrical shock.) Your muscles may contract and you will not be able to let go of the victim, becoming a victim yourself. Turn off the electric circuit, or knock the victim away from the live conductor with an insulating material, for example a wooden chair.

Artificial respiration should be given to the victim if breathing has ceased. Respiratory failure is a common cause of death among shock victims. This is true of people who have been struck by lightning also.

Call an ambulance immediately.

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Unit 1	Household electrical safety
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Safety in household circuits

Every year many lives are lost and much property is damaged or destroyed because of electrical 'accidents' or through electrical faults in both industrial and domestic situations. Accidents occur because basic safety precautions are not followed in dealing with electricity. The effects of electricity on the human body have already been discussed. This section looks at some common electrical faults and the safety devices employed to reduce the danger to people.

Fuses and circuit breakers

One common pitfall is overloading a circuit. In parallel circuits, the total current flowing in the circuit is the sum of the individual currents flowing through the devices in the circuit. Too many appliances operating on a single power circuit will produce a large current in the conducting wires. The wires will get hot and melt their insulation, potentially causing a fire in the walls or ceilings of the building.

A **short circuit** can occur when frayed electrical cords or faulty appliances allow the current to flow from one conductor to another with little or no resistance. This allows the current to increase rapidly, with the same results as an overload.

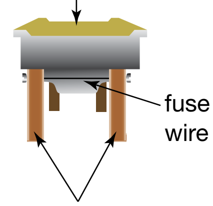
A **short circuit** can occur when frayed electrical cords or faulty appliances allow the current to flow from one conductor to another with little or no resistance. The current increases rapidly, causing the wires to get hot and potentially cause a fire.

A **fuse** is a short length of conducting wire or strip of metal that melts when the current through it reaches a certain value, breaking the circuit.

A **circuit breaker** carries out the same function as a fuse by breaking the circuit when the current through it exceeds a certain value.

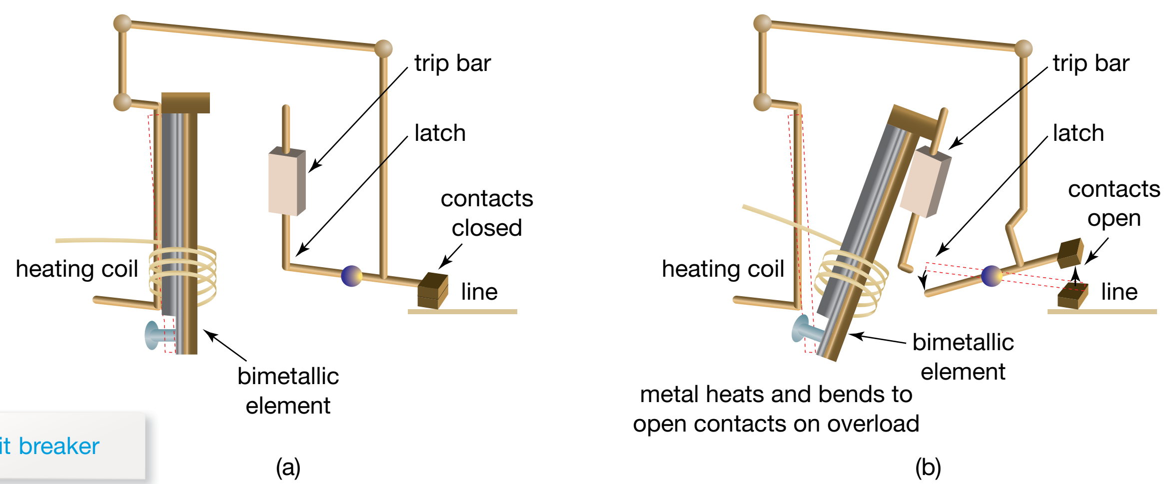
Cheap extension cords are another source of overheating. They are not designed to carry more than 7.0 A safely, and exceeding this amount may result in the insulation melting and allow arcing to occur.

In domestic applications, each circuit is protected by either a **fuse** or a **circuit breaker**. A fuse is a short length of conducting wire or strip of metal that melts when the current through it reaches a certain value. The most common type of fuse is the plug-in type illustrated at right. This has a ceramic body with metal prongs projecting from each end. A short piece of special fuse wire connects the metal prongs. When the current through the fuse exceeds a predetermined value, the wire melts, or 'blows', breaking the circuit.



A plug-in fuse

A circuit breaker carries out the same function as a fuse. It breaks the circuit when the current through the circuit exceeds a particular value. The advantage circuit breakers have over fuses is that they can be reset easily. There are two types of circuit breaker available: thermal and electromagnetic.



A thermal circuit breaker

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When a current flows through the thermal type of circuit breaker, the heating coil heats the bimetallic strip. The two metals in the bimetallic strip expand at different rates when heated, causing the strip to bend. When the current exceeds the predetermined amount, the bimetallic strip bends so much that it opens the catch and the circuit is broken. Because of the time it takes to heat up the strip, these circuit breakers will not trip if the current surge is of a short duration. This type of circuit breaker is not satisfactory if a short circuit occurs and offers little assistance in preventing electrocutions.

The electromagnetic type uses the magnetic effects of electric currents: it uses an electromagnet to lift the catch and break the circuit. The bigger the current is in the coil, the stronger the electromagnetic force will be on the lever system. Again, these circuit breakers are designed to break the circuit at predetermined values of the current. To prevent this type of circuit breaker tripping when a short-duration current surge occurs, the switching mechanism is usually restrained in some way. The magnetic circuit breaker will trip almost instantly when a heavy overload occurs. It provides good protection against short circuits.

Both fuses and circuit breakers are placed in the active wire at the meter box. Light circuits are generally designed to take a maximum safe current of 5.0 A, whereas power circuits have a maximum safe current of 15 A.

Sample problem 6.4

A kitchen circuit has the following appliances operating in it: a 1000 W toaster, a 312 W refrigerator, a 1200 W kettle, a 600 W microwave oven and a 60.0 W juicer. The circuit is protected by a 15 A fuse, and it is connected to a 230 V, 50 Hz supply.

(a) What is the current flowing through the fuse when all the appliances are operating at the same time?

(b) Will the fuse 'blow' if a 2400 W heater is used at the same time as the other appliances?

Solution: (a) The total current in the circuit is the sum of the individual currents of the appliances. This can be calculated using the power ratings of the appliances and the formula $P = VI$ or $I = \frac{P}{V}$.

For the toaster, $I = \frac{1000\text{ W}}{230\text{ V}} = 4.35\text{ A}.$

For the refrigerator, $I = \frac{312\text{ W}}{230\text{ V}} = 1.36\text{ A}.$

For the kettle, $I = \frac{1200\text{ W}}{230\text{ V}} = 5.22\text{ A}.$

For the microwave oven, $I = \frac{600\text{ W}}{230\text{ V}} = 2.61\text{ A}.$

For the juicer, $I = \frac{60\text{ W}}{230\text{ V}} = 0.261\text{ A}.$

So the total current in the circuit is $4.35 + 1.36 + 5.22 + 2.61 + 0.261 = 13.8$ A. The fuse will not melt.

(b) A 2400 W heater will draw an additional 10.4 A, so the total current in the circuit will be 24.2 A. This is much greater than 15 A, so the fuse will blow.

Revision question 6.3

A bathroom fan, light and heater system consists of one 75 W light globe, four 150 W heat lamps and one 100 W fan. It is connected to a 230 V supply.

(a) Calculate the total current through the system when the fan and light globe are in use.

(b) Calculate the total current through the system when the fan and two heat lamps are in use.

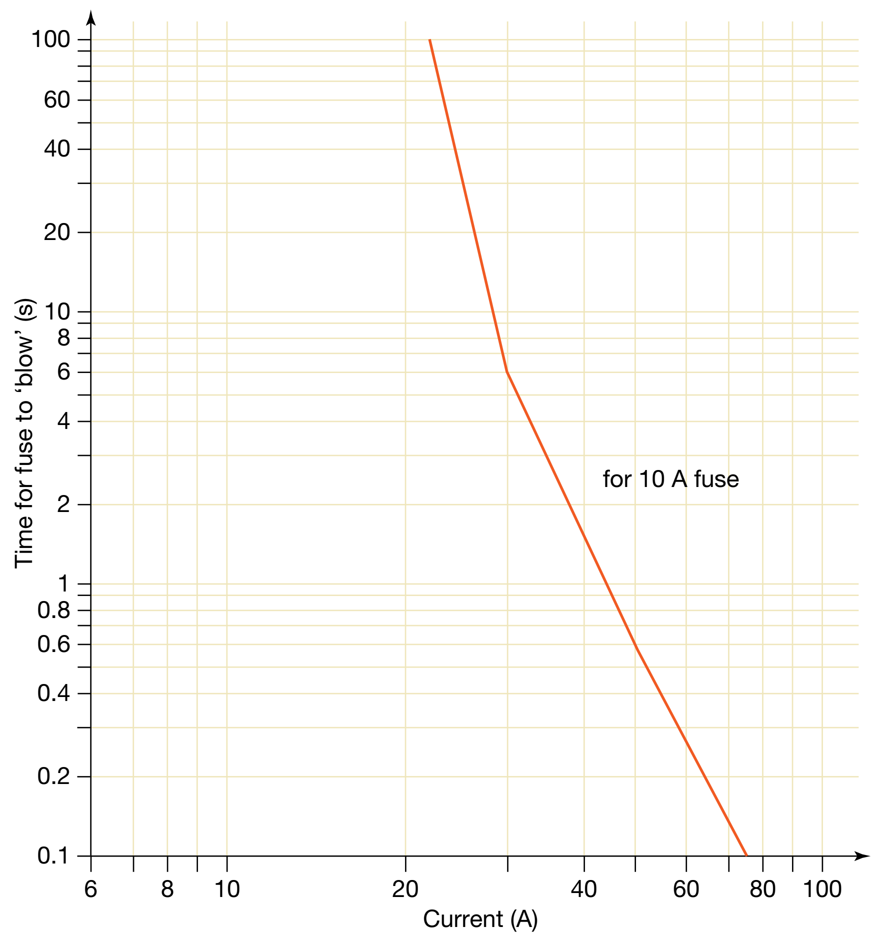
(c) Calculate the total current through the system when all the devices are in use.

Earthing

The earth wire is another safety measure used for power circuits. It connects the metal chassis of an appliance to the earth, which is at 0 V. This connection is made via a metal rod driven into the ground at the switchboard.

An electrical fault could occur if the active wire were to come into contact with the metal case of an appliance. The case would then carry an AC voltage, and anyone touching the case would receive a shock. The earth wire provides a lower-resistance conducting path to the earth than the appliance and the person. The low resistance involved produces a large current in the circuit, and the fuse blows or the circuit breaker trips.

The earth wire does not provide the most reliable protection. As can be seen in the graph below, the amount of time it takes to blow a fuse depends on the size of the current. A quicker method of breaking the circuit is needed if lives are to be saved.



Time before a typical 10 A fuse 'blows', as a function of (rms) current

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Digital docs
Investigation 6.1:
Examination of an electrical device
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Investigation 6.2:
Model circuits
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Electrical safety

If the current is flowing through a person to the earth, the following principles should be followed: the current should be as small as possible, and the time of exposure to the current should be as short as possible. Fuses are not designed to meet these requirements. Their main function is to prevent fires in buildings due to the overheating of wires when they carry too great a current.

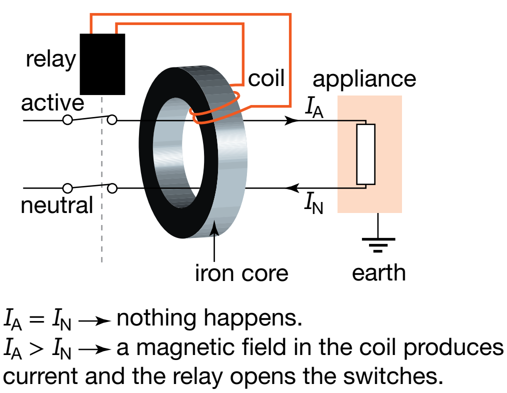
Residual current device

The **residual current device** is illustrated below. It operates by making use of the magnetic effects of a current, and it is similar to a transformer. The current in the active wire flows in the opposite direction to the current in the neutral wire. Both currents pass through the iron loop. When the current in the active wire is equal in magnitude to the current in the neutral wire, each wire produces a magnetic field. These fields are equal in magnitude, but opposite in direction, and have no overall effect.

A **residual current device** operates by making use of the magnetic effects of a current to break a circuit in the event of an electrical fault.

However, if there is an electrical fault and a residual current flows to the earth via the earth wire or a person, the current in the active will be greater than in the neutral. The residual current is the difference between the active and neutral currents. The magnetic effects of the two currents will no longer cancel. A current is then produced in the relay circuit and both the active and neutral wires of the circuit are broken by a switch.

A residual current device operates in about 40 ms, limiting the current to 30 mA. At such values the shock will be perceptible, but not likely to have any harmful effects. The residual current device is useful only when the current flows to earth, not if the current flows through the person between the active and neutral wires.

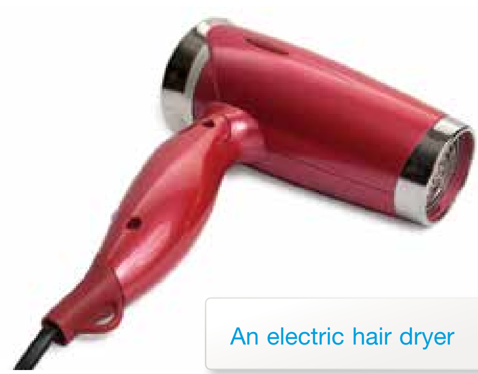


A residual current device

Double insulation

Hand-held electrical tools and appliances, such as electric drills and hair dryers, are protected by double insulation. These appliances have only a 2-pin plug, using only the active and neutral wires. They should not be earthed. The symbol ⧈ on the casing of an appliance means that it is double insulated.

As the name implies, double insulation means that the accessible metal parts cannot become live unless two independent layers of insulation fail. The inner layer is called the functional insulation. This layer has both electrical insulation and heat-resisting properties. The outer layer is called protective insulation and often forms part of the casing.



An electric hair dryer

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Unit 1 | AOS 2 | Topic 3

Using electrical energy

Sit Topic test

Chapter review

Summary

- Household electricity is provided as alternating current with a frequency of 50 Hz.
- Household circuits include an active wire that oscillates between +325 and −325 volts relative to the earth, which is defined as having a voltage of zero. Household circuits also include a neutral wire, which is connected to the earth. Electric current flows backwards and forwards between the active wire and the neutral wire.
- In many circuits an earth wire is used to connect the case of an appliance directly to the earth as a safety device.
- The rules relating to series and parallel circuits can be applied to both AC and DC circuits.
- The kilowatt-hour is a unit widely used to measure the amount of electrical energy consumed.
- An electric shock is a violent disturbance of the nervous system caused by an electrical discharge or current through the body.
- The severity of an electric shock depends on a number of factors, including current, pathway through the body and time of exposure.
- Fuses and circuit breakers are safety devices that use different methods to break an electric circuit when a dangerous level of current flows through it.
- The residual current device opens switches in the active and neutral wires when the currents in these wires become unequal due to an electrical fault. It is designed to protect against electrocution and operates more quickly than a typical fuse.

Questions

Household use of electricity

1. What is meant when it is said that a house is supplied with electricity at 230 V rms, 50 Hz?

2. Why is an overload in a household circuit potentially dangerous?

3. What coloured insulation is used for the active, neutral and earth wires in modern houses?

4. Sketch a power point and plug. Label the active, neutral and earth in each case.

5. Why do many appliances need to be connected to both the neutral and earth wires?

6. When is the earth wire used in household lighting circuits?

7. What is the cost of running a 300 W refrigerator for a year (365 days) if the refrigerator operates on average for 12 hours a day, and electricity costs 31.28 cents per kilowatt-hour?

8. An oil heater is rated at 1000 W and runs off 230 V supply.
(a) What current does the heater draw?
(b) What is the effective resistance of the heater?
(c) If electricity costs 17 cents per kilowatt-hour, what does it cost to run the heater for 5.0 h?

9. The following table gives the power consumption of various products when they are on standby.

Product	Power (W)
Laptop computer	14.5
Modem	3.4
Cordless phone equipment	3.7
DVD player	2.4
Television	6.2

(a) Calculate the energy used by each product if it is left on standby for one year.
(b) Calculate the mass of greenhouse gases produced by these products if they are left on standby for one year, assuming that 1 kW-h of energy produces greenhouse gases that are equivalent to 1.444 kg kilograms of CO_2.

Safety in household circuits

10. What is the difference between a shock and electrocution?

11. Describe factors that reduce the resistance of human skin.

12. Why is the amount of current flowing through the body important in determining the severity of an electric shock?

13. What is fibrillation?

14. What would happen if you touched a shock victim who was still conducting an electrical current?

15. How is the severity of a shock related to the time of exposure?

16. What is 'double insulation'?

17. A worker touched an overhead power line and was electrocuted. A newspaper reported the incident in the following way:

> 'He touched the cable and 50 000 V of electricity surged through his body.'

Criticise this statement.

CHAPTER

7 Radioactivity and the nucleus

REMEMBER

Before beginning this chapter, you should be able to:

- recall that all matter is made up of atoms
- explain the arrangement of particles in an atom, in particular that atoms have a central nucleus containing protons and neutrons.

KEY IDEAS

After completing this chapter, you should be able to:

- use equations to model the random radioactive decay processes of substances with a particular half-life
- describe the origin and properties of α, β^-, β^+ and γ radiation
- explain nuclear transformations and decay chains
- distinguish between the two types of forces holding the nucleus together: the strong nuclear force and the weak nuclear force
- explain nuclear energy as energy resulting from the conversion of mass into energy using $E = mc^2$
- compare the processes of nuclear fusion and nuclear fission
- use a binding energy curve to explain why both fusion and fission are reactions that produce energy.

Marie Curie (1867–1934), Polish-French physicist who won two Nobel Prizes: in 1903 for Physics and 1911 for Chemistry

Natural nuclear radiation

The ideas and events described in this chapter all started from a single chance discovery: Wilhelm Röntgen's discovery of X-rays in 1895. Röntgen's discovery led to a deep understanding of the nature of matter and to technological innovations of impressive and at times catastrophic impact. The timeline below describes many of the discoveries that have happened since then.

This chapter covers the events of the early years of the timeline, when radioactivity was discovered and the structure of the atom determined.

TABLE 7.1 Nuclear timeline

1895	Röntgen accidentally discovers X-rays while investigating the flow of electricity in a gas contained in a tube.
1896	Becquerel discovers natural radioactivity while investigating phosphorescent minerals, such as uranium salts, to see if they also give off X-rays when exposed to sunlight.
1897	Joseph Thomson discovers the electron. He later proposes a 'plum pudding' model of the atom, which suggests the atom is a slightly positive sphere with raisin-like, negatively charged electrons inside.
1898	Marie and Pierre Curie separate out radioactive elements in minerals, in the process discovering two new elements: radium and polonium.
1899	Rutherford shows that there is more than one type of radiation; he identifies α and β rays.
1900	Pierre Curie shows that β rays are negatively charged particles by deflecting them in a magnetic field. He later deflects α rays with a stronger field, showing that they are positively charged particles. Villard discovers gamma rays. Becquerel shows that β particles have the same charge-to-mass ratio as electrons.
1901	Becquerel chemically removes all the β-emitting elements from a uranium sample and puts it aside. Some months later he finds the sample is emitting β particles.
1902	Rutherford repeats Becquerel's work, but he examines the count on a daily basis. He concludes that radioactive decay is a random process leading to an exponential decay curve, with each radioactive nucleus having its own half-life.
1903	Rutherford and Soddy propose a 'spontaneous disintegration theory'.
1906	Rutherford measures the charge-to-mass ratio of α particles. It is half that of the hydrogen ion. Boltwood discovers two forms of thorium with different radioactive properties. Soddy proposes the name 'isotope'.
1908	Rutherford and Geiger measure the charge on α particles. They are doubly charged helium atoms.
1909	Rutherford and Royds fire α particles into a vacuum. After some time they confirm the presence of helium from the spectrum. Geiger and Marsden fire α particles at thin gold leaf and observe that some are scattered back. Rutherford proposes a nuclear model of the atom.
1913	Geiger and Marsden experimentally confirm Rutherford's nuclear model.
1919	Rutherford changes nitrogen into oxygen with α particles.

1920	Chadwick confirms that the nuclear charge is the atomic number.
1920	Rutherford proposes a particle described as a 'neutral doublet' in the nucleus to explain β decay and atomic mass.
1920s	Aston discovers that the masses of atoms are close to exact integers, based on oxygen set at 16, but the difference is measurable. This leads to the concept of nuclear binding energy.
1927	Paul Dirac develops the theory of the electron, which suggests the possibility of anti-matter.
1930	Bothe and Becker bombard beryllium with α particles to produce an unknown form of radiation.
1931	Urey discovers deuterium, known as heavy hydrogen, with one proton and one neutron.
1932	Chadwick shows that the radiation discovered by Bothe and Becker is a neutral particle of mass approximate to that of the proton, to be called the neutron.
1932	Carl Anderson discovers the anti-electron (or positron), the first antiparticle, in cosmic rays. (The positron's existence was proposed by Paul Dirac in 1927 and Ettore Majorana in 1928.) Cockcroft and Walton fire high energy protons at lithium, producing two α particles. Mark Oliphant discovers tritium, an isotope of hydrogen with two neutrons, and helium-3, with only one neutron. He also discovers fusion when he fires a deuterium nucleus at a deuterium target.
1934	Enrico Fermi postulates the existence of the neutrino (Italian for 'little neutral one'), a neutral-charge partner to the electron to ensure energy is conserved in β decay. The theory is confirmed in 1959.
1935	Fermi discovers fission when he fires neutrons at uranium. Radioactive products with unexpected half-lives were found, but he thought that they might have atomic numbers greater than 92.
1939	Hahn and Strassmann repeat Fermi's experiment and chemically analyse the products, finding barium (atomic number 56). Meitner and Frisch call the process 'fission.' They find that thorium and protactinium also split, as well as evidence of bromine, molybdenum, rubidium, antimony, iodine and caesium. They estimate that 200 MeV is released from a single uranium-235 nucleus. Von Halban and Joliot discover that a fission reaction produces two or three high-speed neutrons. The possibility of a self-sustaining or chain reaction is realised.
1945	When uranium-238 accepts a neutron, it becomes uranium-239, which β decays to neptunium-239, which β decays to plutonium-239.
2007	Calcium-48 ions are fired at californium-249 atoms to produce the element with atomic number 118.

Nuclear radiation is an everyday occurrence for all people. We are exposed to a small amount of natural nuclear radiation all the time. There are two types of natural nuclear radiation: terrestrial radiation from the Earth and cosmic radiation from space. This radiation does not cause us permanent damage. There is evidence to suggest that living things have adapted to this background radiation.

Terrestrial radiation

When the Earth was formed, it contained a large number of radioactive nuclei. Some of these nuclei are still emitting radiation from the Earth's crust and atmosphere. This low-level radiation surrounds us. Moreover, our bodies are made from atoms that originally came from the Earth and atmosphere, so we are even emitting some radiation ourselves!

Cosmic radiation

Cosmic radiation comes to us from space. The atmosphere absorbs much of this radiation. This means we receive much less cosmic radiation than we would if we were on the surface of the Moon, which doesn't have an atmosphere. Because of the effect of the atmosphere, people living at higher altitudes receive higher doses of cosmic rays than those living at sea level. People flying in planes receive even more, although these levels are still quite safe.

The latitude at which you live also has a slight effect on the amount of cosmic radiation you receive. Cosmic radiation is affected by the Earth's magnetic field, and its intensity increases as you move towards the poles.

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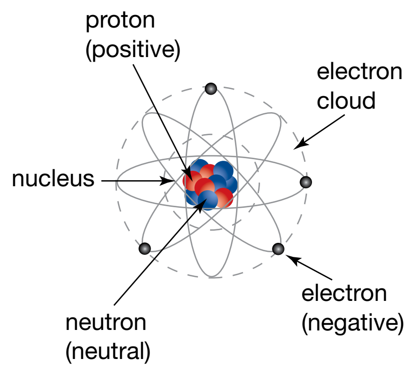
Unit 1	Simple particle model of the nucleus
AOS 3	
Topic 1	Concept summary and practice questions
Concept 1	

What is nuclear radiation?

Nuclear radiation, as the name suggests, is radiation emitted from the nucleus of an atom. In order to explain the mechanisms that release such radiation, it is important to understand a little about the structure of the atom, and the terminology that is associated with it.

All matter is made up of atoms. Each atom consists of a tightly packed, positively charged centre, called the **nucleus**, which is surrounded by a 'cloud' of small, negatively charged particles known as **electrons**. The particles in the nucleus are known collectively as **nucleons**, but there are two different types. Both types have roughly the same mass. The positively charged nucleons are **protons**, and the neutral (chargeless) ones are **neutrons**. Protons and neutrons are about 2000 times heavier than the electrons that surround the nucleus.



The atom

The **nucleus** is the solid centre of an atom. Most of the mass of an atom is concentrated in the nucleus.

An **electron** is a negatively charged particle found around the nucleus of an atom.

The collective name for the particles found in the nucleus of an atom is **nucleon**.

A **proton** is a positively charged particle in the nucleus of an atom.

A **neutron** is a nucleon with no charge.

A substance is an **element** if it consists only of atoms of the same name.

Scientists name atoms according to the number of protons in the nucleus. For example, all atoms with six protons are called carbon, all atoms with 11 protons are called sodium, and all atoms with 92 protons are called uranium. A substance consisting of atoms that all have the same name is called an **element**. Each element's name has its own shorthand symbol that scientists use. Carbon has the symbol 'C', sodium 'Na' and uranium 'U'. It is very important that the upper or lower case of the letters used in the symbols is kept the same. The names of all the elements, and their symbols, can be found in the periodic table in the appendices.

Strangely enough, not all atoms of the same name (and therefore the same number of protons) have the same number of neutrons. For instance, it is possible to find carbon atoms with six, seven and eight neutrons in the nucleus along with the six protons that make it carbon. These different forms of an element are called **isotopes**. To avoid confusion about which isotope is being referred to, scientists have a few standard ways of writing them. The number of nucleons, or **mass number**, of the particular isotope is used. The isotope of carbon with

Atoms containing the same number of protons but different numbers of neutrons are called **isotopes** of an element.

Mass number describes the total number of nucleons in an atom.

The number of protons in a nucleus is called the **atomic number** of the atom.

six protons and six neutrons is written as carbon-12 or ^{12}C, whereas the isotope of carbon with eight neutrons is written as carbon-14 or ^{14}C. Sometimes the number of protons, or **atomic number**, is written directly underneath the mass number, although this is not necessary (for example, $^{14}_{6}C$).

Sample problem 7.1

Write the name of the isotope of an atom with 90 protons and 144 neutrons.

Solution: From the periodic table in the appendices it can be seen that all atoms with 90 protons are called thorium, which has the symbol Th. The mass number (or number of nucleons) of this isotope is 90 + 144 = 234. Therefore the isotope is thorium-234, or ^{234}Th.

Revision question 7.1

How many protons and neutrons are there in one atom of each of the following isotopes?
(a) **Hydrogen-2, also known as deuterium**
(b) **Americium-241**
(c) **Europium-164**

Not all atomic nuclei (the plural of nucleus) are particularly stable. In some instances one isotope of an atom may be stable while another is not. This is why nuclear radiation is released. It is the atom's way of becoming more stable. Isotopes that are not stable are called **radioisotopes**. Many radioisotopes are found in nature; many more are produced artificially.

A **radioisotope** is an unstable isotope.

Types of nuclear radiation

Unstable isotopes can emit various types of radiation while 'striving' to become more stable. There are three naturally occurring forms of nuclear radiation: α, β and γ (pronounced *alpha*, *beta* and *gamma*). Each type of radiation was named with a different Greek letter because, when the different types of radiation were discovered, scientists did not know what they consisted of. The emissions are described as decay processes because the nucleus changes into a different nucleus and the change is irreversible.

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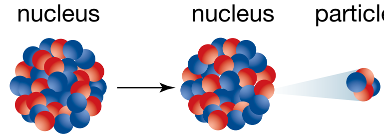
Alpha decay

During α decay an unstable nucleus ejects a relatively large particle known as an **α particle**. This actually consists of two protons and two neutrons, and so may be called a helium nucleus. The remainder of the original nucleus, known as the **daughter nucleus**, is now more stable.



Alpha decay: a nucleus ejects a helium nucleus.

An α **particle** is a relatively slow-moving decay product consisting of two protons and two neutrons. It is equivalent to a helium nucleus and so can be written as $^{4}_{2}He$. α particles carry a positive charge.

The nucleus remaining after an atom undergoes radioactive decay is called a **daughter nucleus**. The daughter nucleus is more stable than the original nucleus.

The number of protons in the nucleus determines the elemental name of the atom. The daughter nucleus is therefore of a different element. For example, uranium-238 decays by emitting an α particle. The uranium-238 atom contains 92 protons and 146 neutrons (238 – 92 = 146). It emits an α particle, with two protons and two neutrons. The original nucleus is left with four less nucleons: 90 protons (92 – 2 = 90) and 144 neutrons (146 – 2 = 144). As the daughter nucleus now has 90 protons, it is called thorium and has the symbol Th. This particular isotope of thorium has

234 nucleons (90 protons and 144 neutrons) and is more correctly written as thorium-234.

The information in the previous paragraph can be written much more effectively in symbols. This is called the **decay equation**:

$$^{238}_{92}U \rightarrow ^{234}_{90}Th + ^{4}_{2}He + energy$$

$$\text{or } ^{238}_{92}U \rightarrow ^{234}_{90}Th + \alpha + energy.$$

A **decay equation** is a representation of a decay reaction. It shows the changes occurring in nuclei and lists the products of the decay reaction.

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Unit 1	Alpha decay
AOS 3	Concept summary and practice questions
Topic 1	
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The ejected α particle is relatively slow and heavy compared with other forms of nuclear radiation. The particle travels at 5–7% of the speed of light: roughly 2×10^7 metres each second. Every object that moves has a form of energy known as kinetic energy, or energy of motion. Because the α particle is moving, it has kinetic energy. That energy is written into the decay equation.

In addition to having energy, the a particle has an overall charge of +2 because it contains two protons. This charge means the particle can be deflected by electric or magnetic fields — properties that helped scientists determine what an a particle consisted of.

Energy

The main unit of energy used in this text is the joule (J). The joule is a very convenient unit when dealing with large amounts of energy. However, the energy of a moving α particle is comparatively small. Often it is more convenient in this area of physics to use electron volts (eV).

An electron volt is the amount of energy an electron or a proton gains when accelerated across a voltage drop of 1 volt. Because the amount of charge on an electron and a proton is $1.602\,176 \times 10^{-19}$ coulombs, 1 electron volt is equivalent to $1.602\,176 \times 10^{-19}$ joules. The symbol 'MeV' means one million electron volts and is equal to $1.602\,176 \times 10^{-13}$ joules. Because the numbers are easier to deal with, the MeV is the unit of preference when working with nuclei.

Energies of nuclear radiation are usually from 0.1 to 10 MeV (megaelectron volts).

Beta decay

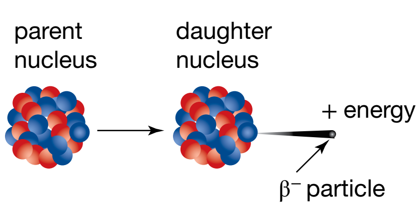
A **positron** is a positively charged particle with the same mass as an electron.

Two types of β decay are possible. The β^- particle is a fast moving electron that is ejected from an unstable nucleus. The β^+ particle is a positively charged particle with the same mass as an electron, and is called a **positron**. Positrons are mostly produced in the atmosphere by cosmic radiation, but some nuclei do decay by β^+ emission.

In β^- decay an electron is emitted from inside the nucleus. Since nuclei do not contain any electrons, this might seem strange, but it is in fact true! There is no change whatsoever to the electrons in the shells surrounding the nucleus.

Some very interesting changes take place inside a nucleus to enable it to emit an electron. One of the neutrons in the nucleus transforms into a proton and an electron. The proton remains in the nucleus and the electron is emitted and called a β^- particle:

$$^{1}_{0}n \rightarrow ^{1}_{1}p + ^{0}_{-1}e$$



β^- decay: a nucleus ejects an electron.

The resulting daughter nucleus has the same number of nucleons as the parent, but one less neutron and one more proton.

An example of β^- decay is the decay of thorium-234. This isotope is the result of the α decay of uranium-238. The nucleus is more stable than it was before the emission of the α particle, but could become more stable by emitting

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Unit 1 | AOS 3 | Topic 1 | Concept 2

Beta decay
Concept summary and practice questions

a β^- particle. During this second decay, the mass number of the nucleus is unchanged (234). The number of protons, however, increases by one when a neutron changes into a proton and an electron. There are now 91 (90 + 1) protons in the nucleus, so the atom must be called protactinium-234. The decay equation is written as:

$$^{234}_{90}\text{Th} \rightarrow {}^{234}_{91}\text{Pa} + \beta^- + \text{energy}$$

$$\text{or } ^{234}_{90}\text{Th} \rightarrow {}^{234}_{91}\text{Pa} + {}^{0}_{-1}\text{e} + \text{energy.}$$

In β^+ decay, the positron is also emitted from inside the nucleus. In this case, strange as it may seem, the proton changes into a neutron and a positron with the neutron staying in the nucleus.

$$^{1}_{1}\text{p} \rightarrow {}^{1}_{0}\text{n} + {}^{0}_{+1}\text{e} + \text{energy}$$

The resulting nucleus has one less proton, but the same number of nucleons. An example of β^+ decay is sodium-22 decaying to neon-22:

$$^{22}_{11}\text{Na} \rightarrow {}^{22}_{10}\text{Ne} + {}^{0}_{+1}\text{e} + \text{energy}$$

Beta particles are very light when compared to alpha particles. They travel at a large range of speeds — from that of an alpha particle up to 99 per cent of the speed of light. Just like α particles, β particles are deflected by electric and magnetic fields.

Sample problem 7.2

Write down the complete decay equation in each case:

$$^{234}_{92}\text{Au} \rightarrow {}^{230}_{90}\text{Th} + ? + \text{energy} \quad [1]$$

$$^{210}_{82}\text{Pb} \rightarrow {}^{210}_{83}\text{Bi} + ? + \text{energy} \quad [2]$$

$$^{11}_{6}\text{C} \rightarrow {}^{11}_{5}\text{B} + ? + \text{energy} \quad [3]$$

Solution: In [1] the number of particles in the nucleus has decreased by 4, while the number of protons has decreased by 2. This implies that an α particle, or helium nucleus, has been released. The full equation is:

$$^{234}_{92}\text{Au} \rightarrow {}^{230}_{90}\text{Th} + {}^{4}_{2}\text{He} + \text{energy.}$$

Equation [2] cannot show an α emission, as the mass number remains constant. The atomic number has increased, indicating that a proton has been formed, and therefore β^- decay has occurred. The equation becomes:

$$^{210}_{82}\text{Pb} \rightarrow {}^{210}_{83}\text{Bi} + {}^{0}_{-1}\text{e} + \text{energy.}$$

In equation [3], the mass number stays the same, but there is one less proton, so it must be β^+ decay. The equation becomes:

$$^{11}_{6}\text{C} \rightarrow {}^{11}_{5}\text{B} + {}^{0}_{+1}\text{e} + \text{energy.}$$

Revision question 7.2

Write the equations for:

(a) the alpha decay of americium-241

(b) the β^- decay of platinum-197

(c) the β^+ decay of magnesium-23.

PHYSICS IN FOCUS

In 1928, Paul Dirac developed a mathematical theory to explain the properties of the electron: its mass, charge, role in beta decay and its energy inside the atom. The calculated values for these properties exactly fitted their measured values, but Dirac's equations suggested there may be two solutions — a negatively charged electron and a positively charged electron with the same mass, but opposite charge. Indeed, he raised the possibility of there being another form of matter, which he called 'antimatter'.

In 1932, Carl Anderson discovered the positron when he was researching cosmic rays, which are high-energy charged particles that originate from outside the solar system. Their progressive impacts with atoms as they pass through the atmosphere generates a shower of particles detectable at the Earth's surface. β^+ decay was subsequently discovered.

Neutrinos

Alpha particles are emitted with particular energies that are unique to the host nucleus, whereas beta particles are emitted with any energy up to a maximum. When examining decay reactions, scientists found that not all of the energy was accounted for. The possible explanations were:

- the Law of Conservation of Energy, one of the foundations of physics, did not apply in nuclear processes
- a second particle, as yet undetected, was emitted. This idea was proposed by Wolfgang Pauli, who said the particle must have no charge, as all the charge was accounted for, and have negligible mass.

Enrico Fermi named the particle 'neutrino', from the Italian for 'little neutral one'. Fermi incorporated Pauli's suggestion into a theory of β decay that not only built on Dirac's work but also derived a mathematical relationship between the half-life of a particular decay and the maximum energy of the emitted β particle. This relationship matched the experimental data, which was convincing evidence for the existence of the neutrino, although it was not actually detected until 1956.

The neutrino has the symbol v, which is the Greek letter *nu*. The complete β^- decay process is:

$$ {}_{0}^{1}\text{n} \rightarrow {}_{1}^{1}\text{p} + {}_{-1}^{0}\text{e} + \overline{v} $$

The word 'energy' in β decay equations should be replaced by v in β^+ decay and $\overline{v}$ in β^- decay ($\overline{v}$ represents an antineutrino). For example:

$$ {}_{90}^{234}\text{Th} \rightarrow {}_{91}^{234}\text{Pa} + {}_{-1}^{0}\text{e} + \overline{v} $$

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Unit 1	**Gamma decay**
AOS 3	Concept summary and practice questions
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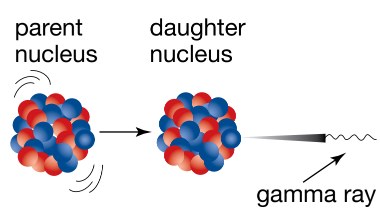
Gamma decay

This form of radioactive decay is quite different from either α or β decay. During γ decay a small packet of electromagnetic energy called a **γ ray**, or photon, is emitted, rather than a particle. Gamma emission occurs after another form of nuclear decay has taken place. Following a decay, the arrangement of protons and neutrons in the nucleus may not be ideal, and the nucleus may need to release some extra energy to become more stable. Before the release of this energy, the nucleus is known as 'excited'. An **excited nucleus** is denoted by an asterisk (*) after the symbol for the element. The excess energy is emitted as a γ ray.



Gamma decay: an excited nucleus ejects a photon.

A **γ ray** is the packet of electromagnetic energy released when a nucleus remains unstable after α or β decay. γ rays travel at the speed of light and carry no charge.

An **excited nucleus** is one that does not have an ideal arrangement of protons and neutrons in its nucleus. An excited nucleus emits γ radiation to become more stable.

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Background radiation
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One example of γ decay occurs after lead-210 emits a β^- particle and becomes bismuth-210. The excited daughter nucleus goes on to emit a γ ray:

$$^{210}_{83}Bi^* \rightarrow ^{210}_{83}Bi + \gamma.$$

This γ ray is a packet of excess energy. It has no mass and no charge and is not deflected by electric or magnetic fields. Because it is a photon, or packet of electromagnetic energy, it travels at the speed of light.

Half-life

It is not possible to predict exactly when a given unstable nucleus will decay. However, we can predict what proportion of a certain number of nuclei will decay in a given time. It is rather like tossing a coin. We can't be sure that a given toss will result in a tail, but we can predict that, from 1000 tosses, about 500 will result in tails. Scientists know that it will take 24 days for half of a group of unstable thorium-234 nuclei to decay to protactinium-234. The time taken for half a group of unstable nuclei to decay is called the **half-life**. Half-lives vary according to the isotope that is decaying. They range from microseconds to thousands of millions of years.

Mathematicians and scientists often use graphs with the same basic shape as the one in the graph below. It shows what is known as a **decay curve**. This type of curve often appears in science. It is called exponential decay.

A **half-life** is the time taken for half of a group of unstable nuclei to decay.

A **decay curve** is a graph of the number of nuclei remaining in a substance versus time elapsed. The half-life of a substance can be determined by looking at the time that corresponds to half of the substance remaining.

TABLE 7.2 Table of half-lives

Element	Decay mode	Half-life
Indium-115	Beta minus	6×10^{14} years
Potassium-40	Beta minus	1.3×10^{9} years
Uranium-235	Alpha	7.1×10^{8} years
Actinium-227	Alpha	22 years
Thorium-227	Alpha	18 days
Carbon-11	Beta plus	20 minutes
Thallium-207	Beta minus	4.8 minutes
Magnesium-23	Beta plus	11 seconds
Polonium-212	Alpha	3×10^{-7} seconds

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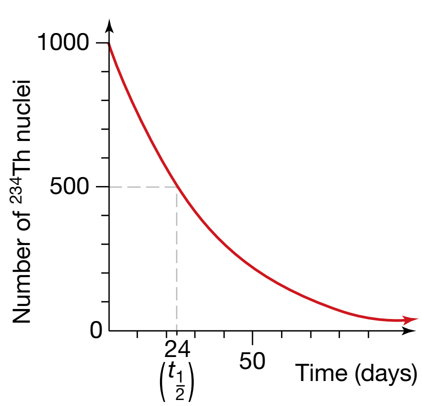
The Law of Radioactive Decay app



Graph showing decay of 1000 thorium-234 nuclei. The time taken for half of the original nuclei (500 nuclei) to remain is called the half-life. It can be seen from this graph that the half-life is 24 days. After the fourth half-life (at time = 96 days) it can be predicted that one-sixteenth of the thorium-234 (about 62 or 63 nuclei) would remain undecayed.

Looking at the graph at left, in the first few days the number of atoms decaying every day is quite high, but towards the end the number is quite low. If there was a Geiger counter near the source at the beginning, it would be clicking quickly, but near the end you would wait minutes for the next click. In fact, a graph of the count rate (the number of clicks per second) will have exactly the same shape and will show the same half-life. The number of decays per second of a radioactive source is a measure of its activity and is measured in Becquerels (Bq).

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Unit 1	Half-life and decay curve
AOS 3	Concept summary and practice questions
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TABLE 7.3 Activities of some everyday items

Item	Activity (Bq)
1 adult human	3000
1 kg coffee	1000
1 kg granite	1000
1 kg coal ash (used in cement)	2000
1 kg superphosphate fertiliser	5000

Sample problem 7.3

Technetium-99 is often used for medical diagnosis. It has a half-life of 6 hours. A patient has a small amount of the isotope injected into the bloodstream. What fraction of the original amount will remain after:

(a) 12 hours
(b) 48 hours?

Solution: (a) The half-life of technetium-99 is 6 hours, so 12 hours is the same as two half-lives. After the first half-life, half the original nuclei remain. After the second half-life, half of this amount, or one-quarter of the original amount, remain undecayed.

(b) 48 hours is 8 lots of 6 hours, so the amount of technetium-99 has reduced by $\left(\frac{1}{2}\right)^8$, which equals $\frac{1}{256}$ or 0.004.

Revision question 7.3

Cobalt-60 is radioactive with a half-life of 5.27 years. It is produced from cobalt-59 by bombardment with neutrons at a nuclear reactor. It emits a low-energy beta particle followed by two high-energy gamma rays. It is used in the sterilisation of medical equipment, in radiotherapy and in industrial applications. A cobalt-60 source will need to be replaced when its activity decreases to $\frac{1}{16}$ of its initial value. How long will this take?

Radioactive series

A **decay chain**, also known as a decay series, is the sequence of stages a radioisotope passes through to become more stable. At each stage, a more stable isotope forms. The chain ends when a stable isotope forms.

In its 'quest' to become stable, an isotope may have to pass through many stages. As a radioactive isotope decays, the daughter nucleus is often radioactive itself. When this isotope decays, the resulting nucleus may also be radioactive. This sequence of radioisotopes is called a **decay chain** or decay series.

Uranium-238 undergoes 14 radioactive decays before it finally becomes the stable isotope lead-206. Two other decay chains, one starting with uranium-235 and another with thorium-232, also end with a stable isotope of lead. Another decay chain once passed through uranium-233, but this chain is almost extinct in nature now due to its shorter half-lives.

Not all naturally occurring radioisotopes are part of a decay series. There are about 10 with atomic numbers less than that of lead, for example potassium-40. How can there be radioisotopes isolated in the periodic table? A look at the half-lives of potassium-40 and indium-115 reveals the answer (see table 7.2, page 107). Their half-lives are so long, greater than the age of the Earth, that they are still decaying from when they were formed in a supernova explosion billions of years ago.

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Numerical model of a decay series
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Unit 1	**Decay series (chain)** Concept summary and practice questions
AOS 3	
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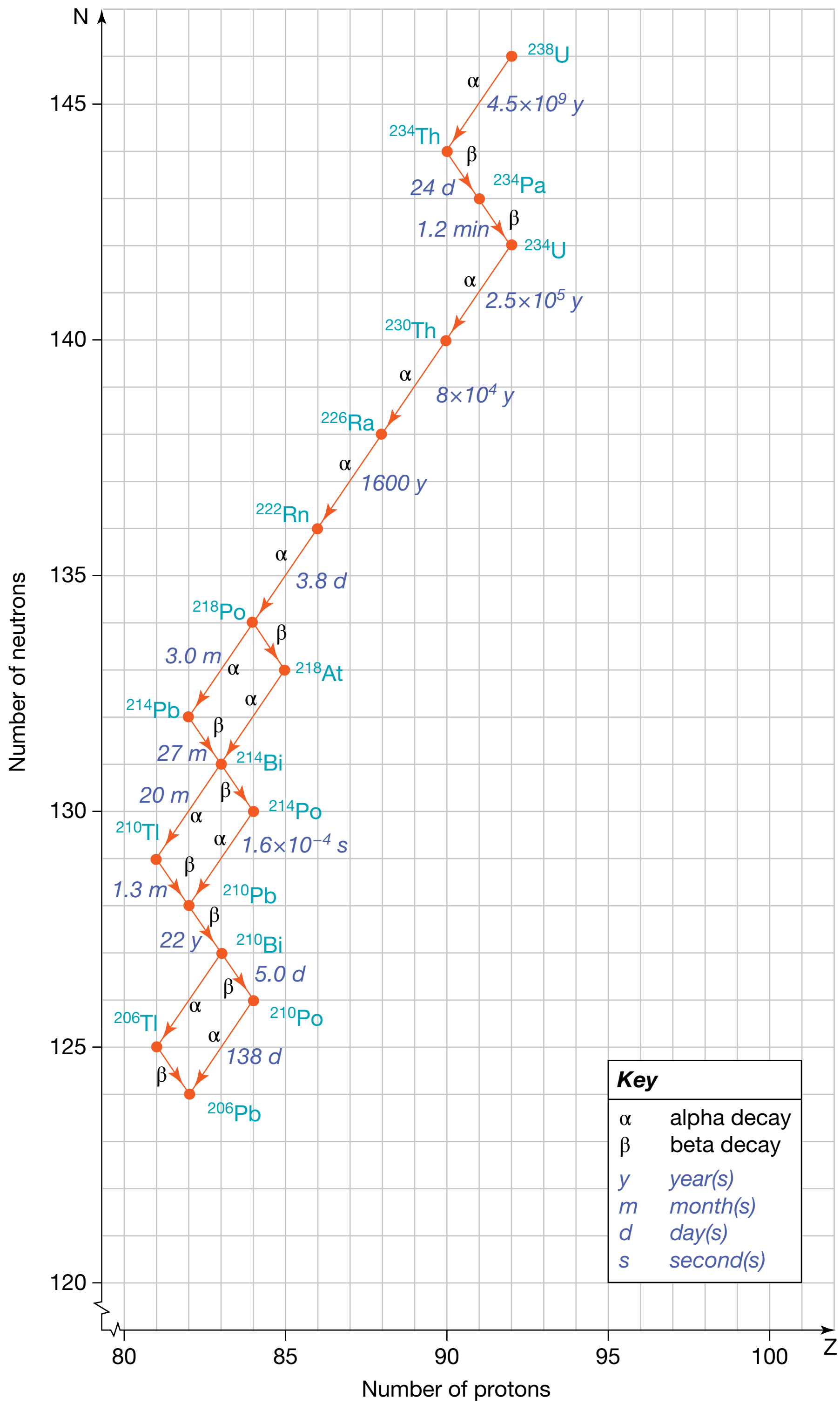


Radioactive series of uranium-238. The half-life is given beside each decay.

Nuclear transformations

Alpha and beta decay are natural examples of nuclear transformations. The numbers of protons and neutrons in the nucleus change during these processes. Artificial nuclear transformations are also possible. These are done either to investigate the structure of the nucleus or to produce specific radioisotopes for use in medicine or industry. The first artificial transformation was made by Ernest Rutherford, who fired alpha particles at nitrogen atoms to produce an isotope of oxygen.

$$^{14}_{7}\text{N} + {}^{4}_{2}\text{He} \rightarrow {}^{17}_{8}\text{O} + {}^{1}_{1}\text{H}$$

This result raised the intriguing possibility of achieving the alchemist's dream of changing lead into gold. Although prohibitively expensive, it appears to be theoretically possible.

The building of particle accelerators in the early 1930s enabled charged particles such as protons and alpha particles to be fired at atoms as well as alpha particles, but with the advantage that their energy could be pre-set. The limitation of both these particles is that since they are positively charged, they have to be travelling at very high speed to overcome the repulsion of the positively charged nucleus. This problem was overcome with the discovery of the neutron in 1932. The neutron, which has no net charge, can enter the nucleus at any speed. Both protons and neutrons are used today to produce radioisotopes. Particle accelerators firing positive ions produce neutron-deficient radioisotopes such as thallium-201 ($t_{1/2} = 73$ days), which is used to show damaged heart tissue, and zinc-65 ($t_{1/2} = 244$ days), which is used as a tracer to monitor the flow of heavy metals in mining effluent. Neutrons from nuclear reactors produce neutron-rich radioisotopes such as iridium-192 ($t_{1/2} = 74$ days), which is used to locate weaknesses in metal pipes, and iodine-131 ($t_{1/2} = 8.0$ days), which is used in the diagnosis and treatment of thyroid conditions.

Particle accelerators are also used to produce new elements with atomic numbers greater than that of uranium. The hunt is on for a new stable element. In 2007, calcium-48 ions were fired at californium-249 atoms to produce the element with atomic number 118. Only three atoms were produced, and as the half-life of this isotope is 0.89 ms, they don't exist any more.

PHYSICS IN FOCUS

What's in the nucleus?

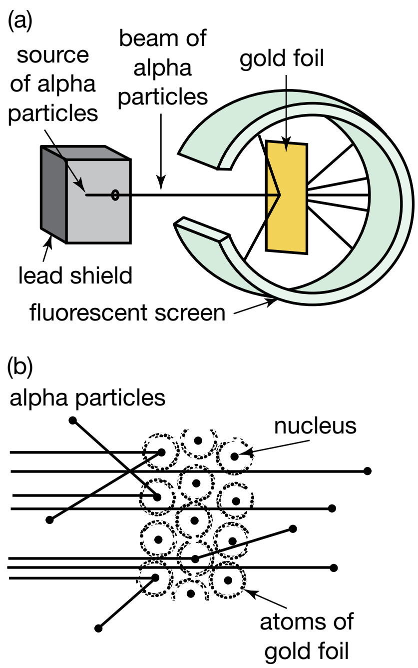
Early experiments with radioactivity produced the nuclear model of the atom with nearly all its mass in a small, positively charged, central core called the nucleus, with negatively charged electrons moving likes planets around it. The number of protons in the nucleus was the element's atomic number, but the mass of the protons was about half the mass of the atom, so there must be something else inside the nucleus.

Beta particles were emitted from the nucleus, so Ernest Rutherford suggested that the additional mass came from proton–electron pairs, called a 'neutral doublet'. He was predicting the existence of a neutron about 12 years before it was discovered by Chadwick.

Discovering the structure of the atom

The nuclear timeline on pages 100–1 shows that Ernest Rutherford was one of the central players in the investigation of radioactivity. By 1908, Rutherford and his team had determined that alpha particles were doubly charged helium ions and that they were moving very fast — at about 5% of the speed of light. They quickly realised that these particles would be ideal 'bullets' to investigate the structure of the atom.

Two of Rutherford's younger colleagues, Hans Geiger and Ernest Marsden, fired alpha particles at a very thin foil of gold, about 400 atoms thick, and measured their angle of deflection. Nearly all of the particles either went straight through or suffered a very small deflection, but about 1 in every 8000 came back.

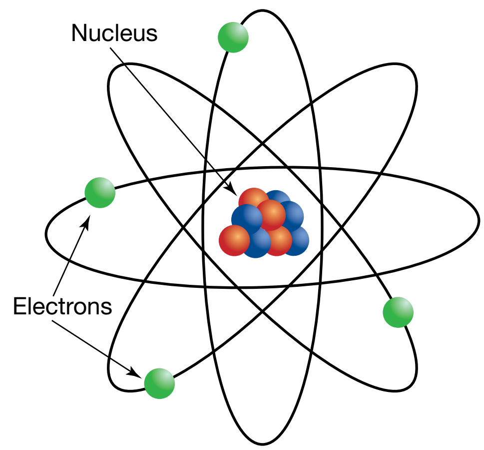


Geiger and Marsden's gold foil experiment

The positively charged α particle was repelled and deflected by the electrostatic interaction with the positive charges in the atom. Rutherford believed that for an α particle to be turned around, these positive charges would need to be concentrated in a very small volume, which he called the 'nucleus'. He calculated that the radius of such a nucleus would be about 10^{-14} m, and the radius of an atom was about 10^{-10} m.

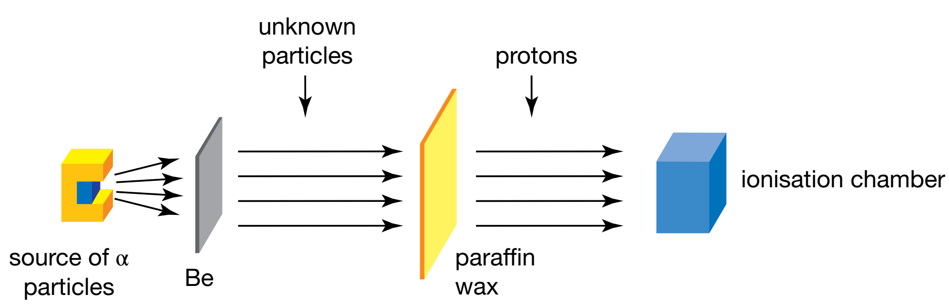
Rutherford's nuclear model of the atom had nearly all the mass of the atom in the central nucleus and the much lighter electrons 'orbiting' around it.

However, this model was incomplete because it did not fully explain the mass of an atom. At the time it was known that an alpha particle, that is a helium ion, had exactly twice the positive charge of a hydrogen ion, so presumably contained two protons, but was almost exactly four times as heavy. There were a number of explanations for this anomaly. One was that the extra mass was made up of proton–electron pairs, which would effectively have zero charge; another was that there was an as yet unknown neutral particle in the nucleus.



Rutherford's model of the atom

It was only in the 1930s that this neutral particle, called the 'neutron', was discovered. In 1930, Walter Bothe and Herbert Becker fired alpha particles at beryllium and detected what they thought was gamma radiation. The husband-and-wife team Frédéric Joliot and Irène Joliot-Curie (daughter of Marie Curie) placed hydrogen-rich paraffin wax in front of this 'gamma radiation' and observed the ejection of protons. While they explored the possibility of very high energy radiation, James Chadwick showed that this was virtually impossible; instead, he demonstrated that a single neutron was ejected when the alpha particle entered the beryllium nucleus, which in turn knocked on a proton in a simple billiard-ball-like collision.



Discovery of the neutron

The discovery of the neutron now provided an explanation for the existence of isotopes: atoms with the same atomic number but different atomic mass due to different numbers of neutrons.

The stability of nuclei

The stability of any nucleus depends on the number of protons and neutrons. For small nuclei to be stable, the number of protons must roughly equal the number of neutrons. As the number of protons increases, however, more neutrons are needed to maintain stability.

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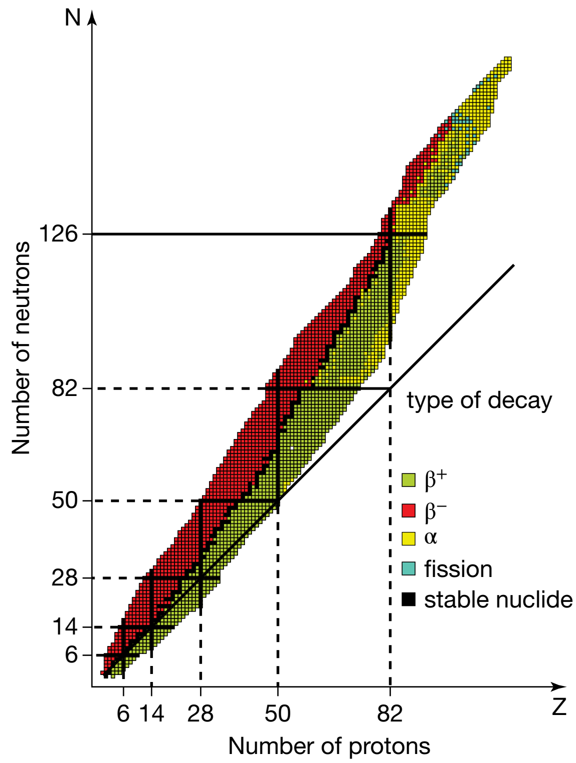
Unit 1 | AOS 3 | Topic 1 | Concept 6

Forces and nuclear stability Concept summary and practice questions

The complex nature of the figure below indicates that there is more to the question of stability than a simple ratio.

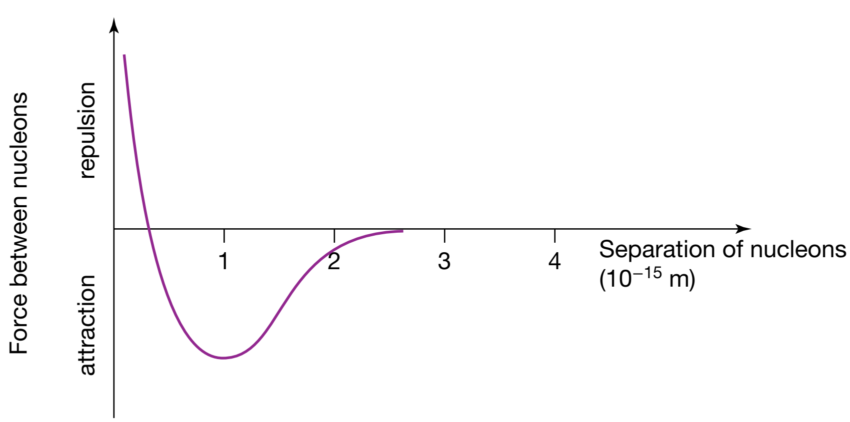


This graph shows which nuclei are stable (black) and which are unstable (other).

What holds the nucleus together?

The force that holds electrons around a nucleus is called an electrostatic force. Electrostatic forces increase as charges move closer together. Electrostatic attraction exists between unlike charges; electrostatic repulsion exists between like charges. So, it seems strange that the positive charges inside a nucleus don't repel each other so strongly that the nucleus splits apart. In fact, two protons do repel each other when they are brought together, but in the nucleus they are so close to each other that the force of repulsion is overcome by an even stronger force — the **strong nuclear force**. While the strong nuclear force is, as its name suggests, a very strong force, it is able to act over only incredibly small distances. Inside a nucleus, the nucleons are sufficiently close that the pull of the strong nuclear force is much greater than the push of the protons repelling each other, and therefore the nucleus remains intact.

The **strong nuclear force** is the force that holds nucleons together in a nucleus of an atom. It acts over only very short distances.



The graph shows how the strong nuclear force between two nucleons varies with the separation of the nucleons.

AS A MATTER OF FACT

The forces that hold the nucleus together are much stronger than the forces that hold electrons to the nucleus. This means that changes to the nucleus can release much more energy than changes to the electrons; therefore, nuclear reactions are much more powerful than chemical reactions. Nuclear changes in a baseball-sized lump of uranium-235 can release a similar amount of energy to the chemical changes in 20 000 tonnes of TNT!

What makes the nucleus change?

The **weak nuclear force** explains the transformation of neutrons into protons and vice versa.

The **weak nuclear force** is the force used to explain the transformation of neutrons into protons and vice versa. It is the mechanism underlying beta decay, fission, which is the splitting of heavy nuclei, and fusion, which is the joining of light nuclei. The strength of the weak nuclear force is about one millionth that of the strong force, and it acts over a distance of 0.1% of the diameter of a proton, which is one thousandth that of the strong force!

TABLE 7.4 Types of forces, their relative strengths and ranges

Force	Strength	Range	Type
Strong nuclear	1	10^{-15} m (diameter of a nucleus)	Attractive
Electric and magnetic	$\frac{1}{137}$	Infinite	Attractive or repulsive
Weak nuclear	$\frac{1}{1000000}$	10^{-18} m (fraction of proton diameter)	Attractive
Gravity	$\frac{1}{10^{38}}$	Infinite	Attractive

Binding energy

The **binding energy** of a nucleus is the energy that is required to split a nucleus into individual nucleons.

The amount of energy needed to overcome the strong nuclear force and pull apart a nucleus is known as the **binding energy**. This is the amount of energy that has to be added to a nucleus to split it into its individual nucleons: that is, to reverse the binding process. For example, it would take 2.23 MeV of energy to split a 'heavy' hydrogen nucleus into a separate proton and neutron.

Each isotope has its own specific binding energy. Nuclei with high binding energies are very stable as it takes a lot of energy to split them. Nuclei with lower binding energies are easier to split. Of course, it is difficult to supply sufficient energy to cause a nucleus to split totally apart. It is much more common for a nucleus to eject a small fragment, such as an α or β particle, to become more stable.

To compare the binding energies of various nuclei, and therefore their stability, it is easier to look at the average binding energy per nucleon. The average binding energy per nucleon is calculated by dividing the total binding energy of a nucleus by the number of nucleons in the nucleus.

It can be seen from the following figure that iron has the highest binding energy per nucleon. This means it is the most stable of all nuclei. In order to become more stable, other nuclei tend to release some of their energy. Releasing this energy would decrease the amount of energy they contained, and therefore increase the amount of energy that must be added to split them apart.

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Interactivity
Making nuclei
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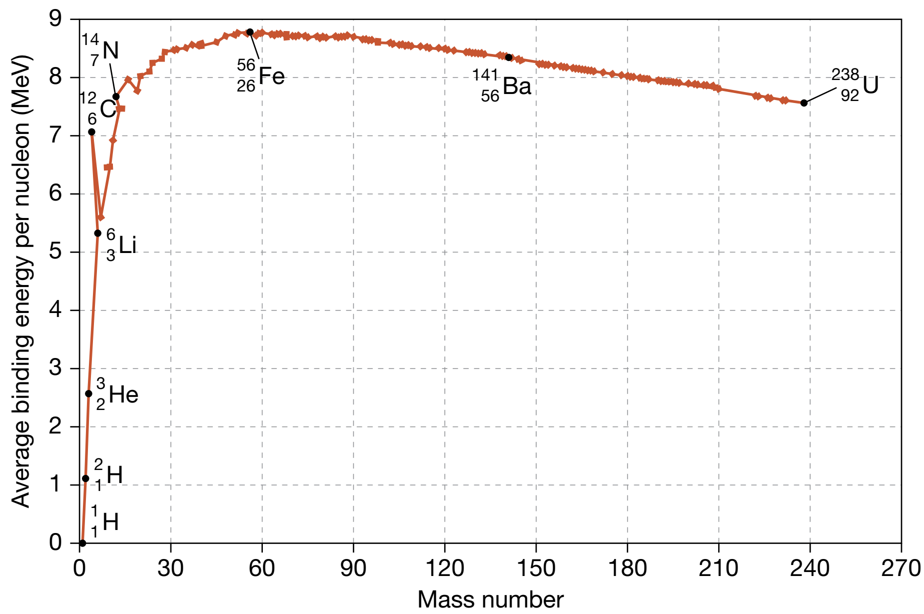
Unit 1 | AOS 3 | Topic 1 | Concept 7

Nuclear binding energy
Concept summary and practice questions



This graph of binding energy versus mass number shows that iron has the most stable nucleus.

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Unit 1 | **AOS 3** | **Topic 1** | **Concept 8**

Nuclear energy
Concept summary and practice questions

Nuclear energy

The binding energy is not only the amount of energy required to separate a nucleus into its component parts, but it is also the amount of energy released when those parts are brought together to form the nucleus. That is, when a proton and a neutron collide to form a 'heavy' hydrogen nucleus, 2.23 MeV of energy is released.

The curve of the binding energy graph above indicates that if two nuclei with low mass numbers could be joined together to produce a nucleus higher up, then a lot of energy would be released. Similarly, if a nucleus with a very high mass number could split into two fragments higher up the graph, then once again a lot of energy would be released. These two possibilities were realised in the 1930s. The released energy can be calculated from Einstein's equation $E = mc^2$, where m is the difference between the total nuclear mass before and after the event, and c is the speed of light.

The joining together of two nuclei is called **nuclear fusion**, and the splitting of a single nucleus is called **nuclear fission**.

Nuclear fusion is the process of joining together two nuclei to form a larger, more stable nucleus.

Nuclear fission is the process of splitting a large nucleus to form two smaller, more stable nuclei.

Nuclear fission

In 1934, Enrico Fermi investigated the effect of firing neutrons at uranium. The products had half-lives different from that of uranium. He thought that he had made new elements with atomic numbers greater than 92. Others repeating the experiment got different half-lives. In 1939, Otto Hahn and Fritz Strassmann chemically analysed the samples and found barium, which has atomic number 56, indicating that the nuclei had split.

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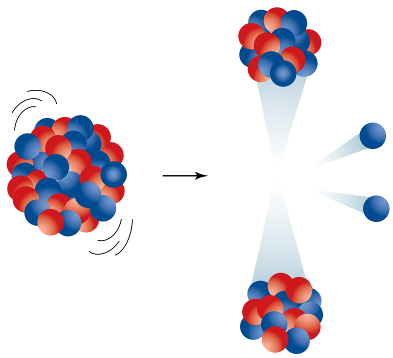
Fission animation

Lise Meitner and Otto Frisch called this process 'fission' and showed that neutrons could also initiate fission in thorium and protactinium. Further chemical analysis revealed a range of possible fission reactions, each with a different combination of **fission fragments** including bromine, molybdenum or rubidium (which have atomic numbers around 40), and antimony, caesium or iodine (which have atomic numbers in the 50s). Cloud chamber photographs showing two heavy nuclei flying off in opposite directions confirmed that fission had occurred. Meitner and Frisch also calculated from typical binding energies that the fission of one uranium-235 nucleus would produce about 200 MeV of energy, mainly as kinetic energy of the fission fragments. This is a huge amount of energy to be released by one nucleus, as can be seen

Fission fragments are the products from a nucleus that undergoes fission. The fission fragments are smaller than the original nucleus.



Fission

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Chain reaction with dominoes
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when it is compared to the burning of coal in power plants. Each atom of carbon used in coal burning releases only 10 eV of energy — about 20 million times less than the energy released in the fission of uranium-235.

Also in 1939, Frederic Joliot and his team confirmed that two or three fast neutrons were emitted with each fission reaction. This allowed for the possibility of a chain reaction, which could potentially release enormous amounts of energy.

Some possible equations for the fission of uranium-235 set off by the absorption of a neutron are:

$$^{235}_{92}\text{U} + ^{1}_{0}\text{n} \rightarrow ^{236}_{92}\text{U} \rightarrow ^{148}_{57}\text{La} + ^{85}_{35}\text{Br} + 3^{1}_{0}\text{n} + \text{energy}$$

$$^{235}_{92}\text{U} + ^{1}_{0}\text{n} \rightarrow ^{236}_{92}\text{U} \rightarrow ^{141}_{56}\text{Ba} + ^{92}_{36}\text{Kr} + 3^{1}_{0}\text{n} + \text{energy}$$

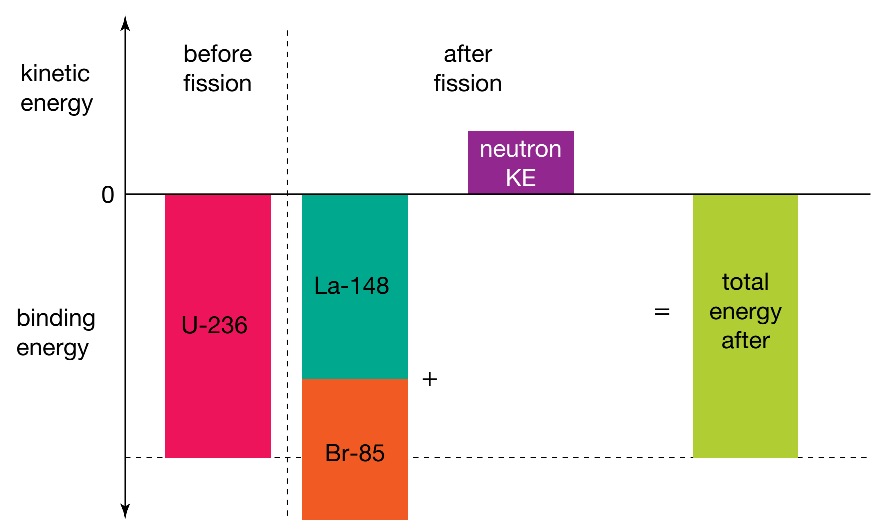
$$^{235}_{92}\text{U} + ^{1}_{0}\text{n} \rightarrow ^{236}_{92}\text{U} \rightarrow ^{140}_{54}\text{Xe} + ^{94}_{38}\text{Sr} + 2^{1}_{0}\text{n} + \text{energy}$$

The data in the previous graph on binding energies and Einstein's equation $E = mc^2$ can be used to calculate the amount of energy released in each of the fission reactions above.

TABLE 7.5 Masses and binding energies of atoms

Nucleus	Symbol	Mass (kg)	Total binding energy (MeV)
Uranium-236	$^{236}_{92}\text{U}$	$3.919\,629 \times 10^{-25}$	1790.415 039
Lanthanum-148	$^{148}_{57}\text{La}$	$2.456\,472 \times 10^{-25}$	1213.125 122
Bromine-85	$^{85}_{35}\text{Br}$	$1.410\,057 \times 10^{-25}$	737.290 649
Barium-141	$^{141}_{56}\text{Ba}$	$2.339\,939 \times 10^{-25}$	1173.974 609
Krypton-92	$^{92}_{36}\text{Kr}$	$1.526\,470 \times 10^{-25}$	783.185 242
Xenon-140	$^{140}_{54}\text{Xe}$	$2.323\,453 \times 10^{-25}$	1160.734 009
Strontium-94	$^{94}_{38}\text{Sr}$	$1.559\,501 \times 10^{-25}$	807.816 711
Neutron	$^{1}_{0}\text{n}$	$1.674\,924 \times 10^{-27}$	

Speed of light, c, = 2.997 924 58 × 108 m/s. 1 MeV = $1.602\,176 \times 10^{-13}$ joules.



Graph of energies in a fission reaction. The sum of the binding energies of La-148 and Br-85 is greater than the binding energy of U-236. The difference is released as kinetic energy of the neutrons and the fission fragments. The total energy after fission is the same as the energy before.

Sample problem 7.4

Answer the following questions about the fission of uranium-236 producing lanthanum-148 and bromine-85. Use table 7.5 for data on masses and binding energies.

(a) What is the difference between the binding energy of the uranium-236 nucleus and the sum of the binding energies of the two fission fragments?

(b) What is the difference between the mass of the uranium-236 nucleus and the sum of the masses of all the fission fragments, including neutrons?

(c) Use $E = mc^2$ to calculate the energy equivalent of this mass difference in joules and MeV.

Solution: (a) From above, we know that the equation for this fission is:

$$^{236}_{92}\text{U} \rightarrow {}^{148}_{57}\text{La} + {}^{85}_{35}\text{Br} + 3\,^{1}_{0}\text{n} + \text{energy}$$

Binding energy of uranium-236 = 1790.415 039 MeV

Sum of binding energies of fragments = 1213.125 122 + 737.290 649 MeV

= 1950.415 771 MeV

Energy difference = 1950.415 771 − 1790.415 039 MeV

= 160.000 732 MeV

(b) Mass of uranium-236 = $3.919\,629 \times 10^{-25}$ kg

Sum of masses of fragments = $2.456\,472 \times 10^{-25} + 1.410\,057 \times 10^{-25} + 3 \times 1.674\,924 \times 10^{-27}$ kg

= $3.916\,777 \times 10^{-25}$ kg

Mass difference = $0.002\,852 \times 10^{-25}$ kg

(c) Energy difference in joules = mc^2

= $0.002\,852 \times 10^{-25} \times (2.997\,924\,58 \times 10^{8})^2$

= $2.563\,250 \times 10^{-11}$ J

Energy difference in MeV = $2.563\,250 \times 10^{-11} \div 1.602\,176 \times 10^{-13}$

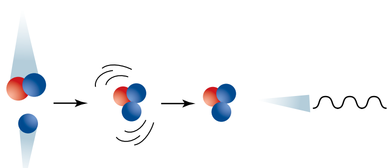
= 159.985 545 MeV

The two answers are effectively identical. The slight difference in the two answers is due to rounding errors, because of the different powers of 10 in the data values.

Revision question 7.4

Now answer the questions from sample problem 7.4 for the fission of U-236 to Ba-141 and Kr-92. Also answer the questions for the fission to Xe-140 and Sr-94.

Nuclear fusion



Nuclear fusion

Nuclear fusion is the process of joining two smaller nuclei together to form a larger more stable nucleus. This was first observed by Australian physicist Mark Oliphant in 1932 when he was working with Ernest Rutherford. He was searching for other isotopes of hydrogen and helium. Heavy hydrogen (one proton and one neutron) was already known, but Oliphant discovered tritium (one proton and two neutrons) and helium-3 (with only one neutron). In his investigation he fired a fast heavy hydrogen nucleus at a heavy hydrogen target to produce a nucleus of tritium plus an extra neutron. This fusion reaction was to become the basis of the hydrogen bomb, but Oliphant was interested only in the structure of the nucleus and did not realise the energy implications. For fusion to occur more extensively, high temperatures and pressures are needed, such as those that exist inside the Sun or in a fission bomb explosion.

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Fusion animation

The Sun's core has a temperature of more than 15 million K, just perfect for fusion to occur! Inside the Sun, hydrogen nuclei fuse together to form helium. As helium is more stable than hydrogen, the excess nuclear energy is released. This energy is emitted from the nuclei as γ radiation, and is eventually received on Earth as light and heat.

Fusion reactions also take place in other stars. Stars that are bigger than the Sun have such severe conditions that larger, more stable nuclei such as silicon and magnesium can be produced from the fusion of smaller nuclei. A star about 30 times more massive than the Sun would be needed to produce conditions that would enable the formation of iron by fusing smaller nuclei.

Our Sun

The chain of events occurring in the Sun is quite complex. The major component of the Sun is ${}^{1}_{1}\text{H}$; that is, nuclei consisting of only one proton and no neutrons. When collisions occur between ${}^{1}_{1}\text{H}$ nuclei, they fuse together in an unusual way. One of the protons is changed into a neutron (in much the same way as a neutron is changed into a proton and an electron during β^- decay). This forms a ${}^{2}_{1}\text{H}$ nucleus. The by-products of this process are a positron and a neutrino.

Positrons are produced when some artificially produced isotopes undergo radioactive decay. Positrons are the opposite of electrons; they have the same mass, but carry a positive charge. When a positron and an electron collide, they immediately annihilate each other. The only thing that remains of either is a gamma ray. Neutrinos are produced when protons change into neutrons and vice versa. They have no charge, are considered massless and travel at close to the speed of light. Fifty trillion neutrinos from the Sun pass through the human body every second.

When a ${}^{1}_{1}\text{H}$ nucleus and a ${}^{2}_{1}\text{H}$ nucleus collide, they form a more stable ${}^{3}_{2}\text{He}$ nucleus, and release the extra energy as a γ ray. If two ${}^{3}_{2}\text{He}$ nuclei collide, they complete the process of turning hydrogen into helium. The collision results in the formation of a ${}^{4}_{2}\text{He}$ nucleus and two ${}^{1}_{1}\text{H}$ nuclei. Again, energy is released. The energy released during nuclear reactions inside the Sun provides energy for life on Earth.

This is the sequence of nuclear equations that occur in the Sun to convert hydrogen to helium:

$$ {}^{1}_{1}\text{H} + {}^{1}_{1}\text{H} \rightarrow {}^{2}_{1}\text{H} + {}^{0}_{1}\text{e} + \upsilon $$

$$ {}^{2}_{1}\text{H} + {}^{1}_{1}\text{H} \rightarrow {}^{3}_{2}\text{He} + \gamma $$

$$ {}^{3}_{2}\text{He} + {}^{3}_{2}\text{He} \rightarrow {}^{4}_{2}\text{He} + {}^{1}_{1}\text{H} + {}^{1}_{1}\text{H} $$

AS A MATTER OF FACT

All the atoms that make up your body (and the rest of the atoms in the Earth) were originally produced in a star. Fusion in stars caused all the atoms to be formed. Those nuclei with atomic numbers up to that of iron were produced in regular stars. However, when large stars stop producing energy from fusion of elements up to iron, they implode, or collapse in on themselves. This causes conditions in which even large atoms will fuse together to produce very heavy elements such as gold, lead and uranium. (This is not energetically favourable, but does occur in very extreme circumstances.) If these stars later explode as supernovas, they spread the elements they have made out into space. The Earth was formed from a cloud consisting of the remnants of an old supernova.

The binding energy can be used to determine the amount of energy released in a fusion reaction.

Sample problem 7.5

In the final reaction above, two helium-3 nuclei collide to produce a helium-4 nucleus and two hydrogen-1 nuclei, that is, two protons. Use the data in the table below to calculate:

(a) the difference between the binding energy of the helium-4 nucleus and sum of the binding energies of the two helium-3 nuclei
(b) the difference between the sum of masses of the helium-4 nucleus and the two protons, and mass of two helium-3 nuclei
(c) the energy equivalent of this mass difference in joules and MeV.

Particle	Symbol	Mass (kg)	Total binding energy (MeV)
Helium-3	$^{3}_{2}He$	$5.022\,664 \times 10^{-27}$	7.718 058
Helium-4	$^{4}_{2}He$	$6.665\,892 \times 10^{-27}$	28.295 673
Proton	$^{1}_{1}p$ or $^{1}_{1}H$	$1.678\,256 \times 10^{-27}$	

Solution: (a) Binding energy of helium-4 nucleus = 28.295 673 MeV

Binding energy of two helium-3 nuclei = 2 × 7.718 058 = 15.436 116 MeV

Difference = 28.295 673 − 15.436 116 = 12.859 557 MeV

(b) Mass before fusion $= 2 \times 5.022\,664 \times 10^{-27} = 10.045\,328 \times 10^{-27}$ kg

$$\text{Mass after fusion} = 6.665\,892 \times 10^{-27} + (2 \times 1.678\,256 \times 10^{-27}) = 10.022\,404 \times 10^{-27} \text{ kg}$$

Mass difference $= 0.022\,924 \times 10^{-27}$ kg

(c) Energy equivalent (in joules) $= mc^2$

$$= 0.022\,924 \times 10^{-27} \times (2.997\,924\,58 \times 10^{8})^2$$
$$= 2.060\,306 \times 10^{-12} \text{ joules}$$

Energy equivalent (in MeV) $= 2.060\,306 \times 10^{-12}$ J $\div$ $1.602\,176 \times 10^{-13}$ (MeV/J)

$$= 12.859\,426 \text{ MeV}$$

PHYSICS IN FOCUS

Lise Meitner (1878–1968)

Lise Meitner was the physicist who coined the term ‘fission’ and, along with her nephew Otto Frisch, explained the splitting of uranium nuclei into barium and lanthanum.

Born in Vienna, Lise was fascinated by the world around her from an early age. A talented student, she wanted to understand the things she observed in nature. Having decided that she would like to pursue her interest in physics and mathematics, Lise engaged a private tutor to prepare her for the university entrance exams, as schools that taught such subjects would not accept girls at that time. She was the second woman to be granted a Doctorate in Physics from the University of Vienna, conferred in 1906.

Lise then moved to the Institute of Experimental Physics in Berlin to work with Otto Hahn. Initially, this proved difficult. Lise was forced to work in a converted workshop as females were not permitted to use the facilities available to male students. As the place of women in the institute became more accepted, Lise was given positions of responsibility, finally being made a professor in 1926. During her time at the institute, Lise made many important contributions to atomic and particle physics, including the co-discovery with Otto Hahn of the radioactive element protactinium.

In 1938 Berlin became a dangerous place for Jews, and Lise moved to Sweden. It was there she and Otto Frisch interpreted the results of experiments conducted by Otto Hahn and Fritz Strassman to come up with the first explanation of the fission process. In doing so, Lise was the first person to use Einstein’s theory of mass–energy equivalence to calculate the energy released during fission.

Her international reputation led to an invitation to join the Manhattan Project in 1941 and work on the development of the atomic bomb. Lise objected to the project and declined the offer. She continued to work in Sweden until moving to England in 1960, finally retiring at the age of 82.

Chapter review

Summary

- Nuclear radiation is emitted from the nucleus of unstable atoms (radioisotopes) that are striving to become more stable.
- There are four types of radiation: α, β^-, β^+ and γ radiation.
- α particles are released during α decay. α particles are slow-moving particles that are equivalent to a helium nucleus and can be represented as $^{4}_{2}He$. After α decay, the mass number of the daughter nucleus is four less than that of the parent nucleus and the atomic number is two less.
- β^- particles are released in β^- decay. β^- particles are high-speed electrons released from the nucleus when a neutron transforms into a proton and an electron. After β^- decay, the mass number of the daughter nucleus is the same as that of the parent nucleus, but the atomic number is one more than that of the parent nucleus.
- β^+ particles are released in β^+ decay. β^+ particles are high-speed positrons emitted from the nucleus when a proton transforms into a neutron. The atomic number of the daughter nucleus is one less than the parent nucleus; the mass number remains the same.
- γ radiation is electromagnetic radiation that is emitted when an excited nucleus becomes more stable. γ rays are emitted during α and β decay.
- In all nuclear transformations, atomic and mass numbers are conserved.
- Half-life is the time for half of a group of unstable nuclei to decay. It is different for every isotope. The shorter the half-life of an isotope, the greater the activity; that is, the greater the number of decays per second. Activity decreases over time as less and less of the isotope remains. Activity is measured in becquerel (Bq).
- Isotopes may pass through a sequence of decays in order to become stable. Such a sequence is called a decay chain, or decay series.
- The force that holds nucleons together in a nucleus of an atom is called a strong nuclear force. It acts over a very short distance and is strong enough to overcome the electrostatic force of repulsion that exists between the protons of a nucleus.
- The nuclei of different atoms have varying degrees of stability. The binding energy of a nucleus is the energy required to completely separate a nucleus into individual nucleons. Therefore the binding energy is a measure of the stability of a nucleus. Iron is the most stable of all nuclei.
- In order for a nucleus to become more stable, it emits energy called nuclear energy. The amount of energy released is related to the size of the difference between the mass of a nucleus and the mass of the individual nucleons.
- Fusion reactions generally occur between nuclei smaller than iron. Fusion occurs in our sun, where it converts hydrogen nuclei into helium nuclei and releases large amounts of energy.
- Fission reactions occur when a nucleus is split into smaller, more stable fission fragments.

Questions

Structure of the atom

1. How many protons and neutrons are in the following atoms?

(a) $^{66}_{30}Zn$ (c) $^{45}_{20}Ca$

(b) $^{230}_{90}Th$ (d) $^{31}_{14}Si$

2. Write the symbols for isotopes containing the following nucleons:

(a) two neutrons and two protons
(b) seven protons and 13 nucleons
(c) 91 protons and 143 neutrons.

3. Write the elemental name and the number of protons and neutrons in each of the following:

(a) Au-197 (b) $^{210}_{83}Bi$ (c) $^{210}_{82}Pb$.

4. Explain why it is possible to have two atoms of different elements with the same number of nucleons.

Radioactive decay and nuclear transformations

5. From where in an atom are α and β particles and γ rays emitted?

6. In each of the following, determine the type of decay that has occurred:

(a) $^{14}_{6}C \rightarrow ^{14}_{7}N + X + \text{energy}$
(b) $^{90}_{38}Sr \rightarrow ^{90}_{39}Y + X + \text{energy}$
(c) $^{238}_{92}U \rightarrow ^{234}_{90}Th + X + \text{energy}$

7. Write a decay equation to show the α decay of:

(a) radium-226
(b) polonium-214
(c) americium-241.

8. Write a decay equation to show the β^- decay of:

(a) cobalt-60
(b) strontium-90
(c) phosphorus-32.

9. Write a decay equation to show the γ decay of excited magnesium-24.

10. Complete the following decay equations.

(a) α decay: ${}^{Z}_{A}X \rightarrow {}^{?}_{?}D + ? + \text{energy}$

(b) β^- decay: ${}^{Z}_{A}X \rightarrow {}^{?}_{?}E + ? + \text{energy}$

(c) γ decay: ${}^{Z}_{A}X^* \rightarrow ? + ?$

(d) ${}^{27}_{13}\text{Al} + {}^{2}_{1}\text{H} \rightarrow {}^{?}_{?}? + {}^{1}_{0}\text{n}$

(e) ${}^{22}_{11}\text{Na} + {}^{4}_{2}\text{He} \rightarrow {}^{?}_{?}? + {}^{1}_{1}\text{H}$

11. Draw a small decay chain graph, similar to that given for uranium-238 on page 109, for the β^- decay of yttrium-90. (*Hint:* There is only one decay.)

12. How is β^- decay of a nucleus possible when a nucleus does not contain electrons?

13. How many α particles are released by one atom of uranium-238 as it becomes lead-206? How many β particles are released? (*Hint:* Look at the change in the proton number and the change in the nucleon number.) Check your answer by using the figure on page 109.

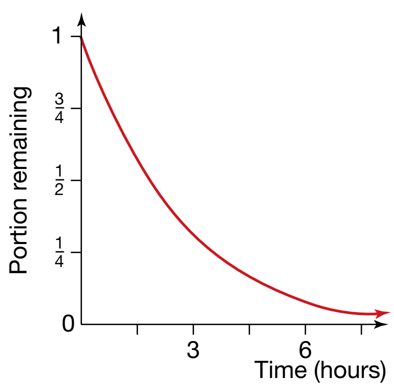
14. Repeat question 13 for the following decay series.
(a) Uranium-235 to lead-207
(b) Thorium-232 to lead-208

15. In a decay chain, radium-226 emits two α particles, then one β^- particle. What is the element at the end of this sequence and what is its atomic mass?

16. Bismuth-212 has two possible decay modes: an α decay followed by a β^- decay, or a β^- decay followed by an α decay. The first mode happens about 36% of the time. Will the two modes produce different final results? Explain.

Half-life

17. What is the half-life of the substance represented in the graph below?



18. Sketch a decay curve for technetium, which has a half-life of 6 hours.

19. Assume the half-life of carbon-14 is 5730 years. If you had 1 g of carbon-14, how many years would it take for one-eighth of it to remain?

20. The artificial isotope ${}^{15}_{8}\text{O}$ is used in medical diagnosis. It has a half-life of 120 seconds. If a doctor requires 1 μg of the isotope at exactly 2 pm, how many grams must be delivered to the room 30 minutes earlier? (*Hint:* How much will be needed at 1.58 pm? How much will be needed at 1:56 pm? At 1:54 pm? Can you see a pattern?)

21. Americium-241 is an alpha emitter with a half-life of 432.2 years. It is used in smoke detectors because when the smoke absorbs the α particles, the current drops and the alarm is triggered. The label on the smoke detector says it contains 0.20 micrograms of americium-241 with an activity of 27.0 kBq.
(a) Determine the activity of the americium-241 after 0, 1, 2, 3 and 4 half-lives.
(b) Plot the data and draw a smooth graph (assuming the half-life is 400 years).
(c) Use your graph to estimate the activity after:
(i) 100 years
(ii) 50 years.
(d) What is the implication of your answers to part (c) for the lifetime of the smoke detector?
(e) Write down the decay equation for americium-241 and do an internet search to determine the decay chain.

22. The activity of a radioactive sample drops from 8.0 kBq to 1.0 kBq in 6.0 hours. What is its half-life?

23. Cobalt-60 has a half-life of 5.3 years. If a sample has an activity of 250 GBq (2.5×10^{11} disintegrations per second), what will the activity be in 21.2 years?

The nucleus

24. Explain how individual nucleons are held together in a nucleus, given that like charges repel.

25. (a) Define the terms 'fusion' and 'fission'.
(b) Which of these reactions occurs in our Sun?

26. Explain why *splitting* uranium-235 nuclei releases energy, but *joining* hydrogen atoms also releases energy.

27. Use the graph of binding energy per nucleon (see the figure on page 114) to estimate the amount of energy released when a uranium-235 nucleus is split into barium-141 and krypton-92. Think carefully about the number of significant figures in your answer. How well does your answer agree with the measured value of 200 MeV?

28. Why is energy released in the process of fusing two small nuclei together?

29. Neutrons are considered to be ionising radiation. Research how neutrons are able to produce ions.

Nuclear fission and fusion

30. Why are neutrons good at initiating nuclear reactions?

31. In what form does the energy released from a nuclear fusion reaction appear?

Use the following table to help answer questions 32, 33 and 34.

Nucleus	Symbol	Mass (kg)	Total binding energy (MeV)
Plutonium-240	$^{240}_{94}Pu$	$3.986\,187 \times 10^{-25}$	1813.454 956
Strontium-90	$^{90}_{38}Sr$	$1.492\,953 \times 10^{-25}$	782.631 470
Barium-147	$^{147}_{56}Ba$	$2.439\,896 \times 10^{-25}$	1204.158 203
Uranium-234	$^{234}_{92}U$	$3.886\,341 \times 10^{-25}$	1778.572 388
Zirconium-95	$^{95}_{40}Zr$	$1.575\,985 \times 10^{-25}$	821.139 160
Tellurium-136	$^{136}_{52}Te$	$2.257\,006 \times 10^{-25}$	1131.440 918
Neutron	$^{1}_{0}n$	$1.674\,924 \times 10^{-27}$	
Proton	$^{1}_{1}p$ or $^{1}_{1}H$	$1.673\,533 \times 10^{-27}$	
Hydrogen-2	$^{2}_{1}H$ or $^{2}_{1}D$	$3.344\,494 \times 10^{-27}$	2.224 573
Hydrogen-3	$^{3}_{1}H$ or $^{3}_{1}T$	$5.008\,267 \times 10^{-27}$	8.481 821
Helium-4	$^{4}_{2}He$	$6.646\,480 \times 10^{-27}$	28.295 673
Lithium-6	$^{6}_{3}Li$	$9.988\,344 \times 10^{-27}$	31.994 564

32. A plutonium-239 nucleus absorbs a neutron to become plutonium-240, which splits to form strontium-90, barium-147 and 3 neutrons.
(a) What is the difference between the binding energy of the plutonium-240 nucleus and the sum of the binding energies of the two fission fragments?
(b) What is the difference between the mass of the plutonium-240 nucleus and the sum of the masses of all the fission fragments, including neutrons?
(c) Use $E = mc^2$ to calculate the energy equivalent of this mass difference in joules and MeV.

33. A uranium-233 nucleus absorbs a neutron to become uranium-234, which splits to form zirconium-95, tellurium-136 and 3 neutrons.
(a) What is the difference between the binding energy of the uranium-234 nucleus and the sum of the binding energies of the two fission fragments?
(b) What is the difference between the mass of the uranium-234 nucleus and the sum of the masses of all the fission fragments, including neutrons?
(c) Use $E = mc^2$ to calculate the energy equivalent of this mass difference in joules and MeV.

34. A fusion reactor could not feasibly use the same reactions as the Sun. A reactor on Earth would have to use a different reaction, preferably a one-step reaction with only two reactants. Three possible reactions for a terrestrial fusion reactor are displayed below; there are many others.

(a) $^{2}_{1}H + ^{3}_{1}H \rightarrow ^{4}_{2}He + ^{1}_{0}n$

(b) $^{2}_{1}H + ^{2}_{1}H \rightarrow ^{3}_{1}H + ^{1}_{1}H$

(c) $^{2}_{1}H + ^{6}_{3}Li \rightarrow ^{4}_{2}He + ^{4}_{2}He$

Using data from the table above, calculate:
(i) the difference between the binding energy of the products and the sum of the binding energies of the reactants
(ii) the difference between the sum of masses of the products and of the reactants
(iii) the energy equivalent of this mass difference in joules and MeV.

CHAPTER

8 Subatomic particles

REMEMBER

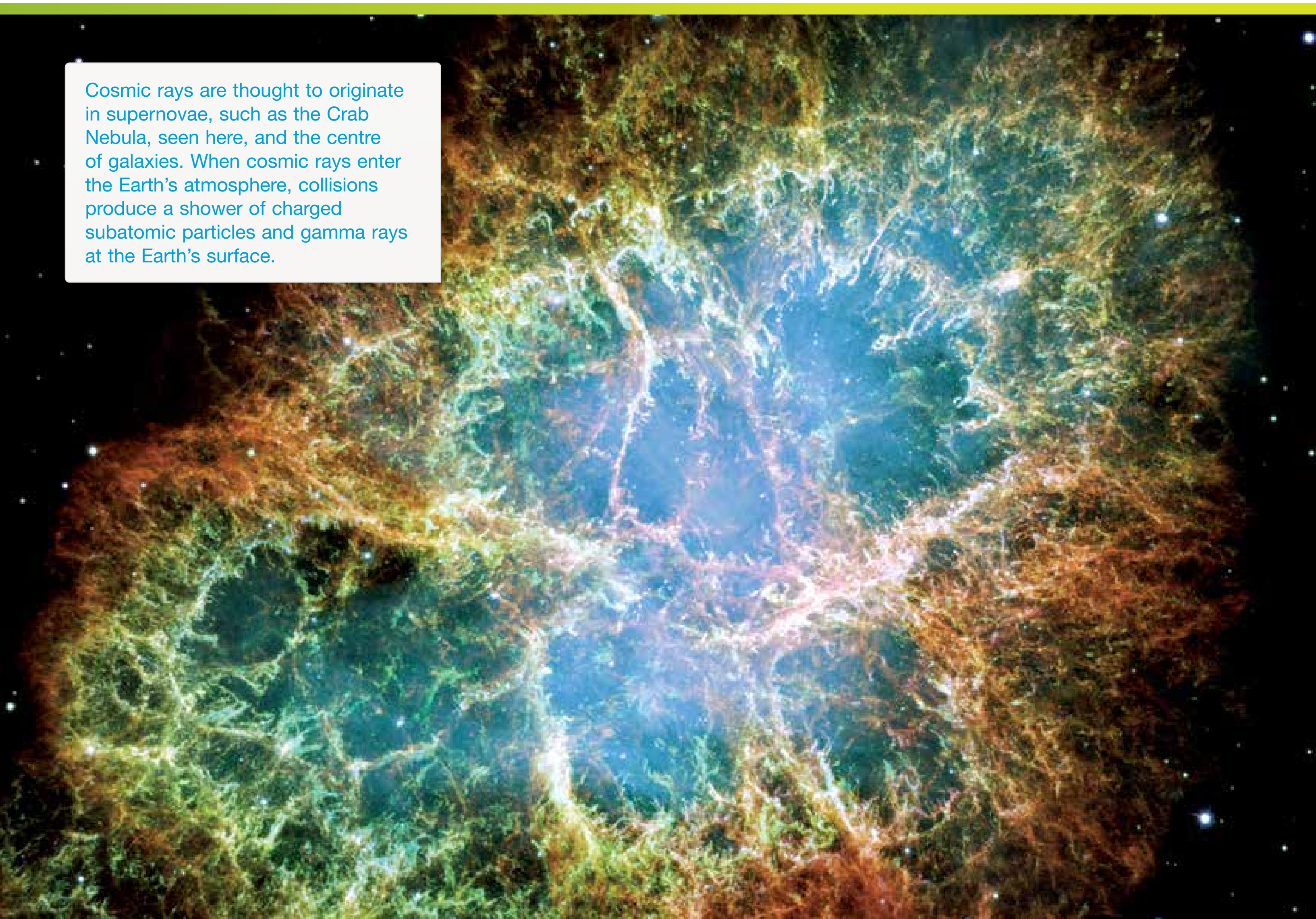
Before beginning this chapter you should be able to:

- recall that all matter is made up of atoms
- explain the arrangement of particles in atoms, in particular that atoms have a central nucleus containing protons and neutrons.

KEY IDEAS

After completing this chapter you should be able to:

- compare and contrast leptons and hadrons, and mesons and baryons
- explain that for every particle that exists there is an antimatter particle of equal mass and opposite charge
- explain that when a particle collides with its antiparticle they annihilate each other, creating radiation
- describe components of sub-atomic particles such as quarks
- relate the discoveries of the neutron, neutrino, positron and Higgs boson to predictions about their existence
- explain how an acceleration of charges produces light, an electromagnetic wave
- describe how an electron radiating energy at a tangent to its circular path produces synchrotron radiation
- describe how electrons moving between energy levels within an atom produce light.



Cosmic rays are thought to originate in supernovae, such as the Crab Nebula, seen here, and the centre of galaxies. When cosmic rays enter the Earth's atmosphere, collisions produce a shower of charged subatomic particles and gamma rays at the Earth's surface.

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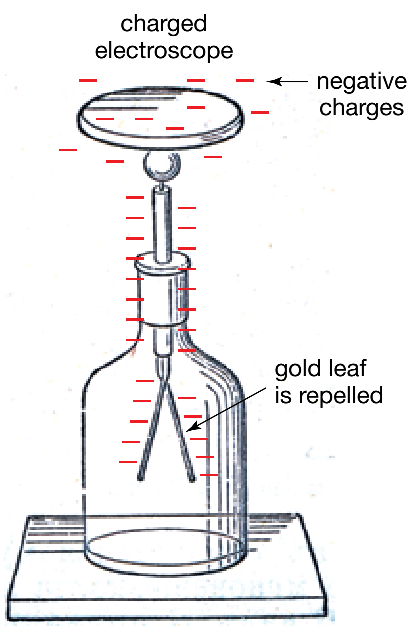


Cosmic rays are very energetic charged particles that enter our atmosphere. They are mainly protons and originate from beyond the solar system.

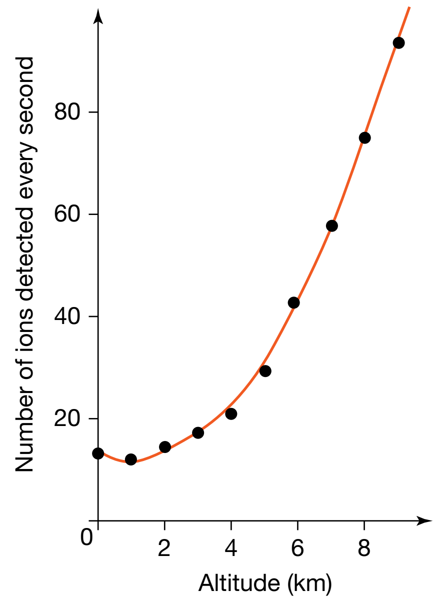
The discovery of subatomic particles

This chapter covers the events of the discovery of subatomic particles from the beginning of the 20th century to the current day. The timeline shown in chapter 7 on pages 100–1 describes many of the steps along the way to what seems now to be a complete understanding of the nature of matter.

Cosmic rays

Natural radioactivity was first discovered when beta particles exposed photographic plates. One of the other technologies used to investigate radioactivity was the gold leaf electroscope. Electroscopes show the presence of electric charge. A charged electroscope slowly loses charge due to the ions in the air produced by radioactive elements in the Earth's crust. It was thought that this effect would decrease with height above the ground.

However, in 1909 it was found that the intensity of radiation was greater on top of the Eiffel Tower. Balloon flights then showed the intensity continued to increase with height, suggesting that the radiation may originate from space. So, the name '**cosmic rays**' was coined.



Number of charged particles from cosmic rays varies by altitude above the Earth's surface

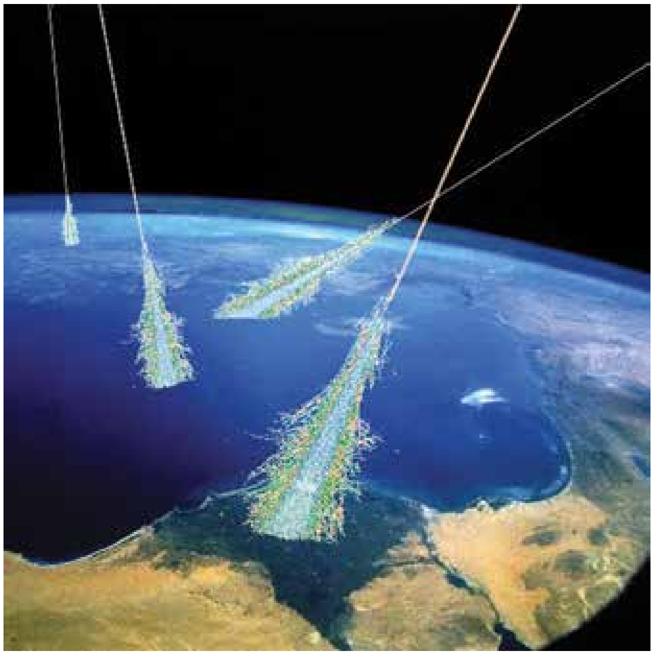
Revision question 8.1

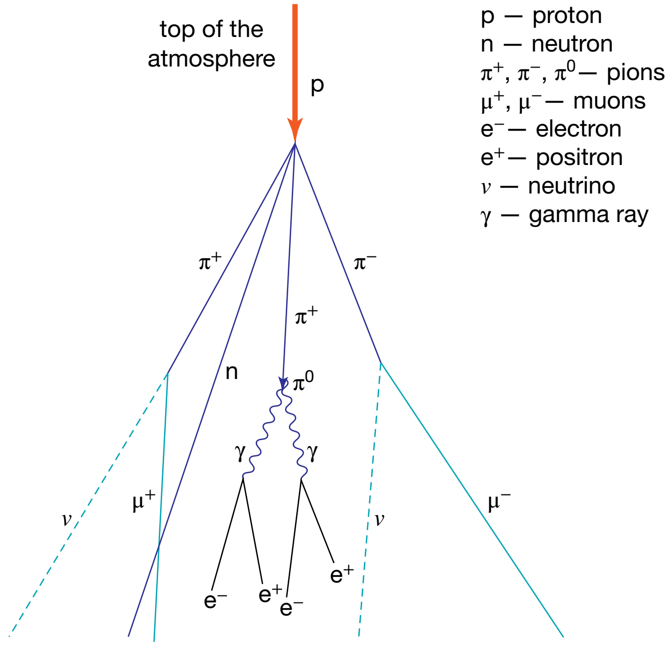
In the graph above, the number of ions detected initially decreases with height, then above 1 km above the Earth's surface it increases quite rapidly. Suggest a reason why there is a strong reading at the Earth's surface that then decreases with height.

Initially cosmic rays were called 'rays' because they were thought to be like light. However, even though they are now known to be particles, the name has stuck. Further investigation over the following decades showed that the particles entering the Earth's atmosphere were mainly protons. The particles seemed to come from beyond the solar system from all points of the sky. Indeed now they are thought to originate in supernovae and the centre of galaxies. They are also extremely fast and energetic. The energy of these protons is 40 million times the energy of the protons in the Large Hadron Collider used to produce the Higgs boson.

When these protons with their massive energy hit an atom in the upper atmosphere, they cause a cascade of successive collisions that produces a shower of charged particles and gamma rays at the Earth's surface.

On average, cosmic rays contribute about 16% of your exposure to ionising radiation from natural sources. This exposure increases the more you fly in a plane and the higher you fly.





Cosmic ray shower hitting the atmosphere

Revision question 8.2

Cosmic rays are often described as cosmic ray 'showers'. Why is this word an appropriate description?

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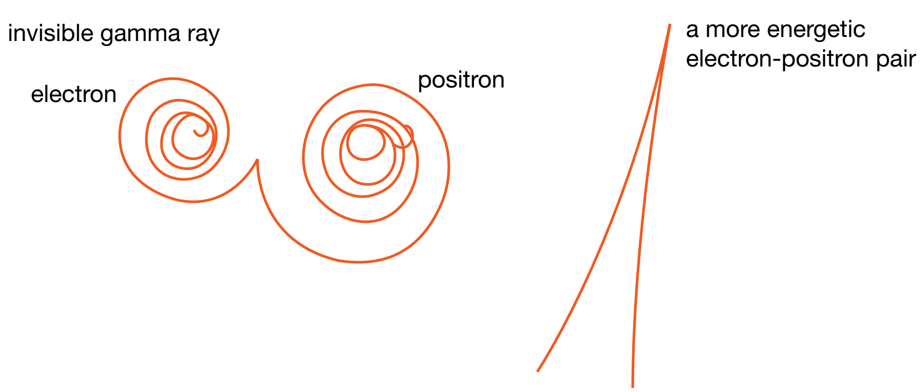
Interactivity
Electrons and positrons
int-6394

In 1933 Carl Anderson was investigating the charged particles in cosmic ray showers and observed a particle that had the same mass as the electron, but with a positive charge. He had discovered a new particle, the positron.

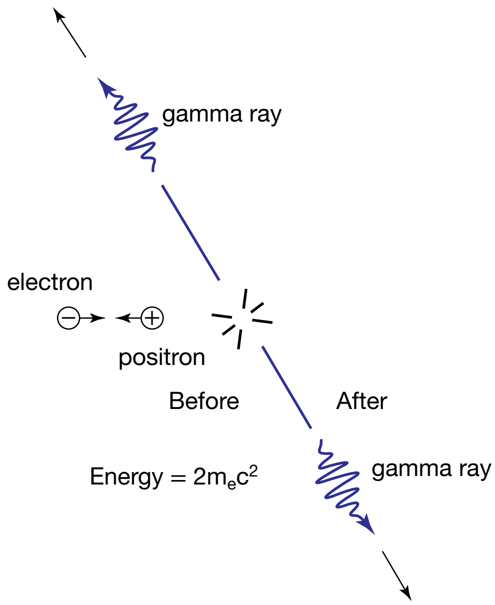
The chamber Anderson used to detect this charged particle was placed in a strong magnetic field so that a positively charged particle would curve one way and a negatively charged particle would curve the other way. In this experimental set up, an incoming gamma ray collides with a nucleus; the energy of the gamma ray is converted into mass, using $E = mc^2$, but because charge needs to be conserved, two particles of opposite sign are produced.



A gamma ray produces an electron and a positron. The spiralling is due to the slow loss of energy as the track is created.

Revision question 8.3

What aspect of the more energetic pair of tracks do you think indicates that the electron and positron are moving faster?



The reverse process is also possible. An electron and a positron, or indeed, any particle and its antiparticle, can collide and annihilate each other, producing two gamma rays.

A particle and antiparticle annihilate each other with their mass producing two gamma rays.

Explaining the strong nuclear force

Also in the 1930s, Hideki Yukawa was seeking an explanation for the properties of the strong nuclear force that exists between particles inside the nucleus. It was known that this force had a very short range, with each proton or neutron attracted only to its near neighbours, not the whole nucleus. Yukawa suggested that a previously unobserved particle acted as 'glue' between pairs of protons in the nucleus, as well as between other pairings. To fit the known features of the strong force, he determined the properties of this unobserved particle. He said it should:

- be about 200 times the mass of the electron
- have the same charge size as the electron
- come in two types: positive and negative
- have a very short half-life of about a millionth of a second
- interact very strongly with nuclei.

In 1936 Carl Anderson's group found such a particle in cosmic ray showers. This particle was named the muon. However, while the muon satisfied the first four points above, it became apparent that its interaction with nuclei was very weak, so the muon was not a good candidate to explain the strong nuclear force.

A few years later, Cecil Powell investigated cosmic ray showers at high altitude in the Pyrenees and the Andes. These observations were higher up in the cascade of collisions that cosmic rays set off when they hit the atmosphere. At this altitude, Powell found another particle that better fit the needs of the strong nuclear force. This particle is called the π-meson or pion.

Shortly after Powell's discovery, the pion was also detected in the laboratory when carbon nuclei were bombarded with high energy alpha particles. After this time, most new particles were found in laboratories using particle accelerators.

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Revision question 8.4

A possible reaction for the formation of the pion from a carbon nucleus and alpha particle is that the alpha particle and carbon nucleus join with the pion being emitted. Complete the nuclear equation below by determining the values of X and Y, and the symbol for the chemical element, Z. Note the pion has a charge of +1.

$$^{4}_{2}\text{He} + ^{12}_{6}\text{C} \rightarrow ^{x}_{y}\text{Z} + ^{0}_{1}\pi$$

So many particles!

In the years that followed, even more particles were discovered, so that now there are over 200 subatomic particles. In the 19th century chemists had to make sense of the large array of chemical elements. The periodic table was the result, with gaps for yet to be found elements. In the late 20th century, physicists needed to find some pattern among the particles.

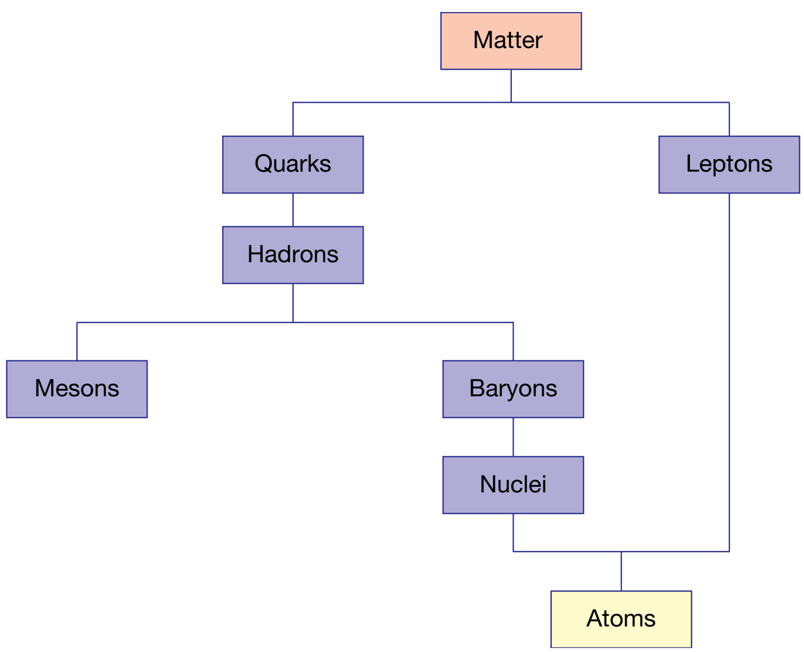
TABLE 8.1 Comparison of the discovery of chemical elements and subatomic particles

Discovery of elements		Discovery of subatomic particles	
Time	**Progress**	**Time**	**Progress**
Late 18th century	About 30 elements known	By 1920	2 known (p and e^-)
Mid 19th century	About 60 elements known; Mendeleev produces periodic table with gaps predicting properties of unknown elements	By 1940 By 1950 By 1960	4 more discovered (n, e^+, μ^+, μ^-) 2 more found (π^+, π^-) Several more particles discovered; quark model proposed, predicting new particles
Early 20th century	92 elements found to fill gaps	By 1970	Predicted particles found

Revision question 8.5

What is the subatomic particle equivalent of Mendeleev's periodic table?

The periodic table initially grouped the elements by common properties, for example, metals and non-metals. Similarly the subatomic particles can be divided into groups. The two groups are leptons and hadrons, with hadrons made up of two subgroups.



The families of subatomic particles and their relationship to matter and atoms

Leptons

Leptons are the simplest and lightest of the subatomic particles. They are fundamental particles with no internal structure.

Leptons are the simplest and lightest of the subatomic particles. The different types of leptons are shown in table 8.2.

Leptons are fundamental particles, that is, they have no internal structure, although muons and tau particles decay into electrons. The neutrinos accompany any interaction of their heavier partner.

TABLE 8.2 Leptons

Name	Symbol	Mass	Charge	First observed	Half-life
Electron	e^-		Negative	1869	Stable
Muon	μ^-	About 200 × mass of electron	Negative	1936	10^{-6} s
Tau	τ^-	About 277 × mass of electron	Negative	1977	10^{-13} s
Electron neutrino	ν_e	Negligible	Neutral	1956	Stable
Muon neutrino	ν_μ	Negligible	Neutral	1962	Stable
Tau neutrino	ν_τ	Negligible	Neutral	2000	Stable

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Unit 1 | AOS 3 | Topic 2 | Concept 1

Antiparticles
Concept summary and practice questions

The electron is found in atoms and determines the chemical properties of elements.

The muon decays to an electron according to the equation: $m^- \rightarrow e^- + \bar{\nu}_e + \nu_m$. The $\bar{\nu}_e$ particle is an anti-electron neutrino. The bar above the symbol indicates that it is an antiparticle. *Note:* The neutrino that is produced in beta decay, that is, when a neutron decays into a proton (see page 106), is actually an anti–electron neutrino.

Muons surprisingly have industrial uses. They are more penetrating than X-rays and gamma rays, and they are non-ionising, so they are safe for humans, plants and animals. Their better penetrating power means that, for example, they can be used to investigate cargo containers for shielded nuclear material. Muons have also been used to look for hidden chambers in the pyramids. Muon detectors were used at the Fukushima nuclear complex to determine the location and amount of nuclear fuel still inside the reactors that were damaged by the Japanese tsunami in 2011.

The tau particle was discovered some time later than the muon. The unusual feature of this particle is that it decays into two pions, which are discussed later. The decay equation is $t^- \rightarrow p^- + p^0 + \nu_\tau$. The negative pion, π^-, then decays into an electron, while the neutral pion, p^0, decays to two gamma rays.

Each of the six leptons has an antiparticle. For the electron, the antiparticle is the positron. The anti-muon and the anti-tau are also positively charged.

Hadrons

Hadrons are composite particles made up of either two or three quarks.

Hadrons are distinctive because they are much heavier than the leptons, but much more importantly they all have an internal structure. Hadrons are made up of different combinations of quarks. Hadrons that are a combination of two quarks are called mesons. The other hadrons are combinations of three quarks and are called baryons.

Mesons

Mesons are hadrons with two quarks.

There are over 60 different types of **mesons**, including the pion mentioned earlier. They play a role in nuclear interactions, but have very short half-lives, so they are very difficult to detect. Each meson also has an antiparticle.

Baryons

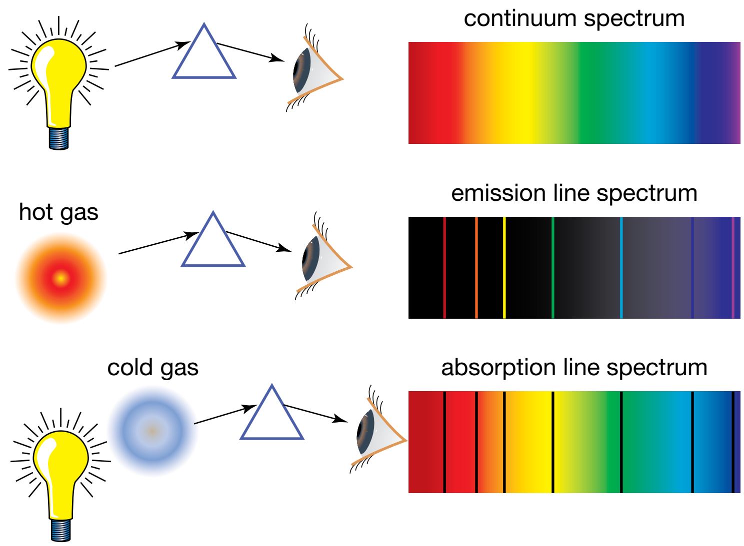
Baryons are hadrons with three quarks.

Baryons include the proton and neutron as well as about 70 other different particles. Only the proton and neutron are stable, with all other baryons having extremely short half-lives. Each baryon also has its own antiparticle.

Why a quark model?

Spectra tell us something about what is inside

In the late 19th century, when visible light was shone through a gas of atoms of a particular element, a spectra of black lines was observed. Each element produced a unique pattern of these lines, called an absorption pattern.



A continuous spectrum and two different ways of producing an element's fingerprint.

On page 36, the greenhouse effect was explained by describing how H_2O and CO_2 molecules respond to particular infra-red wavelengths of electromagnetic radiation.

The lines in the atomic absorption patterns suggested that there was some complexity or structure inside the atom. This structure was discovered early in the 20th century. Similarly, the absorption patterns for H_2O and CO_2 molecules tell us something about how the molecules are put together.

More information about the internal structure of the nucleus can be determined by the energy of alpha particles emitted through radioactive decay. This energy is specific to the nucleus undergoing decay.

If a system is showing evidence that it can have only certain energy values, then it must have a structure, that is, be made up of smaller particles.

During the 1960s it was discovered that when protons and neutrons were hit by a beam of particles, a type of spectra was evident, much like molecules, atoms and nuclei. This meant that protons and neutrons are made up of even smaller particles. This was the beginning of the quark model.

In 1961, Murray Gell-Mann and Kazuhiko Nishijima developed a classification of all the known subatomic particles that, like Mendeleev's periodic table, predicted a new type of particle called a quark, which was found a few years later. Then Gell-Mann and George Zweig developed their idea further into the quark model.

AS A MATTER OF FACT

This Area of Study has described several instances where particles have been predicted and then discovered some time later. The neutron was detected 12 years after its prediction. The positron needed to wait only four years, while the neutrino took 23 years. The Higgs boson, another neutral particle, took over 50 years to be found.

studyon

Unit 1	**Quarks**
AOS 3	Concept summary and practice questions
Topic 2	
Concept 2	

Quarks are fundamental particles that combine to form hadrons.

Quark model

The quark model has six different **quarks**, each with different masses and a fraction of the charge of the electron. Each quark has its own antiparticle. Quarks have rather unusual names, which are shown in table 8.3, along with their charges and mass.

TABLE 8.3 Quarks

Quark	Symbol	Charge	Multiple of proton mass	First observed
Up	u	$+\frac{2}{3}$	0.003	1968
Down	d	$-\frac{1}{3}$	0.006	1968
Charm	c	$+\frac{2}{3}$	1.3	1974
Strange	s	$-\frac{1}{3}$	0.1	1968
Top	t	$+\frac{2}{3}$	184	1995
Bottom	b	$-\frac{1}{3}$	4.5	1977

The top quark has the same mass as a gold atom!

AS A MATTER OF FACT

Where did the name 'quark' come from?

Murray Gell-Mann was seeking a name for the particle model he was proposing. He was reading *Finnegans Wake* by James Joyce and came across the invented word 'quark' in three lines of a poem:

Three quarks for Muster Mark!
Sure he has not got much of a bark
And sure any he has it's all beside the mark.

Where do the names for the various quarks come from?

- Up and down refer to a type of spin that characterises all subatomic particles.
- Strange quarks are components of particular baryons that were found in cosmic ray showers. They had surprisingly long half-lives and so were called 'strange particles.'
- The charm quark was so-called by its discoverers because they were 'fascinated and pleased by the symmetry its discovery brought to the subnuclear world.'
- Top and bottom quarks were named as 'logical partners for the up and down quarks.'

How do you pronounce 'quark'?

It seems there are two possibilities: one sounding like 'mark' and the other sounding like 'quart.' The pronunciation rhyming with 'mark' is the more common.

TABLE 8.4 Table of the 12 fundamental particles

	Charge	Everyday matter	Exotic matter	
Quarks	$+\frac{2}{3}$	u up	c charm	t top
	$-\frac{1}{3}$	d down	s strange	b bottom
Leptons	–1	e electron	μ muon	τ tau
	0	ν_e electron neutrino	ν_μ muon neutrino	ν_τ tau neutrino
	→ mass			

Mesons are composed of one quark and one antiquark. A positive pion (π^+) is made of one up quark and one down antiquark to give a charge of +1. While its antiparticle, π^-, is made of one up antiquark and one down quark to give a charge of –1. Baryons have three quarks. A proton is made up of two up quarks and one down quark to give a charge of +1. A neutron consists of one up quark and two down quarks to give a charge of zero.

Revision question 8.6

(a) The composition of the baryon called the 'charmed double bottom' is 'cbb'. What is its charge?
(b) What would you call a 'ccb' and what is its charge?

Matter and light

The word 'light' is often used as a shorthand collective for all the different types of electromagnetic radiation from radio waves to gamma rays, including infra-red, visible, ultraviolet and X-rays. It is used here in that context.

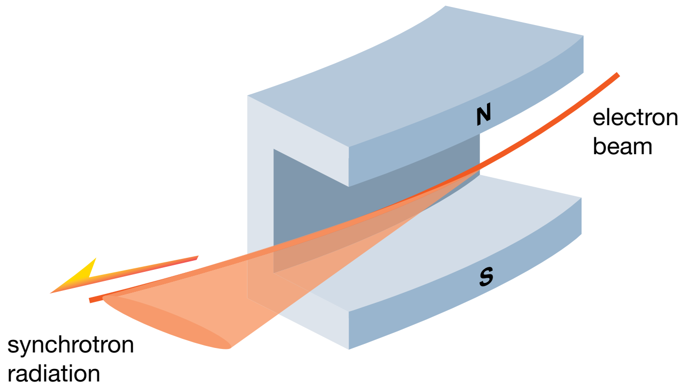
So far in this book matter has produced light in a variety of different ways. The glow of hot objects, such as the Sun, was explained by collisions between the outer electrons of atoms. The electrons' collisions with each other caused a change in direction or speed, or often both. This acceleration of the electron produced light. If the temperature was high and the accelerations sudden, then the object glowed. The same situation applies when electrons are free from their atoms or free in space.

In particle accelerators such as the Large Hadron Collider at CERN in Switzerland and the Australian Synchrotron, charged particles are accelerated by electric fields to speeds close to the speed of light, then deflected into a circular path by magnetic fields. The circular path means a constantly changing direction, so the particles are continually being accelerated and consequently giving off radiation. At CERN, this radiation and loss of energy is an unavoidable nuisance as they want very fast particles, such as protons, to smash into each other.

However, at the Australian Synchrotron, they use electrons accelerated to almost the speed of light. When electrons reach this speed, the radiation comes off in a very narrow beam along the tangent to the circular path. The radiation beam is also very intense and includes all the wavelengths across a large range. The beams at the Australian Synchrotron have a variety of uses including scientific research such as investigating the structure of proteins; medical uses such as high resolution imaging and cancer radiation therapy; as well as the analysis of mineral samples, forensic analysis and the investigation of advanced materials.

Synchrotron radiation is the electromagnetic radiation produced when electric charges are accelerated.

The name **synchrotron radiation** comes from the fact that it was first observed in 1946 when the first synchrotron was built. Since then this type of radiation has been observed in galaxies, when electrons travelling at the speed of light spiral through an intense magnetic field.



Synchrotron radiation is emitted along the tangent of the circular path.

Light from atoms

Earlier in this chapter on page 128 a figure showed a typical absorption spectrum, where light is shone through a gas and specific colours are absorbed. The figure also included an emission spectrum, where a gas is heated to a high temperature and gives a characteristic colour. The inverse of one pattern is almost identical to the other.

Each line has a specific wavelength and frequency. Consequently, the light of that colour in the spectrum has a specific energy. Each line of light in the emission spectrum has come from an electron inside the atom that has jumped from one energy level down to a lower one. The difference in energy between the two level is emitted as light energy. The existence of several lines tells us about the different energy levels that electrons in this atom can have and gives a picture of the structure inside the atom.

Revision question 8.7

Compare the light produced by a synchrotron with an emission spectrum from a hot gas for brightness and spread of wavelengths.

Chapter review

study on

Unit 1 | AOS 3 | Topic 2 — Subatomic particles — Sit Topic test

Summary

- There are two types of fundamental particles of matter: quarks and leptons.
- There are six leptons. They are the electron, muon and tau particle, and each has its own neutrino.
- There are six quarks. They all have an electric charge, which is a fraction of the charge size of the electron. Three have a charge of $+\frac{2}{3}$, and three have a charge of $-\frac{1}{3}$. Their masses vary significantly.
- The quarks combine to form particles called hadrons, of which there are two types: mesons and baryons.
- Mesons are composed of one quark and one antiquark. There are many mesons. They can be positively charged, neutral or negatively charged, and have short half-lives.
- Baryons are composed of three quarks. There are a large number of different types of baryons, with a range of masses and charges ranging from +2 to −2.
- Some of the subatomic particles were predicted well before they were detected.
- Electromagnetic radiation is produced when electric charges are accelerated.
- Electric charges can be accelerated in a number ways to produce electromagnetic radiation.
- Very fast electrons moving in a circular path produce synchrotron radiation.
- Electrons moving between energy levels inside an atom can produce light.

Questions

Subatomic particles

1. Why do you think it has taken so long and been so difficult to find neutral particles such as the neutron, neutrino and the Higgs boson?
2. What do a particle and its antiparticle have in common? How do they differ?
3. How do mesons and baryons differ?
4. Some mesons are their own antiparticle. Explain with an example.
5. How many different mesons are possible, taking into account the previous question? How many different baryons are possible? Ignore antiparticle baryons.
6. The bottom antiquark forms a family of mesons called B mesons with each of the four lighter quarks. Determine the charge and name of each meson in this family.
7. Design baryons with:
   (a) a charge of +2
   (b) a charge of −2
   (c) a charge of zero.
8. What is the charge of:
   (a) the triple bottom baryon
   (b) the baryon that is full of charm?
9. Why do you think baryons with a top quark would be hard to detect?
10. How many baryons, in theory, could be strangely charming?
11. A neutron is described as a 'udd' and a proton as a 'uud'. What do these descriptions mean?
12. (a) The lambda baryon (Λ) was discovered by researchers at the University of Melbourne in 1950. Its quark composition is uds. What is its charge?
    (b) The lambda baryon decays into a proton (uud) and a pion ($\bar{u}$d). The quarks differ in mass. Suggest a possible mechanism for the decay.
13. A neutron (udd) can decay into a proton (uud), an electron and an antineutrino. What do you think has happened inside the neutron?
14. The heavier mesons decay into lighter mesons, which then decay into leptons. Mesons consist of two quarks. Leptons are not quarks. What does this suggest about what can happen to quarks?
15. The tau particle decays into two pions. In light of the quark model, what is unusual about this decay?
16. It is very convincing if a scientific explanation or theory can predict a future event or discovery. What are the examples of this given in this Area of Study and how significant was the discovery for the status of the explanation in each case?

Light and spectra

17. Why might different elements produce different absorption and emission spectra?
18. A gas absorbs some wavelengths of light to produce an absorption spectrum, but the light is very quickly re-emitted. Why doesn't the re-emitted light fill in the dark line?
19. The absorption and emission spectra shown in the figure on page 128 are for hydrogen, which has only one electron. Why do you think there are so many lines in the spectra?
20. In an antenna electrons oscillate backwards and forwards generating radiation. Research the type of electromagnetic radiation an antenna produces.
21. A microwave oven produces electromagnetic radiation in the microwave range. Research how microwave ovens work to find out how the electrons are accelerated.

CHAPTER

9 The origin of atoms

REMEMBER

Before beginning this chapter, you should be able to:

- recall that atoms have a dense nucleus of protons and neutrons bound together by the strong nuclear force with a cloud of electrons surrounding it
- describe wavelength and frequency
- recall that all objects with mass exert a gravitational force on other masses

KEY IDEAS

After completing this chapter, you should be able to:

- explain how the observations of Leavitt, Hubble and others led to the big bang theory for the origin of the universe
- describe how the big bang theory explains not just the beginning of matter but the beginning of time and space as well
- explain how the universe has expanded and cooled over time and how this has resulted in changes to its composition
- apply scientific notation to effectively present and compare the large ranges of magnitudes of time, distance, temperature and mass considered when investigating the universe
- explain how the universe has passed through several stages of development including inflation, elementary particle formation, annihilation of antimatter and matter, a brief period of nuclear fusion, and the formation of atoms
- recognise that scientific understanding develops over time as scientists make sense of new information from new experiments and more powerful instruments.

A long story!

Scientists find it useful to analyse matter in terms of the atoms that make it up. This is the basis of chemistry, and our understanding of biology and geology. But atoms did not always exist; they only exist under the right conditions. Through an amazing journey of exploration, physicists are now confident that the first atoms formed about 13.82 billion years ago, a mere 380 000 years after the universe itself came into being. This chapter explores how physicists have come to this conclusion.

To understand the origin of atoms, we need to understand how the universe began. The big bang is the name given to the theory that scientists use to explain why the universe is as it is. The big bang model of the universe is a triumph of decades of observation, measurement, theory and scientific exploration. However, there is still a lot that is not known, and there are alternative interpretations. The universe is a very active research field with new and surprising discoveries being made and new questions being asked.

Discovering the universe of galaxies

In the early 20th century, significant progress was made in our understanding of atoms and subatomic particles with the discovery of the nuclear atom made up of protons, neutrons and electrons. At the same time, our understanding of the universe was advancing at a tremendous pace. At the turn of the 20th century, there was little grasp of how large the universe was. Astronomers knew that there were a very large number of stars and that these stars seemed to be clustered into a region of space known as the Milky Way. It was not yet clear whether the Milky Way was the extent of the universe, or just one population of stars among many.

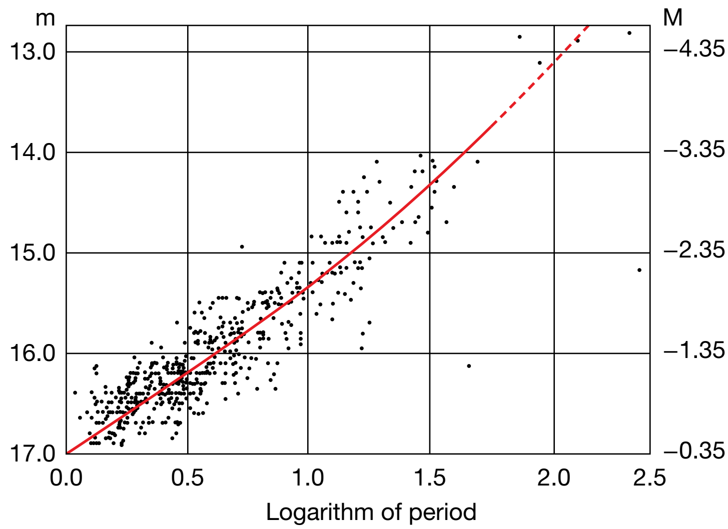
The Milky Way

In 1912, Henrietta Leavitt (1868–1921) made a discovery that was about to shine light on this puzzle. She investigated a type of star called a Cepheid variable. These stars vary in brightness over time in a regular way. Leavitt studied the two clouds of stars called the Large Magellanic Cloud and the Small Magellanic Cloud. She reasoned that the stars in each of these 'clouds' would all be approximately the same distance from us, meaning that any variation in their brightness could be attributed to an actual difference in luminosity,

Henrietta Leavitt

rather than just being the result of varying distance. As with all light sources, stars become dimmer the further away they are. Working with the stars from the Magellanic Clouds proved to be a very powerful technique. Leavitt plotted a graph of the maximum luminosity of the stars versus the period of their variation in brightness. She discovered a clear relationship between the luminosity and period: the brighter the Cepheid variable, the longer its period.

The period is the time it takes for one occurrence of a repeating event. For example, the period of the Earth rotating on its axis is 24 hours; the period of the motion of the second hand on a clock is 60 seconds.



The vertical axis measures the brightness of the star. The horizontal axis shows increasing period plotted on a logarithmic scale; the scale is 10 to the power of the numbers on the axis.

By 1919, Harlow Shapley (1885–1972) had used this relationship to determine how far the Earth is from groups of stars called globular clusters and the Large Magellanic Cloud. All he needed to do was measure the period of the variation in brightness of the Cepheid variable stars in these clusters and then use Leavitt's relationship to determine the luminosity of the star. Comparing this luminosity with the brightness he could measure revealed the distance to the stars, and hence the distance to the clusters they were in. Most of the stars in the Milky Way lie in a plane in the shape of a spiral. Shapely found that the globular clusters were not confined to the plane of the Milky Way, but rather cluster around its centre in a sphere.

A **globular cluster** is a very old, densely packed cluster of stars in the shape of a sphere.

Globular cluster

Globular clusters are spherical clusters of thousands, and sometimes millions, of stars. Shapley used his mapping of globular clusters to determine the general shape and size of the Milky Way galaxy and found that the clusters formed a spherical shell whose centre lay in the direction of the constellation of Sagittarius. This suggested that the centre of the galaxy was in this direction and that our solar system was located towards the edge. Until Shapley's measurements, the solar system was thought to be near the centre of the galaxy.

Edwin Hubble

Shapley's estimate of the size of the galaxy included the Magellanic Clouds and also assumed that the Andromeda nebula was within the Milky Way. He had made quite an error in his estimate. By this time thousands of nebulae in the shape of spirals and ellipses had been catalogued. Some of them seemed to be very small. How could they all be in our galaxy?

From 1919 to 1926, Edwin Hubble (1889–1953) examined the Andromeda nebula in great detail using the large telescopes at Mount Wilson, California. He took long exposure photographs of the spiral arms and counted numerous novae (singular nova; bright stars that were not in previous photographs) and Cepheid variables. Using these, Hubble established the size and distance of the Andromeda nebula from Earth, and found that it lay well beyond our galaxy and was comparable in size to the Milky Way. It seemed that our galaxy was only a tiny portion of the universe after all.

The Andromeda galaxy contains most of its stars in a flat disk similar to the Milky Way. The globular clusters are not restricted to this disk.

PHYSICS IN FOCUS

The debate of Shapley and Curtis

In 1920, Harlow Shapley and another astronomer named Heber Curtis debated the nature of nebulae. Shapley argued that the Milky Way was the entire universe and all the nebulae were therefore to be found within it. Curtis argued that some nebulae were actually separate galaxies of stars, well outside the Milky Way. For Curtis to be right, these galaxies must lie at enormous distances from the Earth, making the universe much greater in size than previously believed.

Curtis and Shapley based their positions on different interpretations of observations of new stars, or novae. Andromeda had been seen only as a nebula, with no stars distinguished, until 1885, when a star suddenly appeared in it. This star was as bright as the rest of the nebula combined. Another nova was observed in a different part of the sky that was close enough for its distance from Earth to be determined by parallax. Knowing its distance and brightness, its luminosity could be determined.

Shapley believed that the nova in Andromeda and the second nova were the same type of event and would therefore have similar luminosities. He used this assumption to estimate the distance to Andromeda and found it to lie well within the Milky Way. Curtis was not convinced by the assumption that the two novae should have equal brightness. If Andromeda were really a separate galaxy, then the star of 1885 burned brighter than the entire galaxy for a time — a supernova! Curtis searched Andromeda for other novae and observed several, which were very dim when compared with the star of 1885. Novae are rare events. Therefore, Curtis reasoned, Andromeda must contain an enormous number of stars, and be at a vast distance, well beyond the edge of the Milky Way.

The debate was ultimately won by Curtis when Hubble showed that Andromeda was a galaxy, and not a nebula within the Milky Way, by measuring its distance from Earth.

Cosmology is the study of how the universe began, has evolved and will end.

One of the most significant results in the history of **cosmology** came from the work of Shapley and Hubble. Hubble correctly interpreted data that had earlier been used by Shapley. In 1919, Shapley noticed that the velocities of nebulae, later found to be galaxies, indicated that they were nearly all moving away from us. Hubble explored further and, in 1929, showed that the more distant the galaxies were from us, the faster they were moving away. The speeds were enormous; one measurement suggested that a galaxy was moving away from us at 42 000 km s^{-1}, more than one-tenth of the speed of light!

The expansion of space

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eLesson
The expansion of the universe
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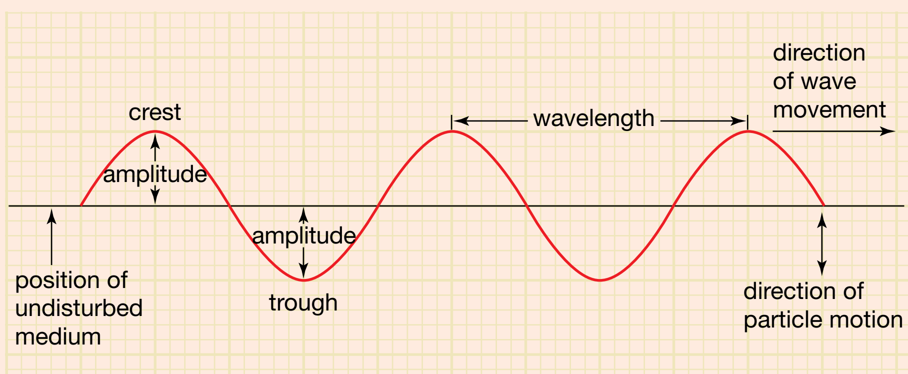
This information was astonishing and very unexpected. Everywhere in the sky that astrophysicists looked, they found galaxies moving away from us. All galaxies are experiencing the same thing. If people in another galaxy looked at us, they would see us racing off in the opposite direction. In fact, it is not the galaxies themselves that are moving away; rather, space is expanding and taking the galaxies with it! Galaxies do also move through space due to gravitational interactions with other galaxies; we know that the Milky Way is currently colliding with the relatively tiny Sagittarius Dwarf Elliptical Galaxy. But these motions do not explain why galaxies are moving away from each other with a speed that increases with distance.

Galaxies and tightly bound clusters of galaxies do not expand as they are held together by gravity. The Milky Way is part of a cluster of galaxies known as the Local Group. The Local Group includes over 30 galaxies, the two largest being Andromeda and the Milky Way. The Large and Small Magellanic Clouds are also members of the Local Group. The Andromeda galaxy is actually approaching us at enormous speed due to gravitational attraction, but as we look at more distant galaxies beyond the Local Group, the expansion of space dominates gravitational forces.

Hubble jumped to the obvious conclusion. All of the galaxies are racing away from each other, so if we imagine running time backwards, we would see that they had all come from the same spot. It was as though the universe was born from some form of explosion that threw space and matter out in all directions. This was the first scientific evidence that the universe had a beginning. Prior to this, scientists assumed that the universe had existed forever.

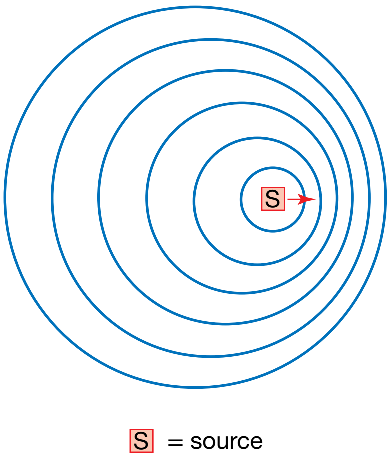
REMEMBER THIS

Waves can be described in terms of their period, frequency, speed and wavelength. The wavelength is the distance between successive corresponding parts of a periodic wave — the length of one cycle. The period of a periodic wave is the time for one part of the wave to travel one wavelength. The frequency of a periodic wave is the number of cycles that occur every second.

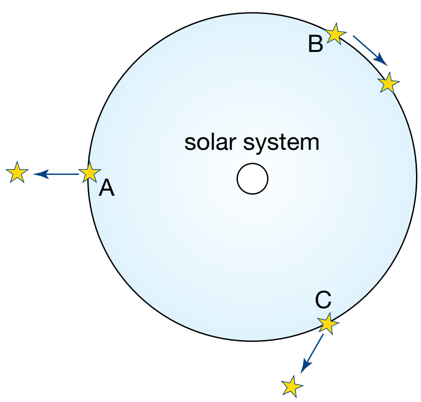


Transverse periodic waves in a piece of string

Red shift is the increase in wavelength that results from a light source moving away from the observer.



The Doppler effect: as the source moves to the right, the wavelengths in front of it are smaller than those behind it.



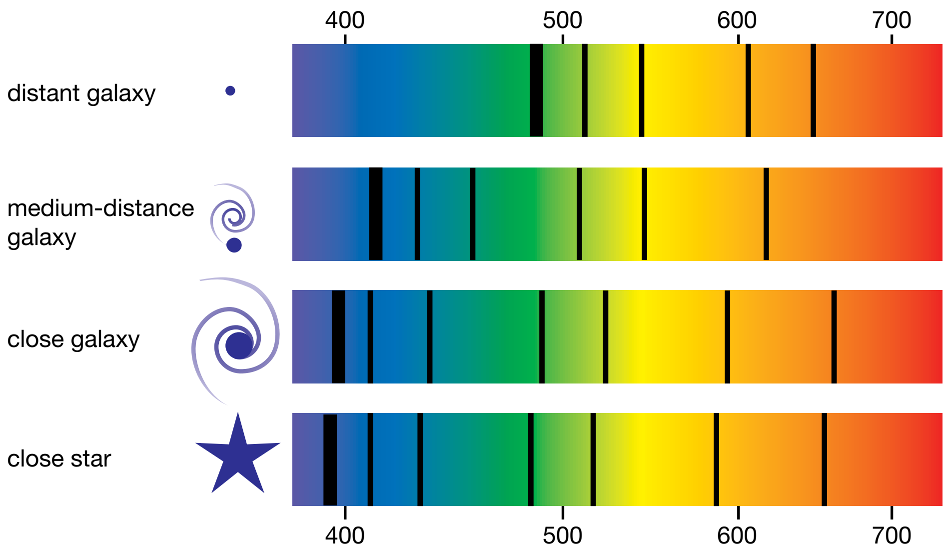
Star A moves radially.
Star B moves tangentially.
Star C moves both tangentially and radially.

A star with only tangential motion would not change its distance from the Earth. The radial component of its motion will move the star toward or away from the Earth.

The Doppler effect

How did Hubble measure the expansion of space? He used a phenomenon called the Doppler effect. We are familiar with its effects on sound. When fast moving objects go by, the sound they make drops in pitch. You can hear this when trains, fire engines or racing cars speed past you. This change in pitch (or frequency) is known as the Doppler effect, after Christian Doppler, who predicted its existence in 1842, before it had been observed.

Doppler realised that, as light has a frequency like sound, it is also changed by this effect. Light emitted by a star or galaxy that is moving away from us is shifted towards the red end of the spectrum. This is commonly called the **red shift**. The faster the galaxy moves away, the greater the shift. Stars or galaxies moving towards us have their light shifted towards the blue end of the spectrum, which is called blue shift.



Spectra showing red shift. The scale indicates the length in nanometres.

REMEMBER THIS

The visible spectrum of light contains red, orange, yellow, green, blue, indigo and violet. The spectrum continues into invisible forms of radiation, including infra-red at lower frequencies than red and ultraviolet at higher frequencies than violet.

Using the Doppler effect on stars

Spectra from stars contain numerous lines, which are characteristic of the gases they are made from. These lines can be identified by comparing them with the spectra of known gases (found by passing light through each gas at rest in a laboratory). When the light from a star is passed through a spectroscope, the characteristic pattern of lines observed may be shifted. A shift towards the red end of the spectrum indicates the star is moving away from us; a shift towards the blue end indicates that it is moving towards us.

Revision question 9.1

What major discovery about the nature of our universe did Hubble make when he considered the Doppler effect in his analysis of spectra from galaxies?

Einstein and general relativity

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Shifting stars
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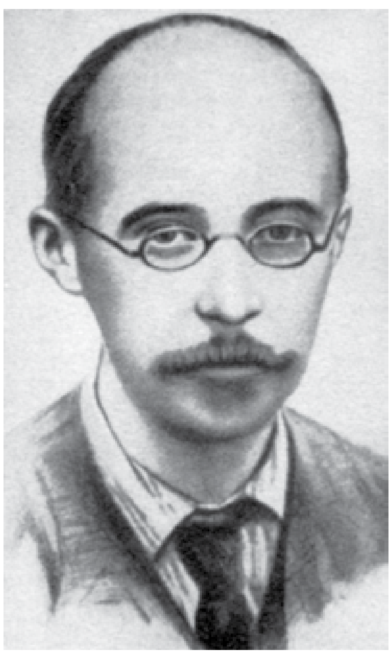
In parallel to the experimental work of Shapley, Hubble and other astronomers, theoretical physics was making tremendous progress. In particular, Albert Einstein published his General Theory of Relativity in 1915, which provided a new way of understanding gravity. Until then, scientists had used Isaac Newton's theory of gravity, which essentially stated that masses exert an attractive force on each other. Einstein's theory was that mass curves space and other masses move in response to the curvature of space. However, there was a problem with both theories. Newton wondered why the universe was not collapsing, given that all masses attract each other, and decided that the universe must be infinite. The idea that the universe is infinite in size and has existed forever endured until the big bang theory was developed. Einstein's theory did not have a good answer to the collapsing universe problem either, so he inserted a cosmological constant into his equations to counter the curvature of space.

Beginning in 1917, scientists proposed cosmological models based on the General Theory of Relativity. Aleksandr Friedman (1888–1925) found that there were a number of solutions to the equations of general relativity, each of which is equally valid in terms of the theory, but of course only one could represent our universe. In some solutions the universe expands forever, in others the universe would expand for a time and then collapse back on itself. It is interesting to note that this theoretical work was established before Hubble measured the recession of the galaxies.

The **big bang** is the name for the dramatic beginning of the universe from an infinitely dense, small point.

Georges Lemaitre (1894–1966) was both a Catholic priest and professor of physics. He was fascinated by what physics might say about the birth of the universe. In 1927, he argued that because the galaxies are currently far apart and getting further apart, at some point in the past all of the material that makes up the universe must have been in one place; it was, in his words, a primeval atom. This atom was about 30 times the size of the Sun and incredibly dense. Lemaitre proposed that it blew apart, forming the universe in the process. This was an early version of what became known as the **big bang** theory.

In 1917, before Friedman and Lemaitre, Willem De Sitter (1872–1934) applied Einstein's theory to the universe. He then encouraged Hubble to look for red shift in distant galaxies, but the red shift that De Sitter predicted was not due to the Doppler effect, but to the expansion of space.



Aleksandr Friedman

Red shift revisited

The Doppler effect is the same no matter how far the observer is from the source. The speed of the source determines the red shift or blue shift. What De Sitter predicted, and what Hubble observed, was that the red shift was greater for more distant galaxies. According to the theory behind the Doppler effect, this must mean that these galaxies were moving away at much greater speeds.

Space is expanding. While the light from a distant source travels through space en route to Earth, the space it passes through stretches, increasing the light's wavelength. The light from distant galaxies takes many millions, if not billions, of years to reach Earth, and during this time the wavelength increases. The longer the light travels through space (that is, the further away the galaxy), the greater the increase in wavelength due to expanding space, and so the greater the red shift.

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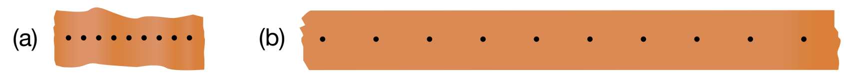
Locally, the Doppler effect is more significant. Some galaxies are moving towards us and some away, under gravitational influences, but in the far reaches of the universe, the Doppler effect due to these local interactions is drowned out by the expansion of the universe.

This expansion effect can be quickly demonstrated using a rubber band to represent space. Mark a rubber band every 2 mm along a 2 cm length. The distance between neighbouring marks represents the wavelength of light. As you stretch the rubber band a little, you will see each mark move away from all of the others. As time goes on the universe keeps expanding, like stretching the rubber band further. As a consequence, the wavelength of light from distant galaxies gets longer over time.

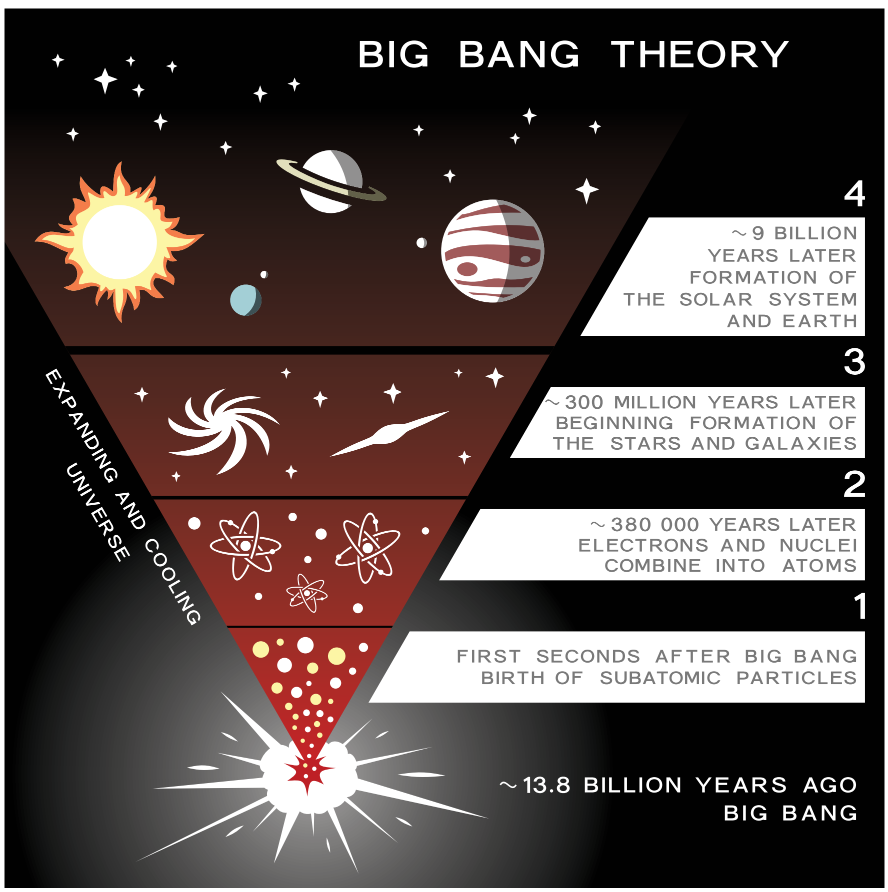


(a) The rubber band before stretching; (b) the stretched rubber band; each dot has moved away from all of the other dots.

Revision question 9.2

Explain how the expansion of space results in light undergoing a red shift similar to that observed in the light emitted from a source moving away from the observer.

The big bang



Hubble's constant is the constant of proportionality relating the speed that galaxies are receding from Earth and their distance from Earth.

Hubble's Law states that the speed of recession of galaxies is proportional to their distance from Earth.

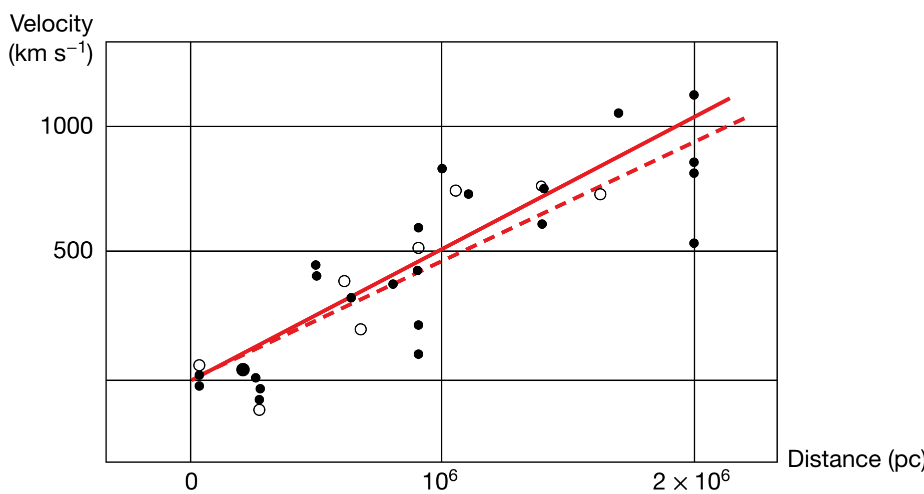
studyon

Unit 1 | AOS 3 | Topic 3 | Concept 2

Hubble's Law and the age of the universe
Concept summary and practice questions

By 1929 there was both a theoretical basis for this new cosmology through the work of Lemaitre, de Sitter and Friedman, and the observational evidence of the red shift of galaxies to support it; however, it was by no means generally accepted.

Hubble plotted the velocity (red shift) of galaxies versus their distance from Earth and ambitiously fitted a straight line to the data, well aware that the distance calculations had large uncertainties. If the galaxies really did fit this straight line rule, then it would be easy to judge the distance to other galaxies; simply measure their red shift and divide by the gradient of the line. This gradient became known as **Hubble's constant** (H) and the relationship between velocity and distance **Hubble's Law** ($\frac{1}{H}$ gives physicists a means of calculating the age of the universe). The value of Hubble's constant has been measured with increasing accuracy since Hubble's time and discoveries in recent years have established its value to a small margin of uncertainty. Using the simplest scenario, that the universe has expanded at a constant rate, Hubble's early measurements put the age of the universe at 2 billion years, but the age of the Earth appeared to be greater than that. The age of the Earth has been dated using the proportion of radioactive isotopes in rocks, the rate of cooling from the Earth's original molten state, the time it would take to develop its geological features, and the time required for the evolution of life. These all pointed to an age greater than 2 billion years — the currently accepted figure for the age of the Earth is about 4.6 billion years.



Hubble's data. The solid dots are the results for galaxies treated individually and the solid line is the line of best fit for these data. The dashed line is fitted to the circles, which are the result of treating galaxies in clusters. One parsec (pc) is 3.09×10^{16} m or 3.26 light-years. Notice the group of blue-shifted galaxies at about 2.5×10^5 parsecs. This corresponds to the Andromeda galaxy and its satellites.

Source: Adapted from Edwin Hubble, 'A relation between distance and radial velocity among extra-galactic nebula', *Proceedings of the National Academy of Science*, vol. 15, no. 3, 15 March 1929, Mount Wilson Observatory, Carnegie Institution of Washington. Communicated 17 January 1929.

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Weblink
The expansion of the universe and Brian Schmidt

It was not until the 1950s that Walter Baade identified two populations of stars that helped resolve the age problem. Baade noticed that Cepheid variables with significant amounts of heavier elements (Population I stars) had a different relationship between intensity and period than those made of little other than hydrogen and helium (Population II stars). This more than halved Hubble's constant, and therefore doubled the calculated value for the age of the universe. The adjustment resulted in a calculated universe age of 5 billion years; still young but at least it was older than the Earth. Improvements in measurement since have put the age of the universe at about 13.8 billion years.

Sample problem 9.1

Use the solid line in the graph of Hubble's data to estimate the age of the universe. Compare this with his estimate of 2 billion years.

Solution:

$$2 \times 10^6 \text{ pc} = 2 \times 10^6 \times 3.09 \times 10^{13}$$
$$= 6.2 \times 10^{19} \text{ km}$$

Hubble's constant is the gradient of the graph:

$$\text{H} = \frac{1100}{6.2 \times 10^{19}}$$
$$= 1.77 \times 10^{-17} \text{ s}^{-1}$$
$$t = \frac{1}{\text{H}}$$
$$= \frac{1}{1.77 \times 10^{-17}}$$
$$= 5.64 \times 10^{16} \text{ s}$$
$$= 1.8 \times 10^9 \text{ years}$$

This is 2 billion years to one significant figure, in agreement with Hubble's estimate.

Revision question 9.3

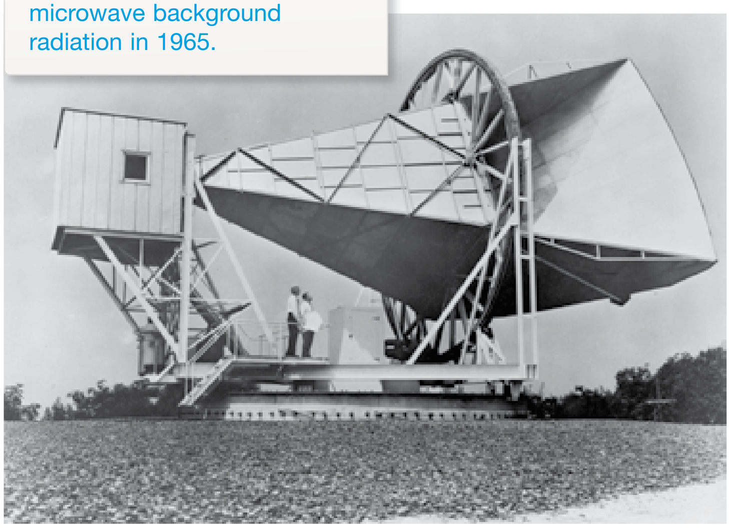
Given the data in Hubble's graph, the currently accepted age of the universe, 13.8 billion years, is quite unexpected. Give two reasons why the modern data are so different to Hubble's.

studyon

Unit 1	**Further evidence for the big bang**
AOS 3	Concept summary and practice questions
Topic 3	
Concept 3	

Other evidence for the expansion model of the universe included surveys showing that galaxy density in distant space was greater than the density of galaxies closer to Earth. This is expected with the expansion model because when we observe distant galaxies, we see them as they were billions of years ago, when the universe had undergone much less expansion.

The young universe must have been very hot and we will learn that a significant event called recombination resulted in photons (light) being able to travel freely for the first time without interacting with electrons. The wavelength of a photon depends on its energy. As the universe expanded, the wavelengths of the photons would have expanded, stretching out to form radio waves with much less energy than when the photons were initially released. These radio waves have become known as cosmic microwave background radiation (CMB) and correspond to a background temperature of about −270 °C or 2.7 Kelvin. Arno Penzias and Robert Wilson discovered this radiation accidentally in 1965 when they were trying to eliminate some noise coming from their radio telescope. The identification of this noise was the turning point for the big bang theory. A graph of the intensities of the microwave radiation for the different wavelengths had the same shape as the radiation graphs on page 26, except this graph gave a temperature of 2.7 K.



Penzias and Wilson accidently discovered the cosmic microwave background radiation in 1965.

The name 'big bang' came from an early opponent of the theory, Fred Hoyle, in 1950. It is not a particularly accurate description as it implies that the creation of the universe was like an enormous explosion, which is not the case.

So in summary we have discovered that:

- the universe is vast, filled with billions of galaxies each containing billions of stars
- these galaxies are moving away from each other at a rate that increases the more distant the galaxies are
- the more distant galaxies (the older ones) are more densely packed than those nearer to us
- the predicted cosmic microwave background radiation has been detected.

Most scientists concluded that these discoveries meant that the universe had a beginning in a relatively small volume that has expanded ever since. This idea has been called the big bang theory.

PHYSICS IN FOCUS

Stephen Hawking and the big bang

The big bang theory raises many questions. What happened before the big bang? What is outside the universe? What is the universe expanding into? Famous physicist Stephen Hawking, in collaboration with others, has posed answers to these questions. He reminds us that in the past people contemplated what would happen if you sailed off the edge of the world. That question turns out to not need an answer because we have a completely different view of the shape of the world; it is a globe, so we never reach an edge. The question of what happened off the edge of the world only arose because of our misunderstanding of the shape of the world, thinking that it was flat.

In his PhD thesis in the mid 1960s, Stephen Hawking proved that Einstein's Theory of General Relativity required the universe to have a beginning in what was called a 'singularity'. A singularity is a point of infinite density that is achieved when we think of what happens if we run time backwards so that the expanding universe collapses back to its beginning. This was a stunning result for general relativity. If the universe was initially very dense, it must also have been incredibly hot and that energy should still be found throughout the universe. This energy was found soon after Hawking's initial work on singularities in the form of the cosmic microwave background radiation. This radiation is central to the topic of this chapter, the origin of atoms.

Later Hawking showed that time becomes like another dimension of space under extreme conditions. It makes no more sense to ask what happened before the big bang than to ask what is south of the South Pole. Hawking asks us to imagine the passing of time as being like decreasing degrees of latitude away from the South Pole. The latitude is 90° at the South Pole and as we move north it becomes 89°, 88° and so on. There is no 91° of latitude and there is no 'before the big bang'. Time began with the big bang and space has no edge to fall off, or to step outside of, to discover what the universe is expanding into.

Looking back in time

To look into space is to look back in time. This is a consequence of the speed of light and the vast distances involved. Light travels faster than anything else in the universe, but it still only travels at just under 300 000 000 metres per second. The distance light travels in a year is called a light-year. The light from the Earth's nearest star, other than the Sun, takes more than four years to reach us, so we see it as it was more than four years ago. When we look out to the nearest large galaxies we see them as they were over two and a half million years ago. This is still recent in the universe's history.

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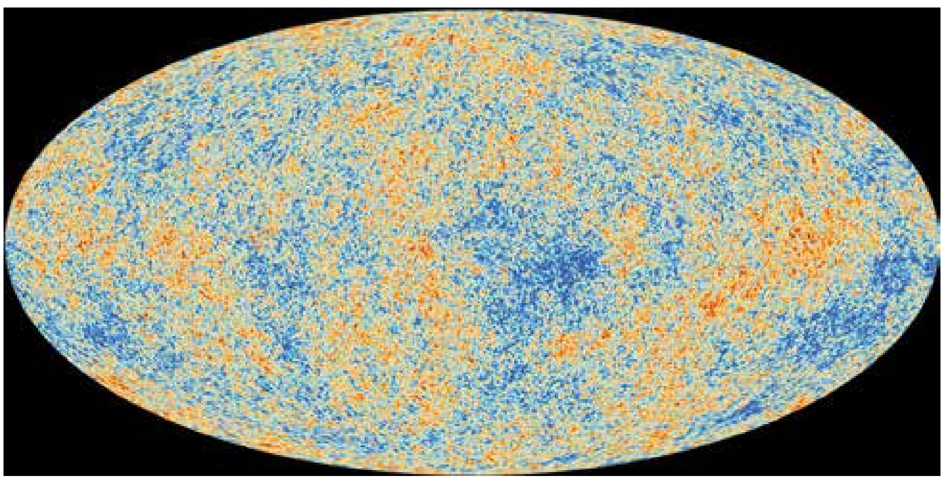
Weblinks
NASA — the big bang
Planck data
The early universe

Looking at the most distant galaxies, we see them as they were over 13 billion years ago. Most of the history of the universe has involved galaxies of stars as the expansion of the universe has taken those galaxies further from each other. These distant galaxies are incredibly faint, so our current telescopes cannot see further. But even if we could, we don't expect to see much more because physicists believe that the first stars would have begun to shine at this time. A little over 13 billion years ago the matter in the universe was hydrogen and some helium in vast clouds, collapsing due to gravity on their way to producing the first stars and galaxies. This period is known as the Dark Ages (borrowed from a term used to describe the period in history following the fall of the Roman Empire). The Dark Ages marks the period from 380 000 years following the beginning of the universe until stars began to shine 150–800 million years later.

To look further back in time, we don't see objects, we see the remnants of an event. This is the cosmic microwave background radiation (CMB) mentioned earlier. The CMB is energy in the form of photons left over from the early universe. Prior to the universe reaching 380 000 years of age, this energy was trapped in a state of constant scattering, a bit like light in a cloud. It was not water molecules that scattered this light but the charged particles that filled the universe. These protons and electrons were too energetic, too hot, to combine to form atoms until the expansion of the universe had cooled it enough for the bonds between electrons and protons and the other nuclei to form. This event is called recombination and marks the time when atoms first formed 380 000 years after the beginning of the universe. The CMB provides physicists with a picture of what the universe was like at 3.8×10^5 years of age because the light that formed it was free to travel through the universe from that time. The CMB has been red shifted uniformly in all directions by the expansion of the universe.



The cosmic microwave background as measured by the Planck satellite. The differences in colour indicate temperature differences that correspond to differences in the density of the universe when it was 380 000 years old.

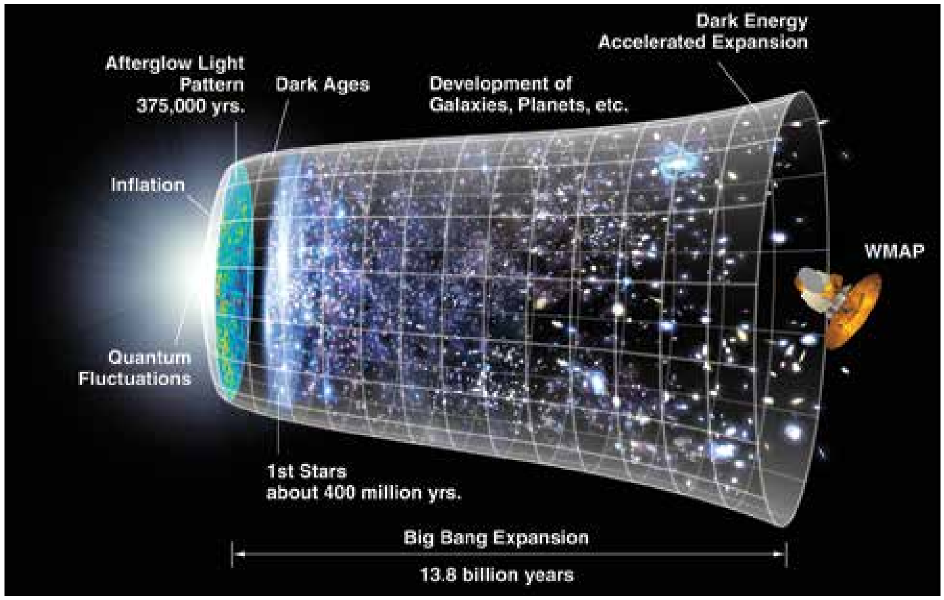
The early universe

The CMB marks the earliest observation we have of the universe. To understand what happened prior to this event, physicists rely on particle physics and the Theory of General Relativity to help them make sense of their observations of the CMB and the universe that followed. Particle physics experiments, such as those in the Large Hadron Collider that discovered the Higgs boson at CERN, create conditions that existed for particles in the early universe, so physicists do have experimental evidence for much of what happened prior to recombination.

Let's piece the story together from the beginning until the formation of atoms.

The first 10^{-43} seconds

This is known as the Planck era and current theories of physics cannot explain what happened in the conditions that were present. The universe was too small, too dense, too hot and existed for too short a time for current physics to say anything precise about it. Physicists refer to what existed prior to when the universe was 10^{-43} seconds old as a singularity. In this period space and time began. Gravity became a distinct force at the end of the Planck era. The temperature was 10^{32} degrees Celsius and the universe was 10^{-35} cm across.



Source: NASA WMAP Science Team

studyon

Unit 1	**Cosmic inflation and early expansion**
AOS 3	Concept summary and practice questions
Topic 3	
Concept 4	

10^{-43} seconds to 10^{-36} seconds

This tiny interval of time in the early universe is known as the grand unified era. During this period, physicists believe that the strong nuclear force, the weak nuclear force and the electromagnetic force did not yet exist as separate forces. The first matter begins to form, but for each particle of matter, there was a particle of antimatter. As soon as a particle was formed, it would meet an antiparticle and be annihilated.

10^{-36} seconds to 10^{-32} seconds

This next period of time is known as the inflation era. During this time, a period of exponential expansion has been proposed to explain a number of features of the universe. During this brief period, the universe is thought to have expanded in size by a factor of 10^{26}, so that it was about 10 cm across. This rapid expansion explains, among other things, why the cosmic microwave background radiation is so uniform, being close to 2.7 degrees above absolute zero in all directions.

Alan Guth proposed this radical idea in 1980. It was a response to some of the limitations of the standard big bang model that worked well for most of the evidence, but fell short when it came to explaining the relative uniformity of the CMB in all directions, and what is known as the 'flatness' of the universe. At first, inflation may look like a crazy idea invented just to explain away problems. However, in all of the time since, no one has come up with a more successful theory to explain why the visible universe is so uniform in temperature or why the universe appears so 'flat'. In a flat universe, parallel lines remain an equal distance apart. In a curved universe, they could be more like north–south lines on the surface of the Earth, which meet at the poles. It is thought that rapid expansion during this era smoothed out deviations in the flatness of the universe that would otherwise have grown with time. A flat universe only just avoids eventual gravitational collapse.

The small variations in the cosmic microwave background detected by the Planck orbiting observatory are consistent with a universe that underwent a period of inflation and resulted in the clumping of matter into clusters of galaxies.

10^{-32} seconds to 10^{-12} seconds

The electroweak era was the period when the strong nuclear force came into play. The Higgs boson formed, enabling particles to have mass.

10^{-12} seconds to 10^{-6} seconds

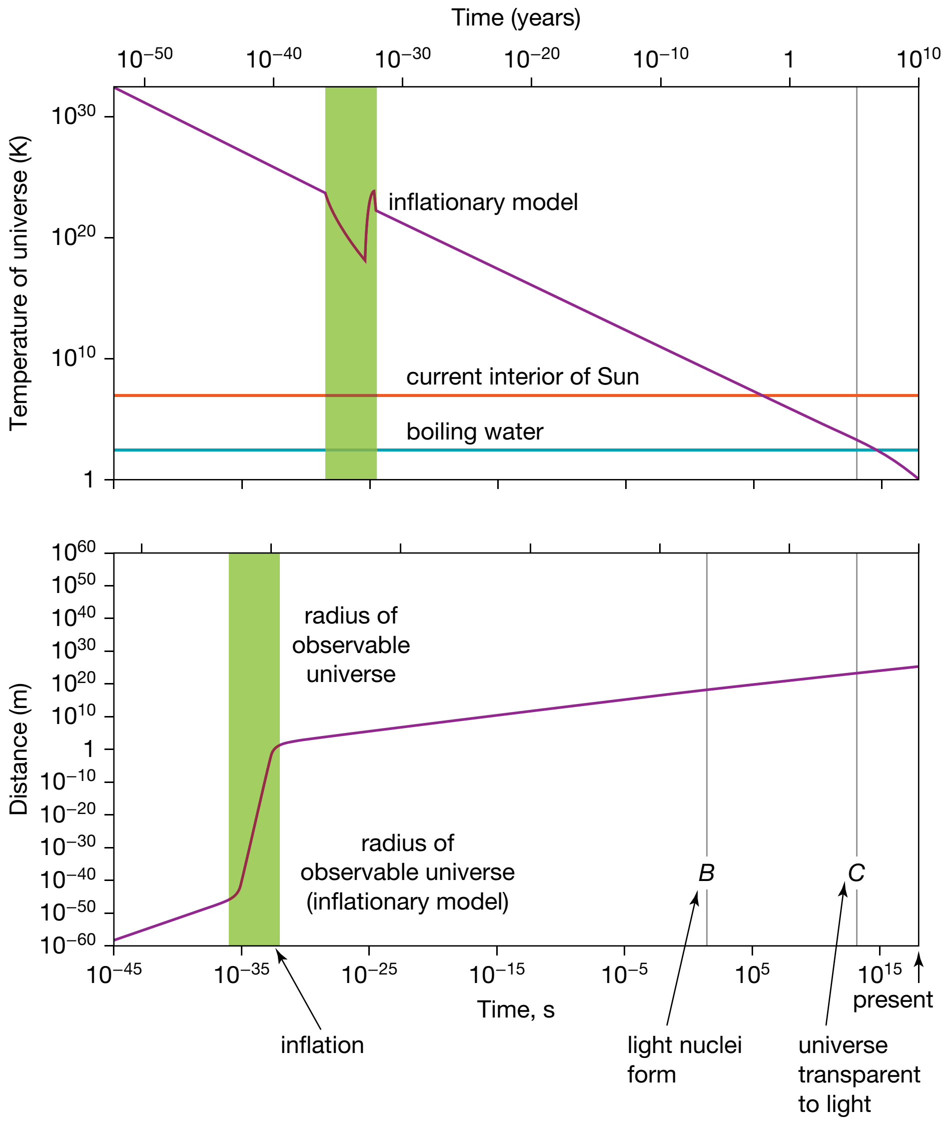
The quark era was when particles began to appear in large numbers. These included quarks, electrons and neutrinos. Most particles still formed in pairs with an antiparticle, but a slight bias towards particles resulted in matter that was not annihilated through contact with antimatter.

10^{-6} seconds to 3 minutes

The hadron era was the period when the temperature of the universe had dropped to the point where three quarks could form protons and neutrons (particles like neutrons and protons made from three quarks are called hadrons). Most are annihilated by contact with their antiparticles, and leptons such as electrons dominate.

3 minutes to 20 minutes

Nucleogenesis occurs. During this era, annihilation with antimatter became less significant and the critical phase of fusion occurs. During these few minutes most of the nuclei in the universe formed. The following section outlines this in detail.



The birth of atoms

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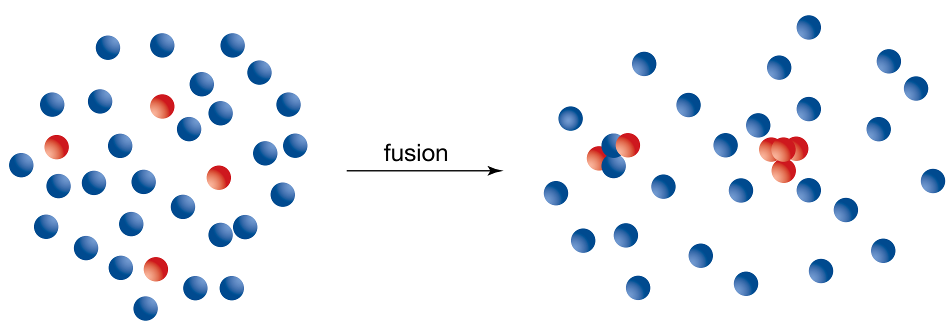
eLesson
From hydrogen to helium
eles-2459

In 1948, George Gamow (1904–1968) and Ralph Alpher (1921–2007) proposed a model that explained how over 99% of the atoms found in the universe could have formed. The protons and neutrons in the early period of the universe readily interacted with the abundance of electrons and neutrinos present, causing them to change from proton to neutron and vice versa. This produced equal numbers of each, but as the universe cooled, fewer protons interacted with electrons with sufficient energy to form neutrons. This resulted in more protons being formed than neutrons in a ratio of about 7 to 1. This formed a universe of hydrogen. In chapter 7, we saw that under the right temperature and pressure protons can fuse, one at a time, to form helium-4. These conditions were present when the early universe was about 400 seconds old, allowing nuclei up to a mass number of 4 to form.

This produced:
- hydrogen (1 proton)
- deuterium (an isotope of hydrogen with 1 proton and 1 neutron)
- tritium (an isotope of hydrogen with 1 proton and 2 neutrons)
- helium-3 (2 protons and 1 neutron)
- helium-4 (2 protons and 2 neutrons).

No stable isotope with a mass number of 5 exists (this has been tested in the laboratory), so fusion of nuclei beyond helium-4 was very limited. Tiny quantities of lithium-7 and beryllium-7 were produced through fusion of helium nuclei, but the step to heavier elements involving the fusion of three helium nuclei to form carbon takes too long. The universe rapidly cooled through its expansion to the point where the conditions no longer supported fusion. This provided the young universe with its composition of about 75% hydrogen and 25% helium by mass.

To understand the prediction of the proportion of hydrogen to helium, consider the ratio of protons to neutrons, which is 7:1. To form a helium-4 nucleus, 2 protons and 2 neutrons are required. According to the 7:1 ratio, for every 2 neutrons in the universe, there were 14 protons, so the formation of helium-4 would take 2 neutrons and 2 protons, leaving 12 protons in the mix. That leaves 4 nucleons in helium and 12 in hydrogen, or 25% of the mass in helium and 75% in hydrogen. The fusion in these first moments of the universe was so rapid and complete that virtually all of the available neutrons went into helium-4. Only a tiny proportion remained as deuterium or tritium (which decays to helium-3) so this simple calculation gives a very good prediction of the composition of the universe prior to star formation.



One of the strongest pieces of measured evidence for the big bang model of the universe (along with the observed expansion and cosmic microwave background) is this predicted proportion of hydrogen and helium. As astrophysicists measure the proportions of the elements in regions of the universe not greatly affected by later fusion in stars, the elements are found in this predicted abundance.

So we have the formation of nuclei in the early universe, but there are no atoms. That will take more time because although the universe has cooled sufficiently for nuclei to form, it is still way too hot for electrons to stay bound to those nuclei. Before atoms could form, 380 000 years would pass.

An overview

The following table outlines significant events in the early universe.

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Unit 1 | AOS 3 | Topic 3 | Concept 5

Scientific calculations
Concept summary and practice questions

TABLE 9.1 Significant events in the early universe

Time since beginning of universe (seconds)	Temperature (K)	Event
0		Universe is born
10^{-36} to 10^{-32}		Inflation occurs
10^{-12} to 10^{-6}	10^{16}	Elementary particles including quarks and leptons form
10^{-6} to 10^{0}	10^{12}	Annihilation of antimatter and matter leave relatively small amount of matter
10^{2}	10^{9}	Commencement of nuclear fusion
10^{3}		Cessation of fusion
10^{13} (380 000 years)	3000	The formation of atoms (recombination), CMB produced
10^{13} to 10^{16}		The Dark Ages (stars yet to form)
10^{16} (800 000 000 years)		The first stars and galaxies form; most atoms re-ionised
10^{17} (9.3 billion years)		The Earth and solar system form
10^{18} (13.82 billion years)	2.7	Today

It was not until 800 million years into the universe's life that the story of the atom resumed, when the first stars formed and new elements began to form in nuclear fusion in their interiors. In the centres of these enormous stars, the temperature and pressure was sufficient for long enough for fusion to continue beyond the formation of helium 4, resulting ultimately in the genesis of all of the elements in nature. For more information on the life of stars, read Chapter 14: What are stars?

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Unit 1 | AOS 3 | Topic 3
The origin of atoms
Sit Topic test

Chapter review

Summary

- Our galaxy, the Milky Way, is only one of billions of galaxies.
- All distant galaxies are moving away from us, and the further away they are, the faster they are receding.
- The expansion of space provided the first evidence that the universe had a beginning, now determined to have occurred 13.8 billion years ago.
- In the earliest moments of the universe, there was a period called inflation where the size of the universe grew exponentially within a fraction of a second.
- After about 20 minutes, the universe consisted of hydrogen and helium nuclei with 25% of the mass in helium and 75% in hydrogen.
- Atoms first appeared 380 000 years into the universe's history when the universe was cool enough for electrons to stay bound to nuclei.
- Light was then free to travel through the universe, which is now visible as the cosmic microwave background radiation.
- Production of heavier elements did not occur until the first stars began fusing hydrogen and helium in their cores, 800 000 000 years after the beginning of the universe.
- The big bang is the name given to the theory that describes the universe beginning from a point of infinite density and expanding to create space and time as we see it today.
- The key evidence for the big bang includes: the expansion of the universe, the higher density of galaxies in the past, the proportion of elements in the universe, and the cosmic microwave background radiation.
- Stephen Hawking showed that the universe may have no boundaries of space or time — time began with the universe, and space and time outside of the universe have no meaning.

Questions

The expanding universe

1. What did Hubble discover in 1929 that led to the formulation of the big bang theory?
2. How did the red shift of the most distant galaxies compare with the red shift of galaxies closer to us?
3. Given that all distant galaxies are red shifted, why is this not evidence that we are at the centre of the universe?
4. What causes the red shift in the light from distant galaxies?
5. The light from the Andromeda galaxy is blue shifted. Explain why it is not red shifted like the light from most galaxies.
6. State Hubble's Law.
7. Why has the value of Hubble's constant changed so much since Hubble first calculated it?
8. Sketch a graph of red shift versus distance that summarises Hubble's observations of galaxy red shifts.
9. How can the speed of recession be determined from the red shift?
10. How is the big bang different from normal explosions?
11. List the key evidence in favour of the big bang theory.
12. How does the big bang theory explain the predominance of hydrogen and helium in the universe?
13. Why was the cosmic microwave background discovery so important in establishing the big bang theory?

The origins of time and space

14. How can cosmologists respond to the question 'What happened before the big bang?'
15. What metaphor does Stephen Hawking use to explain time prior to the big bang?
16. If the universe is expanding with time, then the density of galaxies was greater in the past. Explain how it is possible for us to test this prediction.
17. Stephen Hawking likens the question of 'what space is the universe expanding into?' to the questions asked by those who thought the Earth was flat and feared what would happen when they got to the edge. Are you convinced by this argument? Write down what you find convincing and what it leaves you still wondering.
18. What discovery began to shift scientists from their long-held assumption that the universe had existed forever to the idea that it had a beginning?
19. In physics, particularly cosmology, you can deal with some of the largest and smallest numbers. Why is scientific notation the preferred format for very large and small numbers in physics?

The changing universe

20. There was immense heat in the early universe. Now the average temperature of space is about 2.7 K. Explain the process that resulted in this drop in temperature.

21. The early universe was so hot that even fundamental particles could not exist for long. After how long could protons and neutrons exist without being annihilated?
22. For just a few minutes in the early universe, nuclear fusion could take place. What were the products of this fusion?
23. Investigate the work of Professor Brian Schmidt and his team at ANU and its implications for how the universe will end.
24. One light-year is 9.46×10^{15} m. How far has the CMB travelled since it was released about 13.8 billion years ago?
25. The variations in CMB measured by the Planck space observatory are about 0.000 57 K. Write this in scientific notation.

The development of the universe

26. Inflation is estimated to have occurred between about 10^{-36} and 10^{-32} seconds after the big bang. Write these times in decimal format.
27. Why were heavier nuclei, such as carbon and oxygen, not created during the intense temperatures and pressures in the early universe?
28. Put the following events in time order from first to last: inflation, nuclear fusion, particle–antiparticle annihilation, the formation of atoms, and ignition of the first stars.
29. Describe the hypothesis of inflation and one problem that it solves.
30. Telescopes are not able to see anything prior to recombination, even in theory. What tools do physicists use to improve their understanding of what happens to matter in the conditions in the early universe?
31. What prevented nuclear fusion prior to its commencement some seconds after the beginning of the universe?

UNIT 2

AREA OF STUDY 1

AREA OF STUDY 3

AREA OF STUDY 2

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The Options chapters 14–25 can be found in your eBookPLUS. A copy of each chapter can be downloaded from the Resource panel. A sample of each chapter can be found in the section of this book following Chapter 13. Students will study only one Option chapter.

CHAPTER

10 Analysing movement

REMEMBER

Before beginning this chapter, you should be able to:

- know the units of distance and speed
- estimate distances and lengths
- estimate speeds
- use a graph to plot data.

KEY IDEAS

After completing this chapter, you should be able to:

- distinguish between vector and scalar quantities that describe motion
- use graphs to describe and analyse uniform and non-uniform motion
- analyse uniform motion along a straight line numerically and algebraically.

Whenever you drive a car, you need to be aware of, and to describe, your movement in terms of your position, speed, direction and acceleration.

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Unit 2 | AOS 1 | Topic 1 | Concept 1

Speed and velocity
Concept summary and practice questions

Describing movement

By observing the change in the position of an object during a measured time interval, you are able to describe the speed of the object and the direction in which it is travelling. Only by studying the way in which an object moves can you begin to understand the nature of forces, including those that you cannot see — like gravity, electrostatic forces and magnetic forces, which act without contact, and tension and compression, which act inside a material.

Distance and displacement

Distance is a measure of the length of the path taken by an object. It is a scalar quantity.

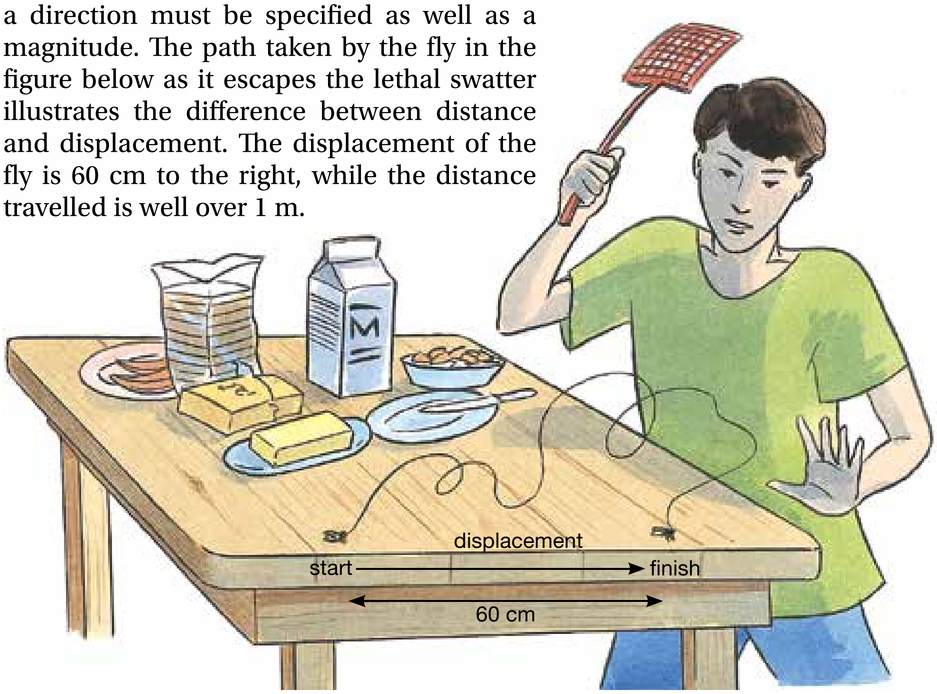
Scalar quantities specify magnitude (size) but not direction.

Displacement is a measure of the change in position of an object. It is a vector quantity.

A **vector** quantity specifies direction as well as magnitude (size).

Distance is a measure of the length of the path taken during the change in position of an object. Distance is a **scalar** quantity. It does not specify a direction.

Displacement is a measure of the change in position of an object. Displacement is a **vector** quantity. In order to describe a displacement fully, a direction must be specified as well as a magnitude. The path taken by the fly in the figure below as it escapes the lethal swatter illustrates the difference between distance and displacement. The displacement of the fly is 60 cm to the right, while the distance travelled is well over 1 m.



Distance and displacement are different quantities.

In a 100 m sprint, the magnitude of the displacement is the same as the distance. However, it is the displacement that fully describes the change in position of the runner because it specifies the direction.

In the case of movement in a straight line, the displacement of an object that has moved from position $\boldsymbol{x}_1$ to position $\boldsymbol{x}_2$ is expressed as:

$$\Delta \boldsymbol{x} = \boldsymbol{x}_2 - \boldsymbol{x}_1.$$

Displacement can also be represented by the symbols $\boldsymbol{x}$ or $\boldsymbol{s}$.

Sample problem 10.1

A hare and a tortoise decide to have a race along a straight 100 m stretch of highway. They both head due north. However, at the 80 m mark, the hare notices his girlfriend back at the 20 m mark. He heads back, gives her a quick kiss on the cheek, and resumes the race, arriving at the finishing line at the same time as the tortoise. (It was a very fast tortoise!)

(a) What was the displacement of the hare during the entire race?
(b) What was the distance travelled by the hare during the race?
(c) What was the distance travelled by the tortoise during the race?
(d) What was the displacement of the hare during his return to his girlfriend?

Solution: (a) Using the start as the reference point, the displacement was 100 m north. In symbols, this calculation can be done by denoting north as positive and south as negative. Thus:

$$\Delta \boldsymbol{x} = \boldsymbol{x}_2 - \boldsymbol{x}_1$$
$$= 100 \text{ m} - 0 \text{ m}$$
$$= 100 \text{ m.} \qquad \text{(representing 100 m north)}$$

(b) The distance is the length of the path taken. The hare travels a total distance of 80 m (before noticing his girlfriend) + 60 m (running back to the 20 m mark) + 80 m (from the 20 m mark to the finishing line). This gives a total of 220 m.

(c) The distance travelled by the tortoise is the length of the path taken, which is 100 m.

(d) The hare returns from a position 80 m north of the reference point (or start) back to a position 20 m north of the reference point. The displacement is 60 m south. Thus:

$$\Delta \boldsymbol{x} = \boldsymbol{x}_2 - \boldsymbol{x}_1$$
$$\Delta \boldsymbol{x} = 20 \text{ m} - 80 \text{ m}$$
$$= -60 \text{ m.} \qquad \text{(representing 60 m south)}$$

Revision question 10.1

(a) A jogger heads due north from his home and runs 400 m along a straight footpath before realising that he has forgotten his sunscreen and runs straight back to get it.
- **(i) What distance has the jogger travelled by the time he gets back home?**
- **(ii) What was the displacement of the jogger when he started to run back home?**
- **(iii) What was his displacement when he arrived back home to pick up the sunscreen?**

(b) A cyclist rides 4.0 km due west from home, then turns right to ride a further 4.0 km due north. She stops, turns back and rides home along the same route.
- **(i) What distance did she travel during the entire ride?**
- **(ii) What was her displacement at the instant that she turned back?**
- **(iii) What was her displacement from the instant that she commenced her return journey until she arrived home?**
- **(iv) What was her total displacement from the time she left home until the time she arrived back home?**

Speed and velocity

Speed is a measure of the rate at which an object moves over a distance. Speed is a scalar quantity.

Speed is a measure of the rate at which an object moves over a distance. When you calculate the speed of a moving object, you need to measure the distance travelled over a time interval.

The average speed of an object can be calculated by dividing the distance travelled by the time taken, that is:

$$\text{average speed} = \frac{\text{distance travelled}}{\text{time interval}}.$$

The speed obtained using this formula is the average speed during the time interval. Speed is a scalar quantity. The unit of speed is m s^{-1} if SI units are used for distance and time. However, it is often more convenient to use other units such as cm s^{-1} or km h^{-1}.

AS A MATTER OF FACT

A snail would lose a race with a giant tortoise! A giant tortoise can reach a top speed of 0.37 km h^{-1}. However, its 'cruising' speed is about 0.27 km h^{-1}. The world's fastest snail covers ground at the breathtaking speed of about 0.05 km h^{-1}. However, the common garden snail is more likely to move at a speed of about 0.02 km h^{-1}. Both of these creatures are slow compared with light, which travels through the air at 1080 million km h^{-1}, and sound, which travels through the air (at sea level) at about 1200 km h^{-1}.

How long would it take the snail, giant tortoise, light and sound respectively to travel once around the equator, a distance of 40 074 km?

Converting units of speed

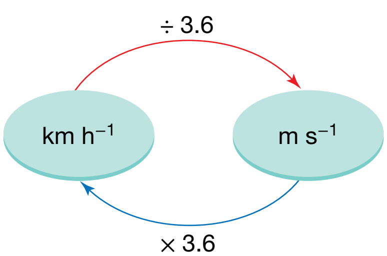
It is often necessary to convert units that are not derived from SI units (such as km h^{-1}) to units that are derived from SI units, such as m s^{-1}.

To convert 60 km h^{-1} to m s^{-1}, the following procedure can be followed.

$$60 \text{ km h}^{-1} = \frac{60 \text{ km}}{1 \text{ h}}$$

$$60 \text{ km h}^{-1} = \frac{60\,000 \text{ m}}{3600 \text{ s}}$$

$$60 \text{ km h}^{-1} = 16.7 \text{ m s}^{-1}$$



In effect, the speed in km h^{-1} has been multiplied by $\frac{1000}{3600}$, or divided by 3.6.

To convert 30 m s^{-1} to km h^{-1}, a similar procedure can be followed.

$$30 \text{ m s}^{-1} = \frac{30 \text{ m}}{1 \text{ s}}$$

$$= \frac{0.030 \text{ km}}{\frac{1}{3600} \text{ h}}$$

$$= \frac{3600 \times 0.030 \text{ km}}{1 \text{ h}}$$

$$= 108 \text{ km h}^{-1}$$

In effect, the speed in m s^{-1} has been multiplied by $\frac{3600}{1000}$, that is, by 3.6.

Sample problem 10.2

A plane carrying passengers from Melbourne to Perth flies at an average speed of 250 m s^{-1}. The flight takes 3.0 hours. Use this information to determine the approximate distance by air between Melbourne and Perth.

Solution:

$$\text{average speed} = \frac{\text{distance travelled}}{\text{time interval}}$$

$\Rightarrow$ distance travelled = average speed × time interval (rearranging)
= 250 m s^{-1} × 3.0 h
= 900 km h^{-1} × 3.0 h (× 3.6 to convert m s^{-1} to km h^{-1})
= 2700 km

Alternatively, the distance could be calculated in metres and then converted to kilometres, a more appropriate unit in this case.

distance travelled = average speed × time interval (rearranging)
= 250 m s^{-1} × 3.0 h
= 250 m s^{-1} × 10 800 s (× 3600 to convert h to s)
= 2 700 000 m
= 2700 km (converting m to km)

Revision question 10.2

(a) A car takes 8.0 hours to travel from Canberra to Ballarat at an average speed of 25 m s^{-1}. What is the road distance from Canberra to Ballarat?

(b) A jogger takes 30 minutes to cover a distance of 5.0 km. What is the jogger's average speed in:

(i) km h^{-1}

(ii) m s^{-1}?

(c) How long does it take for a car travelling at 60 km h^{-1} to cover a distance of 200 m?

Velocity is a measure of the time rate of displacement, or the time rate of change in position. Velocity is a vector quantity.

In everyday language, the word *velocity* is often used to mean the same thing as speed. In fact, velocity is not the same quantity as speed. **Velocity** is a measure of the rate of displacement, or rate of change in position, of an object. Because displacement is a vector quantity, velocity is also a vector quantity. The velocity has the same direction as the displacement. The symbol $\boldsymbol{v}$ is used to denote velocity. (Unfortunately, the symbol $\boldsymbol{v}$ is often used to represent speed as well, which can be confusing.)

The average velocity of an object, $\boldsymbol{v}_{av}$, during a time interval Δt can be expressed as:

$$\boldsymbol{v}_{av} = \frac{\Delta x}{\Delta t}$$

where $\Delta \boldsymbol{x}$ represents the displacement (change in position).

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Investigation 10.1:
Going home
doc-16180

For motion in a straight line in one direction, the magnitude of the velocity is the same as the speed. The motion of the fly in the figure on page 153 illustrates the difference between velocity and speed. If the fly takes 2.0 seconds to complete its flight, its average velocity is:

$$\boldsymbol{v}_{av} = \frac{\Delta x}{\Delta t}$$

$$\boldsymbol{v}_{av} = \frac{60\text{ cm to the right}}{2.0\text{ s}}$$

$$\boldsymbol{v}_{av} = 30\text{ cm s}^{-1}\text{ to the right.}$$

The path taken by the fly is about 180 cm. Its average speed is:

$$\text{average speed} = \frac{\text{distance travelled}}{\text{time interval}}$$

$$\text{average speed} = \frac{180\text{ cm}}{2.0\text{ s}}$$

$$\text{average speed} = 90\text{ cm s}^{-1}.$$

Sample problem 10.3

Calculate the average speed and the average velocity of the hare in Sample problem 10.1 if it takes 20 s to complete the race.

Solution:

$$\text{average speed} = \frac{\text{distance travelled}}{\text{time interval}} = \frac{220\text{ m}}{20\text{ s}} = 11\text{ m s}^{-1}$$

$$\text{average velocity, } \boldsymbol{v}_{av} = \frac{\Delta \boldsymbol{x}}{\Delta t} = \frac{100\text{ m north}}{20\text{ s}} = 5\text{ m s}^{-1}\text{ north}$$

Revision question 10.3

During the final 4.2 km run stage of a triathlon, a participant runs 2.8 km east, then changes direction to run a further 1.4 km in the opposite direction, completing the stage in 20 minutes. What was the participant's:

(a) average speed

(b) average velocity?

Express both answers in m s^{-1}.

study on

Unit 2	**Position–time graph for motion**
AOS 1	Concept summary and practice questions
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Instantaneous speed and velocity — using graphs

Neither the average speed nor the average velocity provide information about movement at any particular instant of time. For example, when Jamaican athlete Usain Bolt broke the 100 m world record in 2009 with a time of 9.58 s, his average speed was 10.4 m s^{-1}. However, he was not travelling at that speed throughout his run. He would have taken a short time to reach his maximum speed and would not have been able to maintain it throughout the run. His maximum speed would have been much more than 10.4 m s^{-1}.

The speed at any particular instant of time is called the **instantaneous speed**. The velocity at any particular instant of time is, not surprisingly, called the **instantaneous velocity**. If an object moves with a constant velocity during a time interval, its instantaneous velocity throughout the interval is the same as its average velocity.

Instantaneous speed is the speed at a particular instant of time.

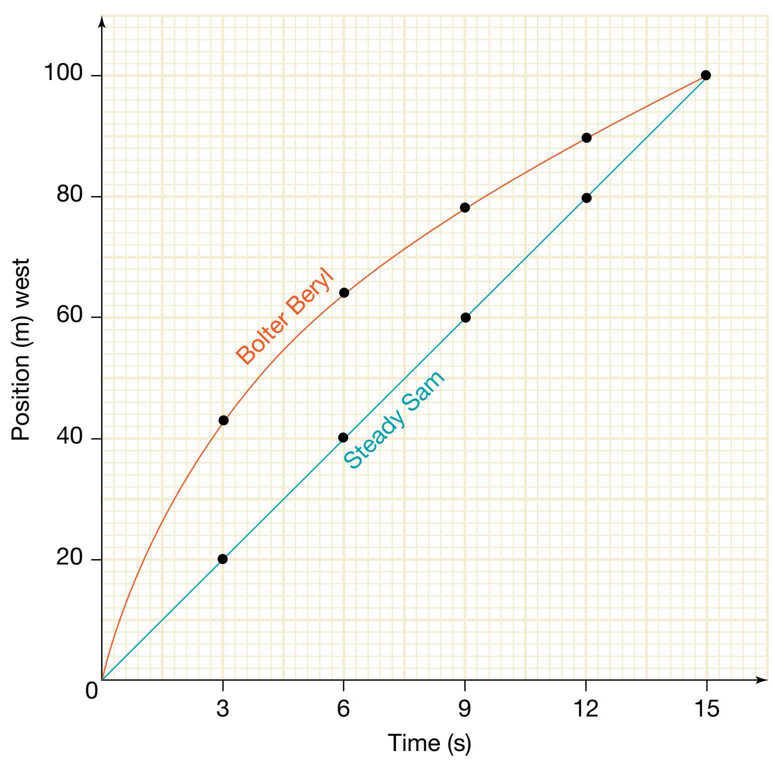
Instantaneous velocity is the velocity at a particular instant of time.

Graphing motion: position versus time

Bolter Beryl and Steady Sam decide to race each other on foot over a distance of 100 m. They run due west. Timekeepers are instructed to record the position of each runner after each 3.0 second interval.

TABLE 10.1 The progress of Bolter Beryl and Steady Sam

Time (seconds)	Position (distance from starting line) in metres: Bolter Beryl	Steady Sam
0.0	0	0
3.0	43	20
6.0	64	40
9.0	78	60
12.0	90	80
15.0	100	100



The graph of position versus time the race was run provides valuable information about the way.

The points indicating Bolter Beryl's position after each 3.0 s interval are joined with a smooth curve. It is reasonable to assume that her velocity changes gradually throughout the race.

A number of observations can be made from the graph of position versus time.

- Both runners reach the finish at the same time. The result is a dead heat. Bolter Beryl and Steady Sam each have the same average speed and the same average velocity.
- Steady Sam, who has an exceptional talent for steady movement, maintains a constant velocity throughout the race. In fact, his instantaneous velocity at every instant throughout the race is the same as his average velocity. Steady Sam's average velocity and instantaneous velocity are both equal to the gradient of the position-versus-time graph since:

$$\boldsymbol{v}_{av} = \frac{\Delta x}{\Delta t}$$

$$\boldsymbol{v}_{av} = \frac{100\,\text{m west}}{15\,\text{s}}$$

$$\boldsymbol{v}_{av} = \frac{\text{rise}}{\text{run}}$$

$$\boldsymbol{v}_{av} = \text{gradient.}$$

  Steady Sam's velocity throughout the race is 6.7 m s^{-1} west.
- Bolter Beryl, in her usual style, makes a flying start; however, after her initial 'burst', her instantaneous velocity decreases throughout the race as she tires. Her average velocity is also 6.7 m s^{-1} west.

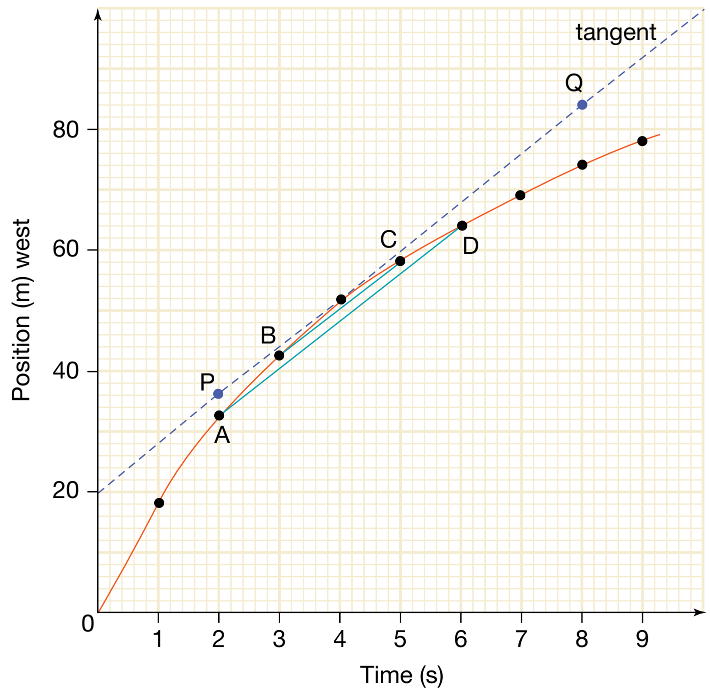
A more detailed description of Bolter Beryl's motion can be given by calculating her average velocity during each 3 s interval of the race (see the table below).

TABLE 10.2 Bolter Beryl's changing velocity

Time interval (s)	Displacement Δx (m west)	Average velocity during interval $v_{av} = \frac{\Delta x}{\Delta t}$ (m s^{-1} west)
0.0–3.0	43 – 0 = 43	14.0
3.0–6.0	64 – 43 = 21	7.0
6.0–9.0	78 – 64 = 14	4.7
9.0–12.0	90 – 78 = 12	4.0
12.0–15.0	100 – 90 = 10	3.3

The average velocity during each interval is the same as the gradient of the straight line joining the data points representing the beginning and end of the interval. An even more detailed description of Bolter Beryl's run could be obtained if the race was divided into, say, 100 time intervals. The average velocity during each time interval (and the gradient of the line joining the data points defining it) would be a very good estimate of the instantaneous velocity in the middle of the interval. In fact, if the race is progressively divided into smaller and smaller time intervals, the average velocity during each interval would become closer and closer to the instantaneous velocity in the middle of the interval.

The graph below shows how this process of using smaller time intervals can be used to find Bolter Beryl's instantaneous velocity at an instant 4.0 seconds from the start of the race. Her instantaneous velocity is not the same as the average velocity during the 3.0 to 6.0 s time interval shown in table 10.2. However, it can be estimated by drawing the line AD and finding its gradient. The gradient of the line BC would provide an even better estimate of the instantaneous velocity. If you continue this process of decreasing the time interval used to estimate the instantaneous velocity, you will eventually obtain a line which is a tangent to the curve. The gradient of the tangent to the curve is equal to the instantaneous velocity at the instant represented by the point at which it meets the curve.



The first 9.0 seconds of Bolter Beryl's run

The gradient of the tangent to the curve at 4.0 seconds in the figure above can be determined by using the points P and Q.

$$\begin{aligned} \text{gradient} &= \frac{\text{rise}}{\text{run}} \\ &= \frac{(84-36)\text{ m}}{(8.0-2.0)\text{ s}} \\ &= \frac{48\text{ m}}{6.0\text{ s}} \\ &= 8.0\text{ m s}^{-1} \end{aligned}$$

Bolter Beryl's instantaneous velocity at 4.0 seconds from the start of the race is therefore 8.0 m s^{-1} west.

Just as the gradient of a position-versus-time graph can be used to determine the velocity of an object, a graph of distance versus time can be used to determine its speed. Because Bolter Beryl and Steady Sam were running in a straight line and in one direction only, their distance from the starting point is the magnitude of their change in position. Their speed is equal to the magnitude of their velocity.

Graphing motion: velocity versus time

The race between Bolter Beryl and Steady Sam described by the position-versus-time graph on page 157 can also be described by a graph of velocity versus time. Steady Sam's velocity is 6.7 m s^{-1} due west throughout the race. The curve describing Bolter Beryl's motion can be plotted by determining the instantaneous velocity at various times during the race. This can be done by drawing tangents at a number of points on the position-versus-time graph on page 157. Table 10.3 shows the data obtained using this method. The velocity-versus-time graph below describes the motion of Bolter Beryl and Steady Sam.

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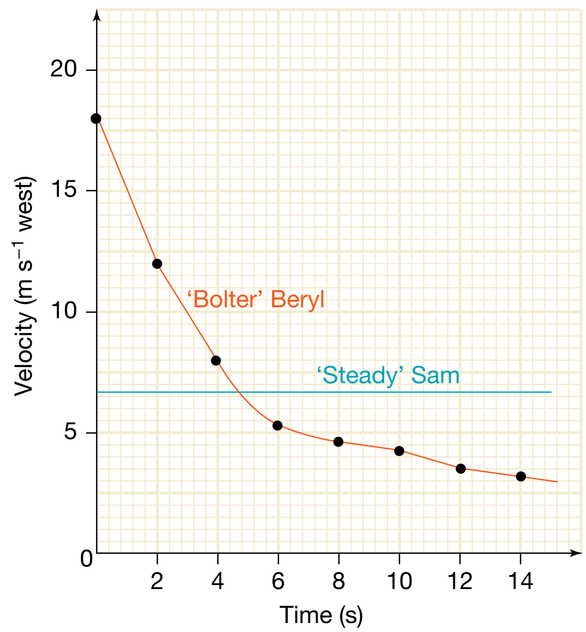
TABLE 10.3 Beryl's velocity during the race

Time (s)	Velocity (m s^{-1} west)
0.0	18.0
2.0	12.0
4.0	8.0
6.0	5.4
8.0	4.7
10.0	4.2
12.0	3.5
14.0	3.1



Graph of velocity versus time for the race

The velocity-versus-time graph confirms what you already knew by looking at the position-versus-time graph, namely that:

- Steady Sam's velocity is constant, and equal to his average velocity
- the magnitude of Bolter Beryl's velocity is decreasing throughout the race.

The velocity-versus-time graph allows you to estimate the velocity of each runner at any time. It provides a much clearer picture of the way that Bolter Beryl's velocity changes during the race, namely that:

- the magnitude of her velocity decreases rapidly at first, but less rapidly towards the end of the race
- for most of the duration of the race, she is running more slowly than Sam. In fact Bolter Beryl's speed (the magnitude of her velocity) drops below that of Steady Sam's after only 4.7 seconds.

study on

Unit 2	**Velocity–time graphs** Concept summary and practice questions
AOS 1	
Topic 1	
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Displacement from a velocity-versus-time graph

In the absence of a position-versus-time graph, a velocity-versus-time graph provides useful information about the change in position, or displacement, of an object. Steady Sam's constant velocity, the same as his average velocity, makes it very easy to determine his displacement during the race.

$$\Delta \boldsymbol{x} = \boldsymbol{v}_{av}\,\Delta t \qquad \left(\text{since } \boldsymbol{v}_{av} = \frac{\Delta \boldsymbol{x}}{\Delta \boldsymbol{t}}\right)$$

$$\Delta \boldsymbol{x} = 6.7\ \text{m s}^{-1}\ \text{west} \times 15\ \text{s}$$

$$\Delta \boldsymbol{x} = 100\ \text{m west}$$

This displacement is equal to the area of the rectangle under the graph depicting Steady Sam's motion.

$$\text{area} = \text{length} \times \text{width}$$
$$= 15 \text{ s} \times 6.7 \text{ m s}^{-1} \text{ west}$$
$$= 100 \text{ m west}$$

Because the race was a dead heat, Bolter Beryl's average velocity was also 6.7 m s^{-1}. Her displacement during the race can be calculated in the same way as Steady Sam's.

$$\Delta \boldsymbol{x} = \boldsymbol{v}_{av} \Delta t$$
$$= 6.7 \text{ m s}^{-1} \times 15 \text{ s}$$
$$= 100 \text{ m west}$$

However, Bolter Beryl's displacement can also be found by calculating the area under the velocity-versus-time graph depicting her motion. This can be done by 'counting squares' or by dividing the area under the graph into rectangles and triangles as shown in the 'As a matter of fact' panel below. The area under Beryl's velocity-versus-time graph is, not surprisingly, 100 m.

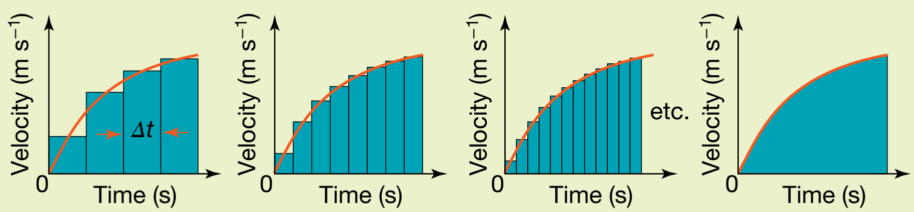
In fact, the area under any part of the velocity-versus-time graph is equal to the displacement during the interval represented by that part.

AS A MATTER OF FACT

When an object travels with a constant velocity, it is obvious that the displacement of the object is equal to the area under a velocity-versus-time graph of its motion. However, it is not so obvious when the motion is not constant. The graphs below describe the motion of an object that has an increasing velocity. The motion of the object can be approximated by dividing it into time intervals of Δt and assuming that the velocity during each time interval is constant. The approximate displacement during each time interval is equal to:

$$\Delta \boldsymbol{x} = \boldsymbol{v}_{av} \Delta t$$

which is the same as the area under each rectangle. The approximate total displacement is therefore equal to the total area of the rectangles.



By dividing the velocity-versus-time graph into rectangles representing small time intervals, the displacement can be estimated.

To better approximate the displacement, the graph can be divided into smaller time intervals. The total area of the rectangles is approximately equal to the displacement. By dividing the graph into even smaller time intervals, even better estimates of the displacement can be made. In fact, by continuing the process of dividing the graph into smaller and smaller time intervals, it can be seen that the displacement is, in fact, equal to the area under the graph.

Sample problem 10.4

In the race between Bolter Beryl and Steady Sam, how far ahead of Steady Sam was Bolter Beryl when her speed dropped below Sam's speed?

Solution: Although it is possible to answer this question using the position-versus-time graph on page 157 (you might like to explain how you would do this!), it is easier to use the velocity-versus-time graph (see the graph on page 160). It shows that Beryl's speed (and the magnitude of her velocity) drops below Steady Sam's 4.7 s after the race starts.

Steady Sam's displacement, after 4.7 s, is equal to the area under the line representing the first 4.3 s of his motion, that is, 4.7 s × 6.7 m s^{-1} west. Steady Sam is therefore 31 m west of the starting line after 4.7 s.

Bolter Beryl's displacement after 4.7 s equals the area under the curve representing the first 4.7 s of her motion. This area can be estimated by determining the shaded area of the triangle P and rectangle Q in the figure below.

$$\begin{aligned}\text{area} &= \text{area P} + \text{area Q}\\ &= \tfrac{1}{2} \times 4.7\,\text{s} \times 11\,\text{m s}^{-1}\text{ west} + 4.7\,\text{s} \times 6.5\,\text{m s}^{-1}\text{ west}\\ &= 25.85\text{ m west} + 30.55\text{ m west}\\ &= 56.40\text{ m west}\end{aligned}$$

Bolter Beryl is therefore 56 m west of the starting line after 4.7 seconds. She is 25 m ahead of Steady Sam when her speed drops below his.

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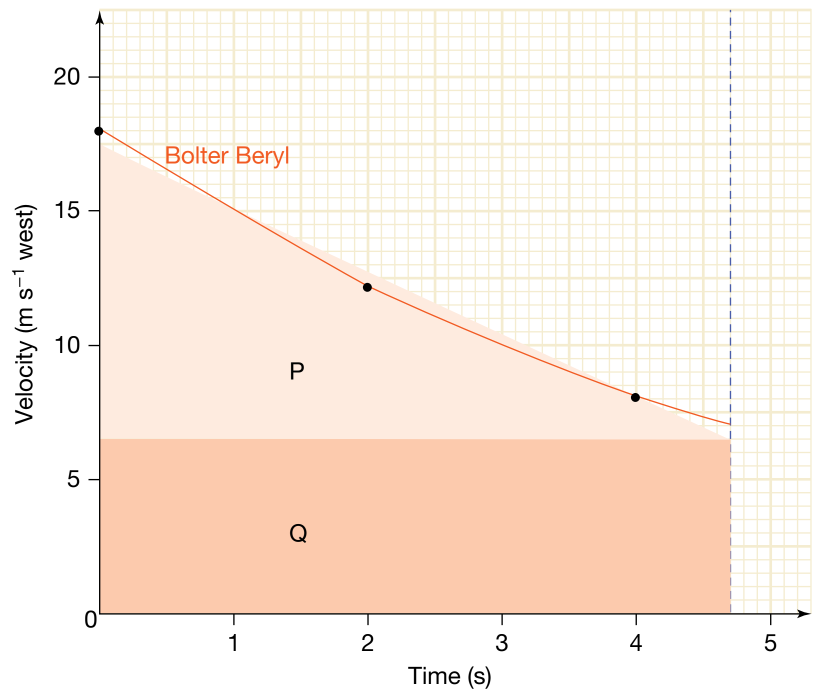

Revision question 10.4

(a) **Use the graph above to estimate Bolter Beryl's displacement after 2.0 s.**

(b) **Use the graph on page 160 to determine how far ahead Bolter Beryl was 10 seconds into the race.**

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Unit 2 | **AOS 1** | **Topic 1** | **Concept 3**

Acceleration
Concept summary and practice questions

Acceleration is the rate of change of velocity.

Acceleration

When the velocity of an object changes, as it does in Bolter Beryl's run (see page 160), it is helpful to describe it in terms of the rate at which the velocity is changing. In everyday language, the word *accelerate* is used to mean 'speed up'. The word *decelerate* is used to mean 'slow down'. However, if you wish to describe motion precisely, these words are not adequate. The rate at which an object changes its velocity is called its **acceleration**. Acceleration is a vector quantity.

A car starting from rest and reaching a velocity of 60 km h^{-1} north in 5 s has an average acceleration of 12 km h^{-1} per second or 12 (km h^{-1})s^{-1} north. This is expressed in words as 12 km per hour per second. In simple terms, it means that the car increases its speed in a northerly direction by an average of 12 km h^{-1} each second.

The average acceleration of an object, $\boldsymbol{a}_{\text{av}}$, can be expressed as:

$$\boldsymbol{a}_{\text{av}} = \frac{\Delta \boldsymbol{v}}{\Delta t}$$

where $\Delta \boldsymbol{v}$ = the change in velocity during the time interval Δt.

The direction of the average acceleration is the same as the direction of the change in velocity.

Sample problem 10.5

Spiro leaves home on his bicycle to post a letter to his sweetheart, Ying. He starts from rest and reaches a speed of 10 m s^{-1} in 4.0 s. He then cycles at a constant speed in a straight line to a letterbox. He brakes at the letterbox, coming to a stop in 2.0 s, posts the letter and returns home at a constant speed of 8.0 m s^{-1}. (He's tired!) On reaching home, he brakes, coming to rest in 2.0 s. The direction away from home towards the letterbox is assigned as positive.

(a) What is Spiro's average acceleration before he reaches his 'cruising speed' of 10 m s^{-1} on the way to the letterbox?
(b) What is Spiro's average acceleration as he brakes at the letterbox?
(c) What is Spiro's average acceleration as he brakes when arriving home?
(d) During which two parts of the trip is Spiro's acceleration negative?
(e) Does a positive acceleration always mean that the speed is increasing? Explain.

Solution: It is a good idea to start by sketching a graph describing the motion. In this case a velocity-versus-time graph would be appropriate. Although these questions can be answered without a graph, a graph provides an overview of the motion and allows you to check that your answers make sense.

(a) $$\boldsymbol{a}_{\text{av}} = \frac{\Delta \boldsymbol{v}}{\Delta t} = \frac{+10\,\text{m s}^{-1}}{4.0\,\text{s}} = +2.5\,\text{m s}^{-2}$$

(b) $$\boldsymbol{a}_{\text{av}} = \frac{\Delta \boldsymbol{v}}{\Delta t} = \frac{-10\,\text{m s}^{-1}}{2.0\,\text{s}} = -5.0\,\text{m s}^{-2}$$

(c) $a_{av} = \dfrac{\Delta v}{\Delta t}$

$= \dfrac{+8.0\text{ m s}^{-1}}{2.0\text{ s}}$

(Take care here! Spiro's velocity changes from −8.0 m s^{-1} to zero. That is a change of *positive* 8.0 m s^{-1}.)

$= 4.0\text{ m s}^{-2}$

(d) Spiro's acceleration is negative while he brakes at the letterbox and when he sets off from the letterbox towards home.

(e) No. Spiro's acceleration is positive while his velocity is increasing in the positive direction. This occurs when he increases his speed as he leaves home and also when he decreases his speed as he returns home. A decreasing speed in the negative direction corresponds to a change in velocity in the positive direction.

Revision question 10.5

(a) A cheetah (the fastest land animal) takes 2.0 s to reach its maximum speed of 30 m s^{-1}. What is the magnitude of its average acceleration?

(b) A drag-racing car reaches a speed of 420 km h^{-1} from a standing start in 6.0 s. What is its average acceleration in:
 (i) km h^{-1} s^{-1}
 (ii) m s^{-2}?

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Motion with constant acceleration
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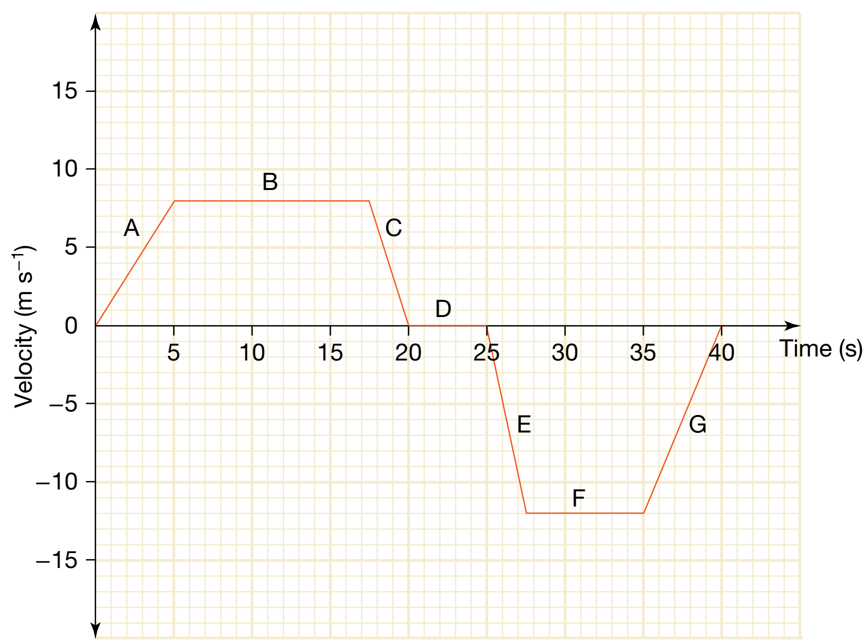
Ball toss
eles-0031

Acceleration from a velocity-versus-time graph

The graph that follows describes the motion of an elevator as it moves from the ground floor to the top floor and back down again. The elevator stops briefly at the top floor to pick up a passenger. For convenience, any upward displacement from the ground floor is defined as positive. The graph has been divided into seven sections labelled A–G.



The motion of an elevator

The acceleration at any instant during the motion can be determined by calculating the gradient of the graph. This is a consequence of the definition of acceleration. The gradient of a velocity-versus-time graph is a measure of the rate of change of velocity just as the gradient of a position-versus-time graph is a measure of the rate of change of position.

Throughout interval A (see the graph), the acceleration, $\boldsymbol{a}$, of the elevator is:

$$\begin{aligned}\boldsymbol{a} &= \frac{\text{rise}}{\text{run}} \\ &= \frac{+8.0\ \text{m s}^{-1}}{5.0\ \text{s}} \\ &= +1.6\ \text{m s}^{-2} \text{ or } 1.6\ \text{m s}^{-2} \text{ up.}\end{aligned}$$

During intervals B, D and F, the velocity is constant and the gradient of the graph is zero. The acceleration during each of these intervals is, therefore, zero.

Throughout interval C, the acceleration is:

$$\begin{aligned}\boldsymbol{a} &= \frac{-8.0\ \text{m s}^{-1}}{2.5\ \text{s}} \\ &= -3.2\ \text{m s}^{-2} \text{ or } 3.2\ \text{m s}^{-2} \text{ down.}\end{aligned}$$

Throughout interval E, the acceleration is:

$$\begin{aligned}\boldsymbol{a} &= \frac{-12\ \text{m s}^{-1}}{2.5\ \text{s}} \\ &= -4.8\ \text{m s}^{-2} \text{ or } 4.8\ \text{m s}^{-2} \text{ down.}\end{aligned}$$

Throughout interval G, the acceleration is:

$$\begin{aligned}\boldsymbol{a} &= \frac{+12\ \text{m s}^{-1}}{5.0\ \text{s}} \\ &= +2.4\ \text{m s}^{-2} \text{ or } 2.4\ \text{m s}^{-2} \text{ up.}\end{aligned}$$

Notice that during interval G the acceleration is positive (up) while the velocity of the elevator is negative (down). The direction of the acceleration is the same as the direction of the *change* in velocity.

The area under the graph is equal to the displacement of the elevator. Dividing the area into triangles and rectangles and working from left to right yields an area of:

$$\begin{aligned}&\left(\tfrac{1}{2} \times 5.0\ \text{s} \times 8.0\ \text{m s}^{-1}\right) + \left(12.5\ \text{s} \times 8.0\ \text{m s}^{-1}\right) + \left(\tfrac{1}{2} \times 2.5\ \text{s} \times 8.0\ \text{m s}^{-1}\right) + \\ &\left(\tfrac{1}{2} \times 2.5\ \text{s} \times -12\ \text{m s}^{-1}\right) + \left(7.5\ \text{s} \times -12\ \text{m s}^{-1}\right) + \left(\tfrac{1}{2} \times 5.0\ \text{s} \times -12\ \text{m s}^{-1}\right) \\ &= 20\ \text{m} + 100\ \text{m} + 10\ \text{m} - 15\ \text{m} - 90\ \text{m} - 30\ \text{m} \\ &= -5.0\ \text{m.}\end{aligned}$$

This represents a downwards displacement of 5.0 m, which is consistent with the elevator finally stopping two floors below the ground floor.

Area under an acceleration-versus-time graph

Just as the area under a velocity-versus-time graph is equal to the change in position of an object, the area under an acceleration-versus-time graph is equal to the change in velocity of an object. The acceleration-versus-time graph of the motion of the elevator described previously is shown in the graph on the following page. The area under the part of the graph representing the entire upwards part of the journey is given by:

$$\begin{aligned}\text{area A} + \text{area C} &= 5.0\ \text{s} \times 1.6\ \text{m s}^{-2} + 2.5\ \text{s} \times -3.2\ \text{m s}^{-2} \\ &= +8.0\ \text{m s}^{-1} + -8.0\ \text{m s}^{-1} \\ &= 0.\end{aligned}$$

This indicates that change in velocity during the upward journey is zero. This is consistent with the fact that the elevator starts from rest and is at rest when it reaches the top floor. Similarly, the area under the whole graph is zero.

The change in velocity during intervals C, D and E is given by the sum of areas C, D and E. Thus:

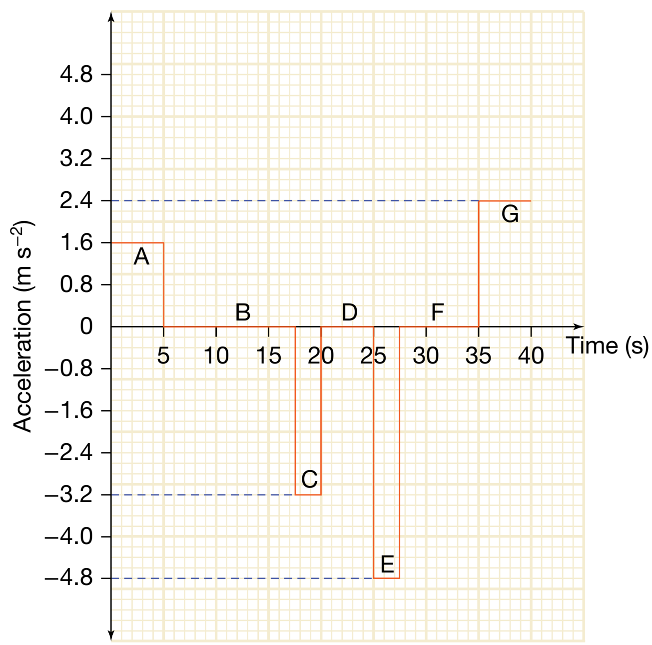
$$\begin{aligned}\text{area C} + \text{area D} + \text{area E} &= 2.5\ \text{s} \times -3.2\ \text{m s}^{-2} + 0 + 2.5\ \text{s} \times -4.8\ \text{m s}^{-2}\\ &= -8.0\ \text{m s}^{-1} + -12\ \text{m s}^{-1}\\ &= -20\ \text{m s}^{-1}.\end{aligned}$$

The change in velocity is -20 m s^{-1}, or 20 m s^{-1} down.

At the beginning of time interval C, the velocity was 8.0 m s^{-1} upwards. A change of velocity of -20 m s^{-1} would result in a final velocity of 12 m s^{-1} downwards. This is consistent with the description of the motion in the velocity-versus-time graph on page 162. The symbol $\boldsymbol{u}$ is used to denote the initial velocity, while the symbol $\boldsymbol{v}$ is used to denote the final velocity:

In symbols, therefore:

$$\begin{aligned}\boldsymbol{v} &= \boldsymbol{u} + \Delta\boldsymbol{u} \qquad (\text{since } \Delta\boldsymbol{v} = \boldsymbol{v} - \boldsymbol{u})\\ &= +8.0\ \text{m s}^{-1} + -20\ \text{m s}^{-1}\\ &= -12\ \text{m s}^{-1}.\end{aligned}$$



An acceleration-versus-time graph for the elevator

Graphing motion in a nutshell

Position-versus-time graphs

- The instantaneous velocity of an object can be obtained from a graph of the object's position versus time by determining the gradient of the curve at the point representing that instant. This is a direct consequence of the fact that velocity is a measure of the rate of change of position.
- Similarly, the instantaneous speed of an object can be obtained by determining the gradient of a graph of the object's distance travelled from a reference point versus time.

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Velocity-versus-time graphs

- The displacement of an object during a time interval can be obtained by determining the area under the velocity-versus-time graph representing that time interval. The actual position of an object at any instant during the time interval can be found only if the starting position is known.
- Similarly, the distance travelled by an object during a time interval can be obtained by determining the corresponding area under the speed-versus-time graph for the object.
- The instantaneous acceleration of an object can be obtained from a graph of the object's velocity versus time by determining the gradient of the curve at the point representing that instant. This is a direct consequence of the fact that acceleration is defined as the rate of change of velocity.

Acceleration-versus-time graphs

- The change in velocity of an object during a time interval can be obtained by determining the area under the acceleration-versus-time graph representing that time interval. The actual velocity of the object can be found at any instant during the time interval only if the initial velocity is known.

AS A MATTER OF FACT

A non-zero acceleration does not always result from a change in speed. Consider a car travelling at 60 km h^{-1} in a northerly direction turning right and continuing in an easterly direction at the same speed. Assume that the complete turn takes 10 s. The average acceleration during the time interval of 10 seconds is given by:

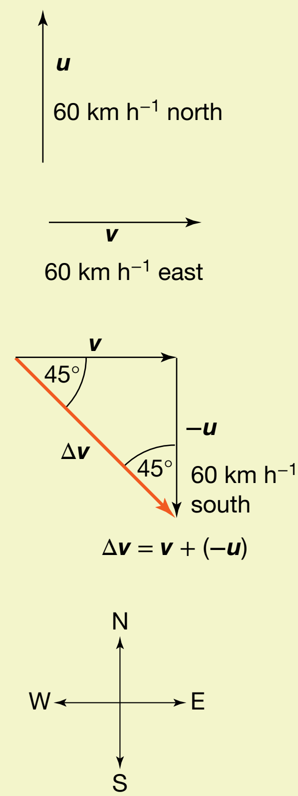
$$\boldsymbol{a}_{av} = \frac{\Delta \boldsymbol{v}}{\Delta t}.$$

The change in velocity must be determined first. Thus,

$$\Delta \boldsymbol{v} = \boldsymbol{v} - \boldsymbol{u}$$
$$= \boldsymbol{v} + -\boldsymbol{u}.$$

The vectors $\boldsymbol{v}$ and $-\boldsymbol{u}$ are added together to give the resulting change in velocity.

The magnitude of the change in velocity is calculated using Pythagoras' theorem or trigonometric ratios to be 85 km h^{-1}. Alternatively, the vectors can be added using a scale drawing and then measuring the magnitude and direction of the sum. The direction of the change in velocity can be seen in the figure at right to be south-east.



$$\boldsymbol{a}_{av} = \frac{\Delta \boldsymbol{v}}{\Delta t}$$
$$= \frac{85\ \text{km h}^{-1}\ \text{south-east}}{10\ \text{s}}$$
$$= 8.5\ \text{km h}^{-1}\ \text{s}^{-1}\ \text{south-east}$$

In fact, the direction of the average acceleration is the same as the direction of the average net force on the car during the 10 s interval. The steering wheel is used to turn the wheels to cause the net force to be in this direction. For more information on vectors, go to appendix 2.

A change in acceleration can occur even if there is no change in speed.

study on

Unit 2 | AOS 1 | Topic 1 | Concept 5

Motion with constant acceleration
Concept summary and practice questions

Constant acceleration without graphs

In the absence of a graphical representation, a number of formulae can be used to describe straight-line motion as long as the acceleration is constant. These formulae are expressed in terms of the quantities used to describe such motion. The terms are:

- initial velocity, u
- final velocity, v
- acceleration, a
- time interval, t
- displacement, s.

Because the formulae describe motion along a straight line, vector notation is not necessary. The displacement, velocity and acceleration can be expressed as positive or negative quantities.

The first formula is found by restating the definition of acceleration.

$$\boldsymbol{a} = \frac{\Delta \boldsymbol{v}}{\Delta t}$$

where

$\Delta v =$ the change in velocity

$\Delta t =$ the time interval.

Thus,

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

$$\Rightarrow \quad v - u = at$$

$$\Rightarrow \quad v = u + at \qquad [1]$$

The second formula is found by restating the definition of average velocity.

$$v_{\text{av}} = \frac{\Delta s}{\Delta t}$$

where $\Delta s =$ the change in position.

But $\quad v_{\text{av}} = \dfrac{u+v}{2}.$

Thus,

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

$$\Rightarrow \quad s = \tfrac{1}{2}(u+v)t. \qquad [2]$$

Three more formulae are obtained by combining formulae [1] and [2].

$$s = \tfrac{1}{2}(u + u + at)t$$ (substituting $v = u + at$ from formula [1] into formula [2])

$$= \tfrac{1}{2}(2u + at)t$$

$$= \left(u + \tfrac{1}{2}at\right)t$$

$$\Rightarrow \quad s = ut + \tfrac{1}{2}at^2 \qquad [3]$$

$$s = \tfrac{1}{2}(v - at + v)t$$ (substituting $u = v - at$ from formula [1] into formula [2])

$$= \tfrac{1}{2}(2v - at)t$$

$$= \left(v - \tfrac{1}{2}at\right)t$$

$$\Rightarrow \quad s = vt - \tfrac{1}{2}at^2 \qquad [4]$$

A final formula can be found by eliminating t from formula [2].

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

But $t = \frac{v-u}{a}$. (rearranging formula [1])

$$\Rightarrow \quad s = \tfrac{1}{2}(u+v)\left(\frac{v-u}{a}\right)$$

$$= \tfrac{1}{2}\,\frac{v^2 - u^2}{a}$$ (expanding the difference of two squares)

$$\Rightarrow \quad 2as = v^2 - u^2$$

$$\Rightarrow \quad v^2 = u^2 + 2as \qquad [5]$$

In summary, the formulae for straight-line motion are:

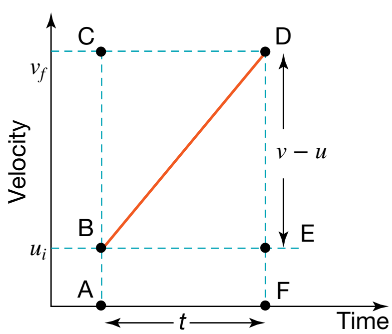
$$v = u + at \qquad [1]$$

$$s = \tfrac{1}{2}(u + v)t \qquad [2]$$

$$s = ut + \tfrac{1}{2}at^2 \qquad [3]$$

$$s = vt - \tfrac{1}{2}at^2 \qquad [4]$$

$$v^2 = u^2 + 2as \qquad [5]$$



A velocity-versus-time graph for an object travelling in a straight line with constant acceleration

Each of the five formulae derived here allow you to determine an unknown characteristic of straight-line motion with a constant acceleration as long as you know three other characteristics. Although the formulae have not been derived from graphs, they are entirely consistent with a graphical approach.

acceleration = gradient

$$= \frac{\text{rise}}{\text{run}}$$

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

$$\Rightarrow \quad a = v - \frac{u}{t}$$

$$\Rightarrow \quad v = u + at \qquad [1]$$

displacement = area under graph

= area of trapezium ABDF

$$= \tfrac{1}{2}(u+v)t \qquad [2]$$

displacement = area under graph

= area of rectangle ABEF + area of triangle BDE

$$= ut + \tfrac{1}{2}t \times at \qquad (v - u = at \text{ from } [1])$$

$$= ut + \tfrac{1}{2}at^2 \qquad [3]$$

displacement = area under graph

= area of rectangle ACDF – area of triangle BCD

$$= vt - \tfrac{1}{2} \times t \times at \qquad (v - u = at \text{ from } [1])$$

$$= vt - \tfrac{1}{2}at^2 \qquad [4]$$

Formula [5] can be derived by combining formula [1] with any of formulae [2], [3] or [4].

Sample problem 10.6

Ying (hopelessly in love with Spiro) drops a coin into a wishing well and takes 3.0 s to make a wish. The coin splashes into the water just as she finishes making her wish. The coin accelerates towards the water at a constant 10 m s^{-2}.

(a) What is the coin's velocity as it strikes the water?

(b) How far does the coin fall before hitting the water?

Solution: (a) $v = ?$

$u = 0$, $a = 10$ m s^{-2}, $t = 3.0$ s (assigning down as positive)

The appropriate formula here is $v = u + at$ because it includes the three known quantities and the unknown quantity v.

$$v = 0 \text{ m s}^{-1} + 10 \text{ m s}^{-2} \times 3.0 \text{ s}$$
$$= 30 \text{ m s}^{-1}$$

The coin is travelling at a velocity of 30 m s^{-1} down as it strikes the water.

(b) $s = ?$

The appropriate formula here is $s = ut + \frac{1}{2}at^2$ because it includes the three known quantities along with the unknown quantity s.

$$s = 0 + \tfrac{1}{2} \times 10 \text{ m s}^{-2} \times (3.0 \text{ s})^2$$
$$= 45 \text{ m}$$

The coin experiences a displacement of 45 m down during the fall.

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Revision question 10.6

A parked car with the handbrake off rolls down a hill in a straight line with a constant acceleration of 2.0 m s^{-2}. It stops after colliding with a brick wall at a speed of 12 m s^{-1}.

(a) For how long was the car rolling?

(b) How far did the car roll before colliding with the wall?

Sample problem 10.7

The driver of a car was forced to brake in order to prevent serious injury to a neighbour's cat. The car skidded in a straight line, stopping just 2 cm short of the startled but lucky cat. The driver (who happened to be a physics teacher) measured the length of the skid mark to be 12 m. His passenger (also a physics teacher with an exceptional skill for estimating small time intervals) estimated that the car skidded for 2.0 seconds.

(a) At what speed was the car travelling as it began to skid?

(b) What was the acceleration of the car during the skid?

Solution: (a) $u = ?$

$s = 12$ m, $t = 2.0$ s, $v = 0$ (assigning forward as positive)

The appropriate formula here is:

$$s = \tfrac{1}{2}(u + v)t$$
$$12 \text{ m} = \tfrac{1}{2}(u + 0)2.0 \text{ s}$$
$$u = 12 \text{ m s}^{-1}. \text{ (rearranging and solving in one step)}$$

The car was travelling at a speed of 12 m s^{-1}, about 43 km h^{-1}.

(b) $a = ?$

The appropriate formula here is $s = vt - \frac{1}{2}at^2$. Note that it is better to use the given data rather than calculated data. That way, if an error is made in an earlier part of the question, it will not affect this answer.

$$s = vt - \tfrac{1}{2}at^2$$

$$12\text{ m} = 0 - \tfrac{1}{2}a(2.0\text{ s})^2$$

$$\Rightarrow \quad 12\text{ m} = -2.0\text{ s}^2 \times a$$

$$\Rightarrow \quad a = \frac{-12\text{ m}}{2.0\text{ s}}$$

$$= -6.0\text{ m s}^{-2}$$

The car's acceleration was -6.0 m s^{-2}. In other words, it slowed down at the rate of 6.0 m s^{-1} each second.

Revision question 10.7

A car travelling at 24 m s^{-1} brakes to come to a stop in 1.5 s. If its acceleration (deceleration in this case) was constant, what was the car's:

(a) stopping distance

(b) acceleration?

It is worth noting that sample problems 10.6 and 10.7 could both have been solved without the use of the constant acceleration formulae. Both examples could have been completed with a graphical approach and a clear understanding of the definitions of velocity and acceleration. Why not go ahead and try to answer both problems without the formulae?

Practical investigations

- Place a small ruler over the edge of a desk. Hit the end so that it flies away. How far does it travel horizontally? What factors might affect this, and how? Investigate.
- How does the initial acceleration of a sprinter depend on the spacing between their feet on the blocks?
- Fill a bottle with some liquid. Lay it down on its side and give it a push. The bottle may first move forward and then oscillate before it comes to rest. Investigate the bottle's motion.
- Make a small parachute out of a piece of cloth, lengths of cotton and Blu-Tack. Drop it with the canopy open. The parachute accelerates, then maintains a steady speed. Investigate the motion and what factors affect the initial acceleration and the final speed.

Chapter review

Summary

- Displacement is a measure of the change in position of an object. Displacement is a vector quantity.
- In order to fully describe any vector quantity, a direction must be specified as well as a magnitude.
- Speed is a measure of the rate at which an object moves over distance and is a scalar quantity. Velocity is the rate of displacement and is a vector quantity.
- Average speed $= \dfrac{\text{distance travelled}}{\text{time interval}}$
- Average velocity $= \dfrac{\text{displacement}}{\text{time interval}}$. The average velocity of an object, $\boldsymbol{v}_{av}$, during a time interval, t, can be expressed as $\boldsymbol{v}_{av} = \dfrac{\Delta s}{\Delta t}$.
- Instantaneous speed is the speed at a particular instant of time. Instantaneous velocity is the velocity at a particular instant of time.
- The instantaneous velocity of an object can be found from a graph of its displacement versus time by calculating the gradient of the graph. Similarly, the instantaneous speed can be found from a graph of distance versus time by calculating the gradient of the graph.
- The displacement of an object during a time interval can be found by determining the area under its velocity-versus-time graph. Similarly, the distance travelled by an object can be found by determining the area under its speed-versus-time graph.
- Acceleration is the rate at which an object changes its velocity. Acceleration is a vector quantity. The average acceleration of an object, $\boldsymbol{a}_{av}$, can be expressed as $\boldsymbol{a}_{av} = \dfrac{\Delta \boldsymbol{v}}{\Delta t}$ where $\Delta \boldsymbol{v}$ = the change in velocity during the time interval Δt.
- The instantaneous acceleration of an object can be found from a graph of its velocity versus time by calculating the gradient of the graph.
- When acceleration of an object is constant, the following formulae can be used to describe its motion:

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

Questions

Describing movement

1. Which of the following are vector quantities?
   (a) distance
   (b) displacement
   (c) speed
   (d) velocity
   (e) acceleration
2. On the planet Znab, a Znabbian ran a distance of 5 znotters north, turned left and ran 12 znotters west. The total time taken was 6.5 znitters.
   (a) What distance was travelled by the Znabbian?
   (b) What was the displacement of the Znabbian?
   (c) Determine the average velocity and average speed of the Znabbian.
   (d) What is the unit of acceleration on the planet Znab?
3. The speed limit on Melbourne's suburban freeways is 100 km h^{-1}. Express this speed in m s^{-1}.
4. Leisel Jones's average speed while swimming a 100 m breaststroke race is about 1.5 m s^{-1}. Calculate what her average speed would be in km h^{-1}.
5. The speed limit on US freeways is 55 miles per hour. Express this speed in:
   (a) km h^{-1}
   (b) m s^{-1}.
   One mile is approximately equal to 1.6 km.
6. The world records for some men's track events (as at early 2015) are listed in the table below.

TABLE 10.4 World records for men's track events

Athlete	Event	Time
Usain Bolt (Jamaica)	100 m	9.58 s
Usain Bolt (Jamaica)	200 m	19.19 s
Michael Johnson (USA)	400 m	43.18 s
David Rudisha (Kenya)	800 m	1 min 40.91 s
Hicham el Guerrouj (Morocco)	1 500 m	3 min 26.00 s
Daniel Komen (Kenya)	3 000 m	7 min 20.67 s
Kenenisa Bekele (Ethiopia)	5 000 m	12 min 37.35 s
Kenenisa Bekele (Ethiopia)	10 000 m	26 min 17.53 s

   (a) Calculate the average speed (to three significant figures) of each of the athletes listed in the table.

(b) Why is there so little difference between the average speeds of the world-record holders of the 100 m and 200 m events despite the doubling of the distance?
(c) How long would it take Hicham el Guerrouj to complete the marathon if he could maintain his average speed during the 1500 m event for the entire 42.2 km course? (The world record for the men's marathon (set on 28 September 2014) is 2 h 2 min 57 s.)
(d) Which of the athletes in the table has an average speed that is the same as the magnitude of his average velocity? Explain.

7. In 2010, cyclist Sarah Hammer, of the USA, set a world record of 3 min, 22.269 s for the 3000 m pursuit.
(a) What was her average speed?
(b) How long would it take her to cycle from Melbourne to Bendigo, a distance of 151 km, if she could maintain her average speed for the 3000 m pursuit for the whole distance?
(c) How long does it take a car to travel from Melbourne to Bendigo if its average speed is 80 km h^{-1}?
(d) A car travels from Melbourne to Bendigo and back to Melbourne in 4.0 hours.
 (i) What is its average speed?
 (ii) What is its average velocity?

8. Once upon a time, a giant tortoise had a bet with a hare that she could beat him in a foot race over a distance of 1 km. The giant tortoise can reach a speed of about 7.5 cm s^{-1}. The hare can run as fast as 20 m s^{-1}. Both animals ran at their maximum speeds during the race. However, the hare was a rather arrogant creature and decided to have a little nap along the way. How long did the hare sleep if the result was a tie?

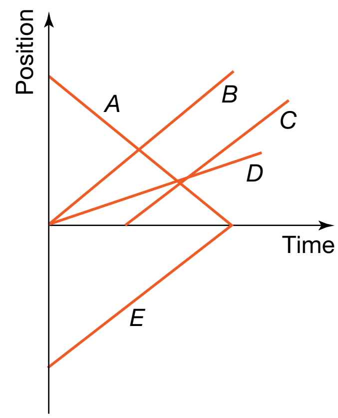
9. An unfit Year 11 student arrives at school late and attempts to run from the front gate of the school to the physics laboratory. He runs the first 120 m at an average speed of 6.0 m s^{-1}, the next 120 m at an average speed of 4.0 m s^{-1} and the final 120 m at an average speed of 2.0 m s^{-1}. What was the student's average speed during his attempt to arrive at his favourite class on time?

10. A holidaying physics teacher drives her old Volkswagen from Melbourne to Wodonga, a distance of 300 km. Her average speed was 80 km h^{-1}. She trades in her old Volkswagen and purchases a brand-new Toyota Prius. She proudly drives her new car back home to Melbourne at an average speed of 100 km h^{-1}.
(a) Make a quick prediction of her average speed for the whole trip.
(b) Calculate the average speed for the entire journey and explain any difference between the predicted and calculated average speed.

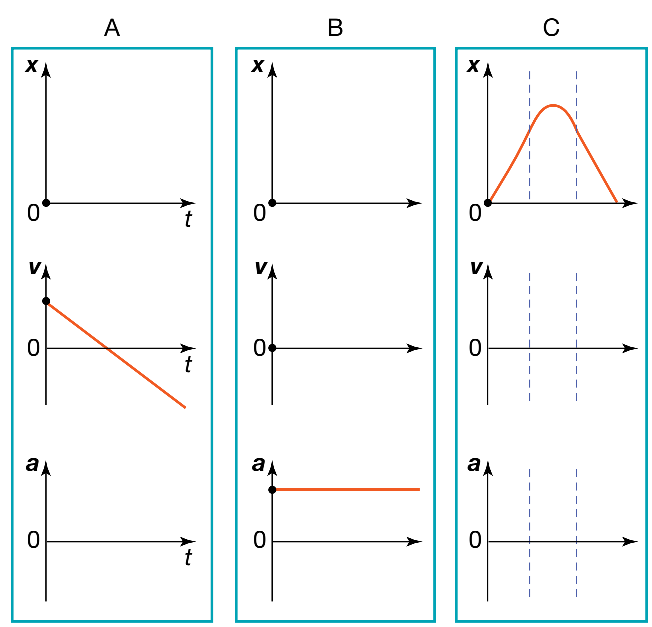
Instantaneous speed and velocity — using graphs

11. Why can't you ever measure the instantaneous velocity of an object with a stopwatch?

12. The position-versus-time graph shown above right describes the motion of five different objects which are labelled *A* to *E*.
(a) Which two objects start from the same position, but at different times?
(b) Which two objects start at the same position at the same time?
(c) Which two objects are travelling at the same speed as each other, but with different velocities?
(d) Which two objects are moving towards each other for the whole period shown on the graph?
(e) Which of the five objects has the lowest speed?



13. Describe in words the motion shown for each of scenarios A, B and C below. Copy the incomplete graphs for each scenario into your workbooks and then complete each graph.



14. Sketch a velocity-versus-time graph to illustrate the motion described in each of the following situations.
   (a) A bicycle is pedalled steadily along a road. The cyclist stops pedalling and allows the bicycle to come to a stop.
   (b) A parachutist jumps out of a plane and opens his parachute midway through the fall to the ground.
   (c) A ball is thrown straight up into the air and is caught at the same height from which it was thrown.

15. Sketch a position-versus-time graph for each scenario in question 8.

Acceleration

16. During motion with a constant acceleration, at what instant of time is the instantaneous velocity the same as the average velocity?

17. Determine (i) the change in speed and (ii) the change in velocity of each of the following situations.
   (a) The driver of a car heading north along a freeway at 100 km h^{-1} slows down to 60 km h^{-1} as the traffic gets heavier.
   (b) A fielder catches a cricket ball travelling towards him at 20 m s^{-1}.
   (c) A tennis ball travelling at 25 m s^{-1} is returned directly back to the server at a speed of 30 m s^{-1}.

18. A car travelling east at a speed of 10 m s^{-1} turns left to head south at the same speed. Has the car undergone an acceleration? Explain your answer with the aid of a diagram.

19. Estimate the acceleration of a car in m s^{-2} as it resumes its journey through the suburbs after stopping at traffic lights.

20. Use the data in table 10.4 on page 172 to help you estimate the average acceleration of a world-class 100 m sprinter at the beginning of a race.

21. How long does it take for:
   (a) a car to accelerate on a straight road at a constant 6.0 m s^{-2} from an initial speed of 60 km h^{-1} (17 m s^{-1}) to a final speed of 100 km h^{-1} (28 m s^{-1})
   (b) a downhill skier to accelerate from rest at a constant 2.0 m s^{-2} to a speed of 10 m s^{-1}?

22. In Acapulco, on the coast of Mexico, professional high divers plunge from a height of 36 m above the water. (The highest diving boards used in Olympic diving events are 10 m above the water.) Estimate:
   (a) the length of the time interval during which the divers fall through the air
   (b) the speed with which the divers enter the water.

   Assume that throughout their dive, the divers are falling vertically from rest with an acceleration of 10 m s^{-2}.

23. A skateboard rider travelling down a hill notices the busy road ahead and comes to a stop in 2.0 s over a distance of 12 m. Assume a constant negative acceleration.
   (a) What was the initial speed of the skateboard?
   (b) What was the acceleration of the skateboard as it came to a stop?

24. A car is travelling at a speed of 100 km h^{-1} when the driver sees a large fallen tree branch in front of her. At the instant that she sees the branch, it is 50 m from the front of her car. The car travels a distance of 48 m *after* the brakes are applied before coming to a stop.
   (a) What is the average acceleration of the car while the car is braking?
   (b) How long does the car take to stop once the brakes are applied?
   (c) What other information do you need in order to determine whether the car stops before it hits the branch? Make an estimate of the missing item of information to predict whether or not the car is able to stop in time.

25. A dancer in a school musical is asked to leap 80 cm into the air, taking off vertically on one beat of the music and landing with the next beat. If the music beats every 0.5 s, is the leap possible? The acceleration of the dancer during the leap can be assumed to be 10 m s^{-2} downwards.

26. A brand-new Rolls Royce rolls off the back of a truck as it is being delivered to its owner. The truck is travelling along a straight road at a constant speed of 60 km h^{-1}. The Rolls Royce slows down at a constant rate, coming to a stop over a distance of 240 m. It is a full minute before the truck driver realises that the precious load is missing. The driver brakes immediately, leaving a 25 m long skid mark on the road. The driver's reaction time (time interval between noticing the problem and depressing the brake) is 0.5 s.

   How far back is the Rolls Royce when the truck stops?

27. A girl at the bottom of a 100 m high cliff throws a tennis ball vertically upwards. At the same instant a boy at the very top of the cliff drops a golf ball so that it hits the tennis ball while both balls are still in the air. The acceleration of both balls can be assumed to be 10 m s^{-2} downwards.

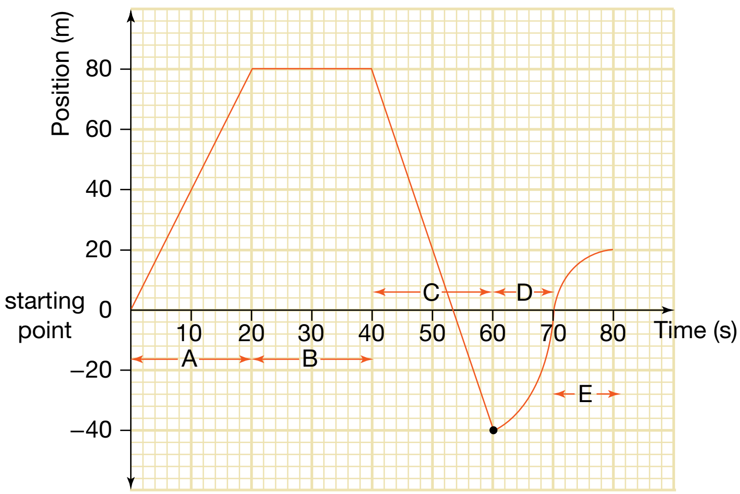
(a) With what speed is the tennis ball thrown so that the golf ball strikes it at the top of its path?

(b) What is the position of the tennis ball when the golf ball strikes it?

More questions on graphical analysis

28. The graph in the following figure is a record of the straight-line motion of a skateboard rider during an 80 s time interval. The time interval has been divided into sections labelled A to E.

The skateboarder initially moves north from the starting point.



(a) During which section of the interval was the skateboard rider stationary?

(b) During which sections of the interval was the skateboarder travelling north?

(c) At what instant did the skateboard rider first move back towards the starting line?

(d) What was the displacement of the skateboarder during the 80 s interval?

(e) What distance did the skateboarder travel during the 80 s interval?

(f) During which section of the interval was the skateboard rider speeding up?

(g) During which section of the interval was the skateboard rider slowing down?

(h) What was the skateboarder's average speed during the entire 80 s interval?

(i) What was the velocity of the skateboarder throughout section C?

(j) Estimate the velocity of the skateboarder 65 s into the interval.

29. The graph in the figure that follows is a record of the motion of a battery-operated toy robot during an 80 s time interval. The interval has been divided into sections labelled A to G.

(a) During which sections is the acceleration of the toy robot zero?

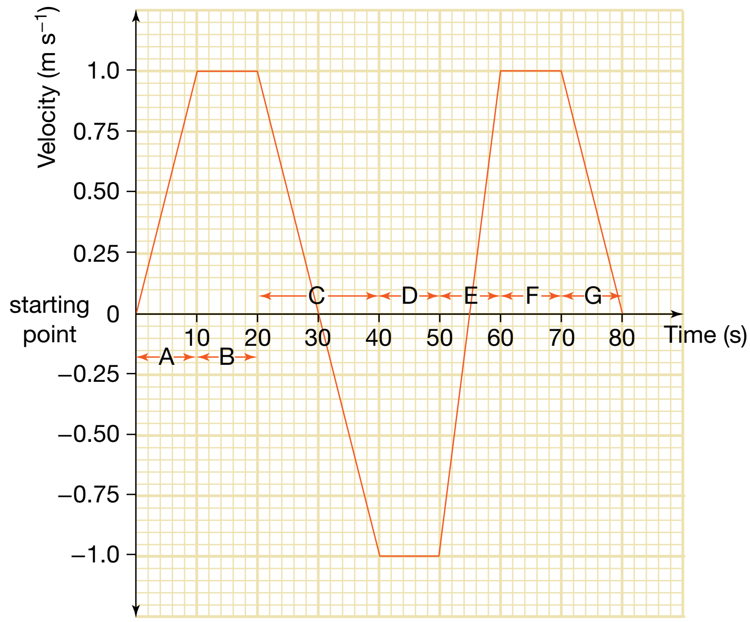
(b) What is the displacement of the toy robot during the 80 s interval?

(c) What is the average velocity of the toy robot during the entire interval?

(d) At what instant did the toy robot first reverse direction?

(e) At what instant did the toy robot first return to its starting point?

(f) During which intervals did the toy robot have a negative acceleration?



(g) During which intervals did the toy robot decrease its speed?

(h) Explain why your answers to (f) and (g) are different from each other.

(i) What is the acceleration of the toy robot throughout section E?

(j) What is the average acceleration during the first 20 s?

(k) Describe the motion of the toy robot in words.

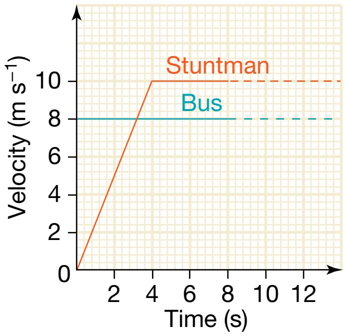
30. During the filming of a new movie, a stuntman has to chase a moving bus and jump into it. The stuntman is required to stand still until the bus passes him and then start chasing it. The velocity-versus-time graph in the figure that follows describes the motion of the stuntman and the bus from the instant that the bus door passes the stationary stuntman.

(a) At what instant did the stuntman reach the same speed as the bus?

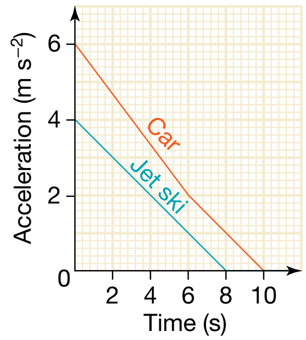
(b) What is the magnitude of the acceleration of the stuntman during the first 4.0 s?

(c) At what instant did the stuntman catch up with the bus door?

(d) How far did the stuntman run before he reached the door of the bus?



31. The figure that follows compares the straight-line motion of a jet ski and a car as they each accelerate from an initial speed of 5.0 m s^{-1}.



(a) Which is first to reach a constant speed — the jet ski or the car — and when does this occur?

(b) What is the final speed of:

(i) the jet ski

(ii) the car?

(c) Draw a speed-versus-time graph describing the motion of either the jet ski or the car.

CHAPTER

11 Forces in action

BASE jumpers use a high point such as a cliff to launch themselves. The forces involved in the jump must be carefully calculated to allow the parachute to open in plenty of time.

REMEMBER

Before beginning this chapter, you should be able to:

- give examples of forces
- recognise that friction can aid or retard motion
- use graphical and algebraic methods to analyse motion with a constant acceleration.

KEY IDEAS

After completing this chapter, you should be able to:

- explain how the action of a force changes the way an object moves
- model weight as a force acting on a body through its centre of mass
- explain changes in motion in terms of Newton's three laws of motion, and apply these laws to objects on which one or more forces act
- apply vector addition and resolution to components of readily observable forces such as weight, friction and reaction forces
- describe and analyse simple interactions between objects in terms of change in momentum and impulse
- apply torque to the analysis of the stability of simple structures.

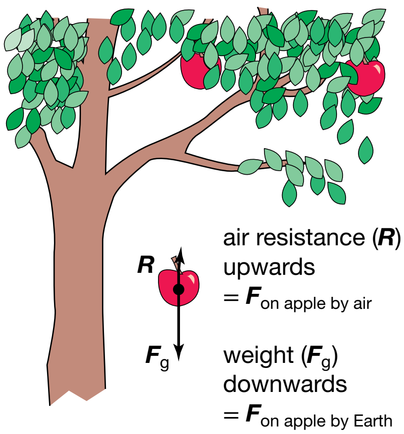
Describing a force

A **force** is a push or a pull. Force is a vector quantity.

A **force** is a push or a pull applied by one object on another. Forces can start things moving, stop them, or change their speed or direction. Forces can spin objects or change their size or shape. Some types of force require contact. For example, the force applied by your hand on a netball or basketball when shooting a goal requires contact between your hand and the ball. The friction applied by the road on a bicycle or car requires contact between the road surface and the tyres. Some forces do not require contact. For example, the force of gravity applied on your body by the Earth is present even when you are not in contact with the Earth. A magnet attracts certain materials without being in contact with them. Note that descriptions of forces indicate both the object that the force is applied on and the object that applies the force.

The **centre of mass** of an object is the point at which all of its mass can be considered to be.

In diagrams showing forces, such as the one at left, a labelled arrow should be drawn from the **centre of mass** of the object upon which the force acts. The length of the arrow should indicate the relative size of the force.



Force is a vector quantity. A vector quantity in this text is represented by symbols in ***bold italic*** type.

To fully describe a force, you need to specify its direction as well as its magnitude or size. A quantity that can be fully described only by specifying a direction as well as a magnitude is called a vector quantity. Force is a vector quantity. A vector quantity can be described in writing or by a labelled arrow. If a symbol is used to represent a vector quantity, it should have a half-arrow above it (some people use a 'squiggly' line below the symbol instead). In this text, vector quantities are represented by symbols in bold italic type.

The length of the arrow should indicate the relative size of the force. When labelling forces, it helps to describe the force as $\boldsymbol{F}_{\text{on A by B}}$; for example, the arrow representing the weight of the apple is labelled $\boldsymbol{F}_{\text{on apple by Earth}}$.

The SI unit of force is the newton (N). The force of gravity on a 100 g apple is about 1 N downwards. A medium-sized car starting from rest is subjected to a forward force of about 4000 N.

Quantities that can be described without specifying a direction are called scalar quantities. Mass, energy, time and temperature are all examples of scalar quantities.

An attraction to the Earth

The apple in the figure above left is attracted to the Earth by the force of gravity. Even before it falls, the force of gravity is pulling it down. However, before it falls, the tree branch is pulling it up with a force of equal magnitude.

The force of gravity is a force of attraction that exists between any pair of objects that have mass. Gravity is such a small force that, unless at least one of the objects is as massive as a planet or a natural satellite like the Moon, it is too small to measure.

Weight is the force applied to an object, due to gravitational attraction.

The force on an object due to the pull of gravity is called **weight** and is usually given the symbol $\boldsymbol{F}_g$. On Earth, your weight can be described as the force applied on you by the Earth. The magnitude of the weight of an object is directly proportional to its mass (m). So,

$$\boldsymbol{F}_g \propto m.$$

Gravitational field strength ($\boldsymbol{g}$) is the force of gravity on a unit of mass.

The weight of an object also depends on where it is. For example, the weight of your body on the Moon is considerably less than it is on Earth. Your mass remains the same wherever you are because it is a measure of the amount of matter in an object or substance. The **gravitational field strength**, which is usually given the symbol $\boldsymbol{g}$, is defined as the force of gravity on a unit of mass. The magnitude of the gravitational field strength at the surface of the Moon is

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approximately one-sixth of that at the surface of the Earth. Gravitational field strength is a vector quantity. The direction of the weight force on an object is towards the centre of the source of attraction. In symbols:

$$\boldsymbol{g} = \frac{\boldsymbol{F}_g}{m}.$$

Thus,

$$\boldsymbol{F}_g = m\boldsymbol{g}.$$

The SI unit of gravitational field strength is N kg^{-1}. In simple terms, $\boldsymbol{g}$ is a measure of the force of gravity on a 1 kg mass.

The magnitude of gravitational field strength at the Earth's surface is, on average, 9.8 N kg^{-1}. The magnitude of $\boldsymbol{g}$ decreases as altitude (height above sea level) increases. It also decreases as one moves from the poles towards the equator. Table 11.1 shows the magnitude of $\boldsymbol{g}$ at several different locations.

TABLE 11.1 Variation in gravitational field strength

Location	Altitude (m)	Latitude	Magnitude of g (N kg^{-1})
Equator	0	0°	9.780
Sydney	18	34°S	9.797
Melbourne	12	37°S	9.800
Denver	1609	40°N	9.796
New York	38	41°N	9.803
North Pole	0	90°N	9.832

The magnitude of $\boldsymbol{g}$ at the Earth's surface will be taken as 9.8 N kg^{-1} throughout this text. At the surface of the Moon, the magnitude of $\boldsymbol{g}$ is 1.60 N kg^{-1}.

Sample problem 11.1

What is the weight of a 50 kg student:
(a) on the Earth
(b) on the Moon?

Solution:
(a) $\boldsymbol{F}_g = m\boldsymbol{g}$
$= 50 \text{ kg} \times 9.8 \text{ N kg}^{-1}$ downwards
$= 490$ N downwards
(b) $\boldsymbol{F}_g = m\boldsymbol{g}$
$= 50 \text{ kg} \times 1.60 \text{ N kg}^{-1}$ downwards
$= 80$ N downwards

Note that the direction must be stated to describe the weight fully because weight is a vector.

Revision question 11.1

(a) What is the difference between a 70.0 kg person's weight at the North Pole and the same person's weight at the equator?
(b) A hospital patient is very accurately measured to have a mass of 64.32 kg and a weight of 630.08 N. In which of the locations in table 11.1 could the patient be?

AS A MATTER OF FACT

Bathroom scales are designed for use only on Earth. Fortunately (at this point in time), that's where most of us live.

If a 60 kg student stood on bathroom scales on the Moon, the reading would be only about 10 kg. Yet the mass of the student remains 60 kg. Bathroom scales measure force, not mass.

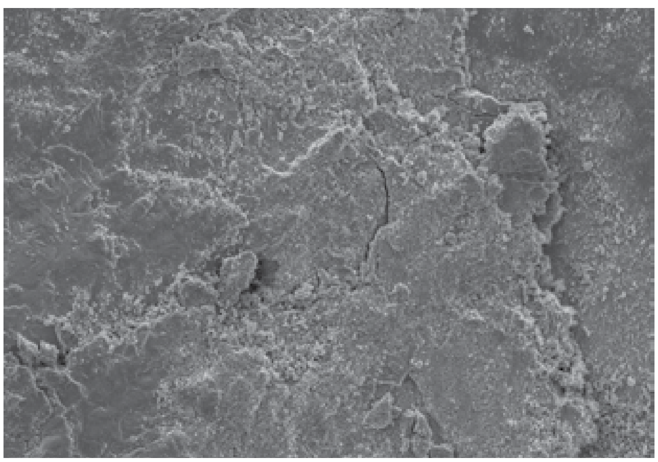
However, scales are designed so that you can read your mass in kilograms. Otherwise, you would have to divide the measured force by 9.8 to determine your mass. The manufacturer of the bathroom scales saves you the trouble of having to do this.

The 60 kg student has a weight of about 588 N on Earth. However, on the Moon the student's weight is only about 100 N. The reading on the scales will be 100 N divided by 9.8 N kg^{-1}, giving the result of 10.2 kg.

Friction — what a drag!

Friction is the force applied to the surface of an object when it is pushed or pulled against the surface of another object.

Friction is a force that surfaces exert on each other when they 'rub' together. The magnitude of the friction force depends greatly on the nature of each of the two surfaces. Smooth surfaces experience smaller friction forces than rough surfaces. However, even very smooth surfaces are rough on a microscopic scale.



Even very smooth surfaces are rough under a microscope. This scanning electron micrograph shows a magnified metal surface.

It is this roughness that is mostly responsible for the resistance to motion that we call friction. As two surfaces move across each other, they intermesh, resisting the motion.

For better or worse

Friction can be a real nuisance at times. It makes doors squeak. It causes wear and tear in car engines and can make them overheat.

Friction is also a necessary force in many situations. If you have ever walked on a banana peel or ice, you know the importance of friction to walking. When you walk, you push backwards against the ground so that the ground pushes forward on your foot. Without a significant friction force, your foot slides backwards and you fall.

Friction is also needed for safe driving in a car. A large friction force is needed to start moving, change direction and stop. The rubber tyres of a car have a deep tread to ensure that the friction force is still present on a wet road when water forms a lubricating film between the road and the tyres. Smooth tyres would slide across a wet road, making it difficult to stop, turn or accelerate. The deep grooves in tyres pick up the water from the road and throw it backwards, providing a drier road surface and greater friction. The lubricating effect of water is also evident in ice-skating. The moving blade melts the surface of the ice beneath it, creating a thin lubricating film of water on which it glides.

Olympic swimmers, cyclists and track athletes are becoming increasingly aware of the effects of fluid friction as the accuracy of timing improves. The resistance to

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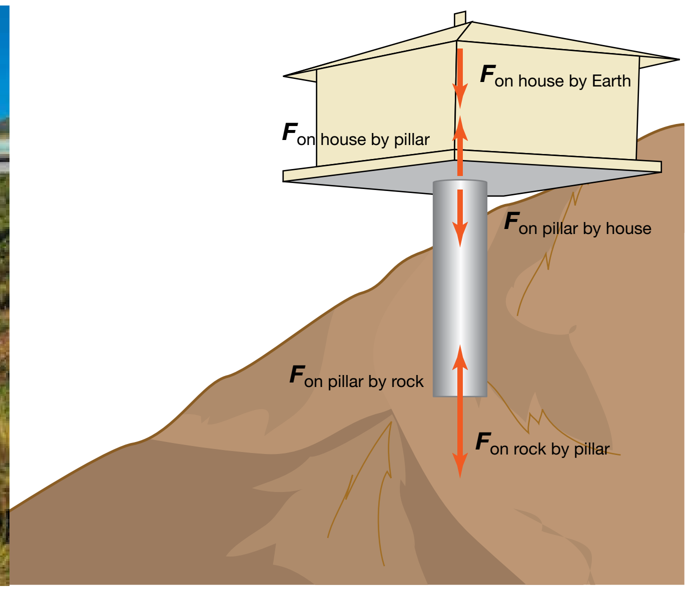
the motion of objects through air and water is an example of fluid friction. The desire to win gold medals has resulted in swimmers shaving their heads, cyclists shaving their legs, new bicycle designs and tighter-fitting costumes. Because fluid friction increases with the speed of the object, streamlining is particularly important in cars, planes, watercraft and bicycles. Streamlining involves creating a shape that reduces the slowing effect of collisions with particles of the fluid.

While air resistance can be a problem, it is an absolute necessity for parachutists and para-gliders.

Racing cyclists reduce the effects of fluid friction (air resistance) by wearing streamlined costumes and using aerodynamically designed bicycles.

Compression and tension

Compression and tension are forces produced when materials are squashed or stretched. Springs are a good example of where these forces apply, but any material, including concrete, bone and metal rods, can be compressed to some extent. Some materials, such as metal wires, rubber and even bone, can be stretched.



The 'Pole House' located on the Great Ocean Road is supported by a concrete column that goes several metres into the ground.

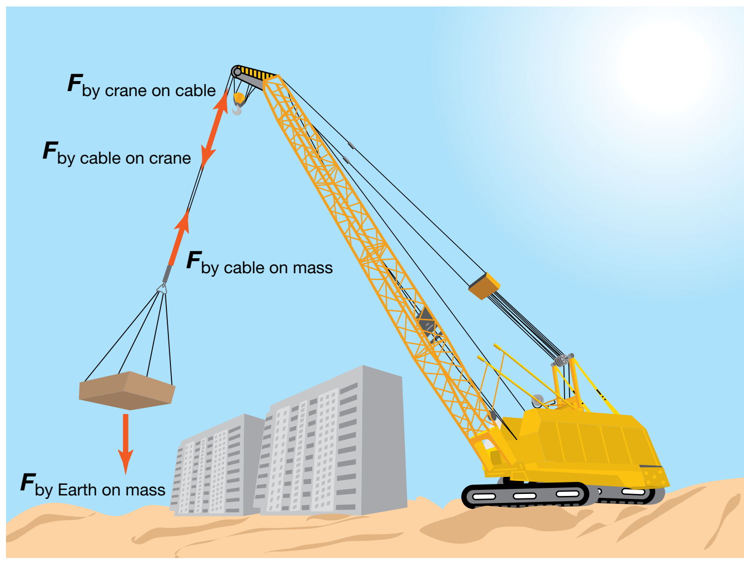
Compression

In the photo of the pole house shown previously, the atoms and molecules in the concrete column are pushed together, the outer electrons are forced closer together and push back because of the electrostatic repulsion of like charges. The direction of the compression force at each end is outwards.

The normal reaction force

The **normal reaction force** is a force that acts perpendicularly to a surface as a result of an object applying a force to the surface.

At this moment you are probably sitting on a chair with your feet on the floor. The material in the chair, whether it is plastic, timber, foam or steel springs, has been compressed and is pushing back up. This force that is pushing up is called a reaction force because if you were not sitting on the chair, there would be no force. This force is more properly called a **normal reaction force**, $\boldsymbol{N}$, as it acts at right angles to the surface.



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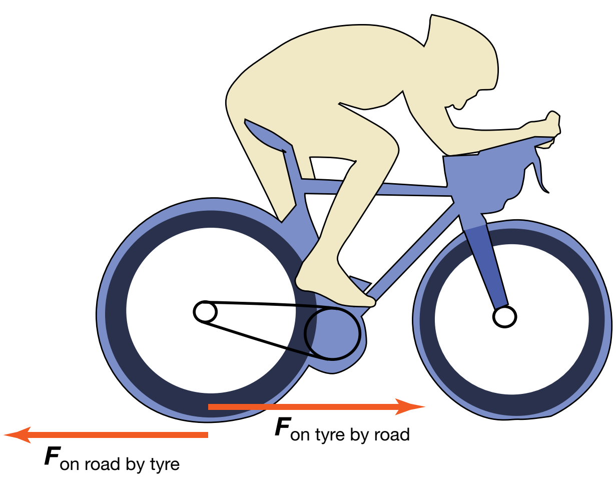
Tension

In a similar manner to the compressed concrete pillar supporting the house, the atoms in the cable above are being stretched apart by the pulling forces at either end.

The atoms resist being separated and pull the ends of the cable inwards. The diagram above shows the forces acting within the cable. In this case, the direction of the tension force is inwards at each end.

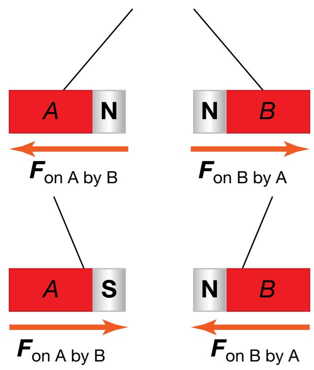


Forces in pairs

To explain the motion of everyday objects, Isaac Newton devised some basic principles. A key starting point is the nature of force. Newton said that forces always act in pairs. Forces explain the interaction between two objects. Each object acts on the other, so where there is one force by one object, there is always another force by the other object.

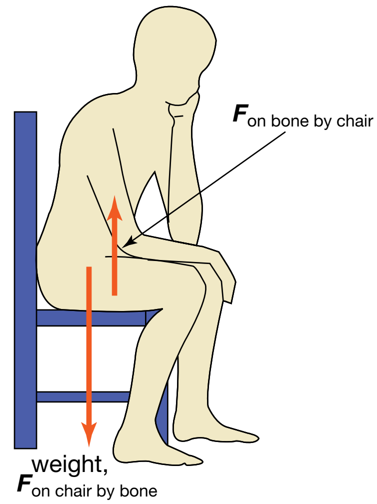
Examples of forces in pairs include:

- Bicycle back tyre: the action of the pedals push the tyre backwards against the road surface. The frictional interaction between the tyre and the road results in a forward force by the road on the tyre.



- Two suspended magnets: In the top diagram on the left, each magnet is pushing the other away. In the bottom diagram, each is pulling the other towards it.
- Sitting in a chair: The normal reaction force from the chair pushes up on the bones in the pelvis and the compressed bone pushes down. This compression is what you feel when you are sitting.

The pairing of these forces is apparent in the symmetry of their labels. If the label for one force is $\boldsymbol{F}_{\text{on B by A}}$, then the label for the other is $\boldsymbol{F}_{\text{on A by B}}$. It is important to note that in these pairs of forces, the forces act on different objects and are caused by different objects.



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Newton's Third Law
Concept summary and practice questions

Newton's Third Law of Motion

Newton not only identified forces acting in pairs, but he also said that these two forces act in opposite directions, and are equal in magnitude or size. This statement became Newton's Third Law of Motion. Newton's first two laws describe how objects move when forces act and will be covered later.

A precise statement of Newton's third law is:

If object B applies a force to object A, then object A applies an equal and opposite force to object B.

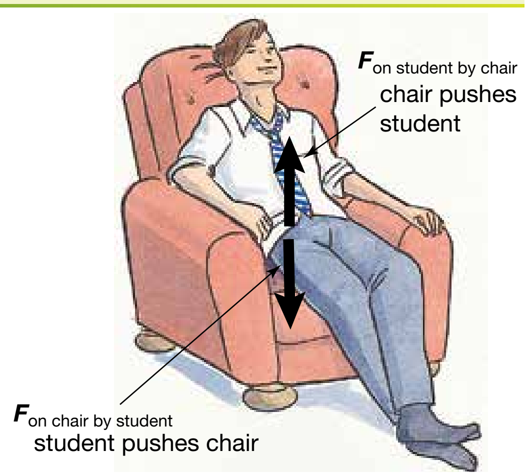
$$\boldsymbol{F}_{\text{on A by B}} = -\boldsymbol{F}_{\text{on B by A}}$$

This symmetry between the pair of forces can be used to identify the other of the pair if only one is given.

AS A MATTER OF FACT

Some books summarise Newton's third law as 'For every action, there is an equal and opposite reaction.' This version is not preferred. The word 'reaction' here has a different meaning to its use in 'normal reaction force'. The statement also implies one force in the pair is a response to the other, which is wrong.

It is important to remember that when an object A applies a force on an object B, the reaction is a force applied by object B on object A. There are four forces acting as two force pairs when you sit on that comfortable chair. The Earth pulls down on you, compressing the springs and foam, and the compressed springs and foam push up on you, compressing the bones in your pelvis. So, one force pair is the upward push by the springs on you and the downward push by the bones



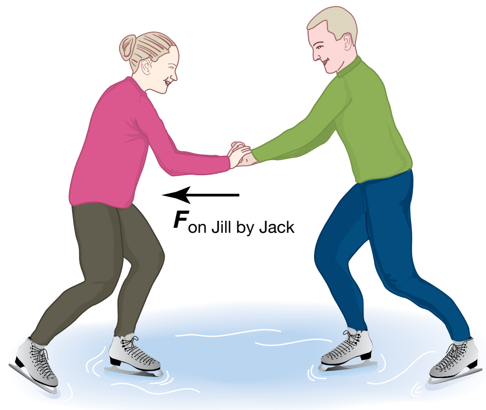
Forces always act in pairs.

in your pelvis on the chair. The second force pair is the Earth pulling down on you and you pulling the Earth upwards.

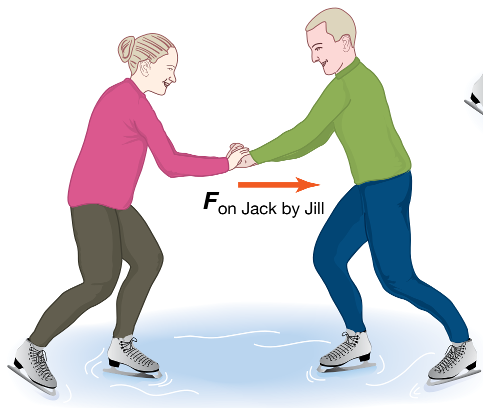
The net force on the student sitting in the chair is the vector sum of all the forces acting on the student, that is, accounting for the direction of each force. The net force is zero because the upward push by the chair, $\boldsymbol{F}_{\text{on student by chair}}$, is balanced by the downward, and of equal size, pull of the force of gravity, or weight of the student, $\boldsymbol{F}_{\text{on student by Earth}}$.

Sample problem 11.2

Two ice skaters, Jack and Jill, push each other away. The figure at right shows the force on Jill by Jack with a black arrow. Draw an arrow and label it to show the force on Jack by Jill.



Solution:

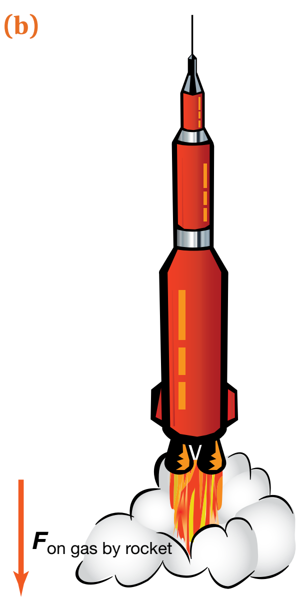


Revision question 11.2

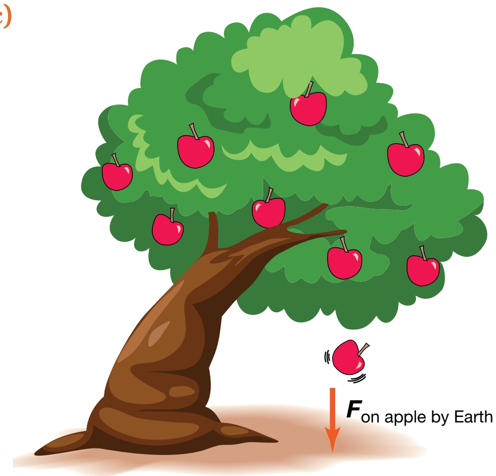
Draw the arrow for the other force in the force pair and label it.

(a)

(b)



(c)



(d)

Moving forward

The rowing boat shown below is propelled forward by the push by water on the oars. As the face of each oar pushes back on the water, the water pushes back with an equal and opposite force on each oar. The push by the oars, which are held tightly by the rowers, propels the rowers and their boat forward. A greater push on the water results in a greater push on the oar.

This rowing team relies on a reaction force to propel itself forward.

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In fact, none of your forward motion, whether you are on land, water or in the air, could occur without a third law force pair.

- When you swim, you push the water backwards with your hands, arms and legs. The water pushes in the opposite direction, propelling you forwards.
- In order to walk or run, you push your feet backwards and down on the ground. The ground pushes in the opposite direction, pushing forwards and up on your feet.
- The forward driving force on the wheels of a car is the result of a push back on the road by the wheels.
- A jet or a propeller-driven plane is thrust forwards by air. The jet engines or propellers are designed to push air backwards with a very large force. The air pushes forward on the plane with an equally large force.

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Unit 2 | AOS 1 | Topic 2 | Concept 1

Forces, vectors and net force
Concept summary and practice questions

The net force

What happens if more than one force acts on an object?

It is rare for just one force to be acting on an object. For example, a moving car has friction forces, reaction forces and its own weight force acting on it. A suspended magnet will experience its weight, a tension force and a magnetic force.

An effective way to visualise the forces on an object is a forces diagram, sometimes called a free body diagram. When drawing a forces diagram, the object is at the centre, represented as a point or a square. The forces are represented by arrows from the point or the centre of the square. The length of the arrow is not critical, but the arrow should point in the direction of the force.

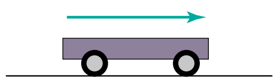
Sample problem 11.3

Draw a forces diagram for each of the following:

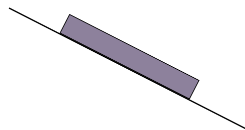
(a) Moving ice skater

(b) Ball hanging straight down on a string

(c) Trolley slowing down

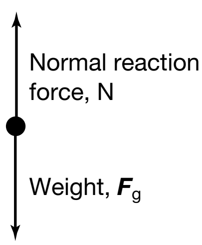


(d) Block stationary on slope

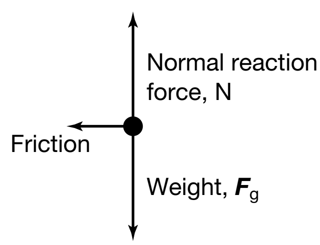


Solution:

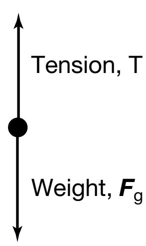
(a)



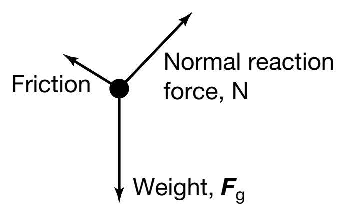
(c)



(b)



(d)



Revision question 11.3

Draw a forces diagram for each of the following:

(a) A falling stone

(b) A mass being pulled at a steady speed

(c) A suspended magnet pulled to the side.

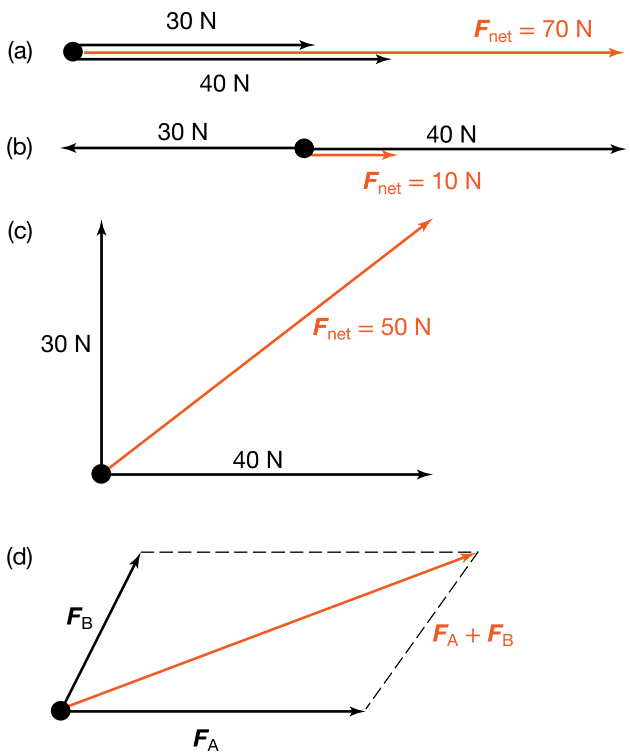
The vector sum of the forces acting on an object is called the **net force**.

The **net force** is the result of combining all the forces into one force. Sometimes all the forces can balance leaving a net or overall force of zero. At other times there is a non-zero force left, and because it is a vector, it has a particular direction, which may be different from any of the individual forces acting on the object. However, because force is a vector, combining forces is not just simple arithmetic, but is a vector sum as the direction of the force has to be taken into account.

Adding forces together

When more than one force acts on an object, the net force is found by the vector addition of the forces. If an object has two forces acting on it, one of 30 N and another of 40 N, the sum of the two forces, or net force, is 70 N only if both forces are acting in the same direction. Three of the diagrams at left, (b), (c) and (d), show these two forces acting in different directions; the fourth, (a), shows them acting in the same direction. The net force is indicated in each of the three examples. The net force is usually denoted by the symbol $\boldsymbol{F}_{\text{net}}$.

To distinguish the net force vector from the vectors for the actual forces, the arrow for $\boldsymbol{F}_{\text{net}}$ is often drawn in another colour or as a dashed line. Appendix 2 has further details on the uses of vectors and how to add them. A geometric method of adding vectors uses a parallelogram, where the vector sum is the diagonal. This is shown in figure (d).



Adding forces together

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Unit 2	**Newton's First Law**
AOS 1	Concept summary and practice questions
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Explaining motion: forces in and out of balance

It is difficult to explain the motion of objects without an understanding of force. The ancient Greek philosopher Aristotle (384–322 BCE) concluded from his observations that a moving object would come to rest if no force was pushing it. Aristotle thought that steady motion required a constant force and that 'being at rest' was the natural state of matter. This view held sway for almost 2000 years, although contrary views were expressed by philosophers such as Epicurus and Lucretius.

It was not until Galileo (1564–1642) that this explanation of motion was seriously challenged. Galileo argued that if a ball rolled down an inclined plane gained speed and a ball rolled up an inclined plane lost speed, a ball rolled along a horizontal plane should neither gain nor lose speed. Galileo knew that this did not really happen. He claimed that if there was a lot of friction, the ball slowed down quickly; if there was little friction, the ball slowed down more gradually. However, he predicted that if there were no friction at all, the ball would continue to move with a constant speed forever unless something else caused it to slow down or stop.

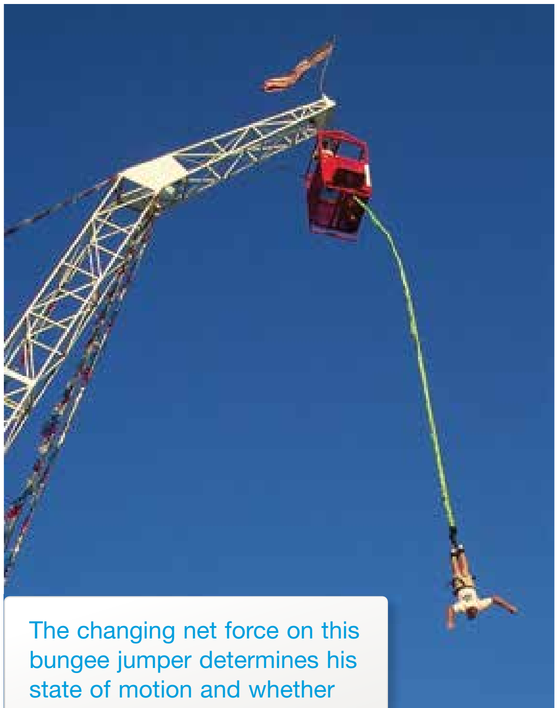
Galileo introduced the concept of friction as a force and concluded that objects retain their velocity unless a force, often friction, acts upon them. Galileo stated in his *Discorsi* (1638):

> *A body moving on a level surface will continue in the same direction at constant speed unless disturbed.*

Sir Isaac Newton (1643–1727) was able to refine Galileo's ideas about motion. In 1687, he published his *Philosophia Naturalis Principia*, which included three laws of motion. Translated from Latin, Newton's First Law of Motion can be stated as:

> *Every object continues in its state of rest or uniform motion unless made to change by a non-zero net force.*

A coin flicked across a tabletop changes its motion because the net force on it is not zero. In fact, it slows down because the direction of the net force is



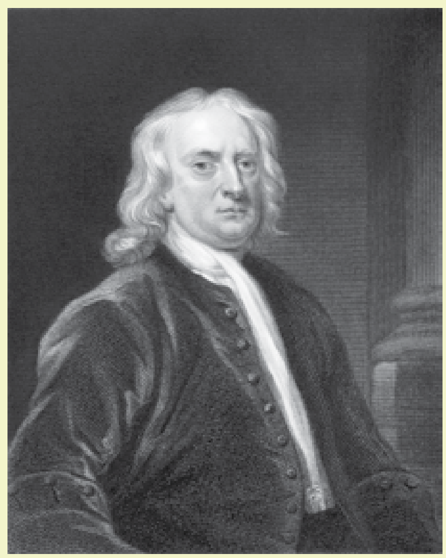
The changing net force on this bungee jumper determines his state of motion and whether or not he will stop in time.

opposite to the direction of motion. The vertical forces, weight and the support force of the table balance each other. The only 'unbalanced' force is that of friction.

A coin pushed steadily across a tabletop moves in a straight line at constant speed as long as the net force is zero (that is, as long as the magnitude of the pushing force is equal to the magnitude of friction). The coin will speed up if you push horizontally with a force greater than the friction. It will slow down if the force of friction is greater than the horizontal pushing force.

The motion of a bungee jumper can be explained in terms of Newton's First Law of Motion. Until the bungee cord tightens, the net force is downwards and the speed of the bungee jumper increases. As the jumper's speed increases, so does the air resistance. However, the air resistance is quite small compared with the jumper's weight. Until the cord begins to tighten, the tension pulling the jumper up is zero. As the rope tightens, the tension increases. Until the tension and air resistance forces together balance the weight, the bungee jumper continues to speed up. The tension continues to increase, eventually resulting in an upwards net force which allows the bungee jumper to slow down, stop (just in time) and rise again.

AS A MATTER OF FACT



Sir Isaac Newton

Sir Isaac Newton was one of many famous scientists who were not outstanding students at school or university. Newton left school at 14 years of age to help his widowed mother on the family's farm. He turned out to be unsuited to farming, and spent much of his time reading. At the age of 18, he went to Cambridge University, where he showed no outstanding ability.

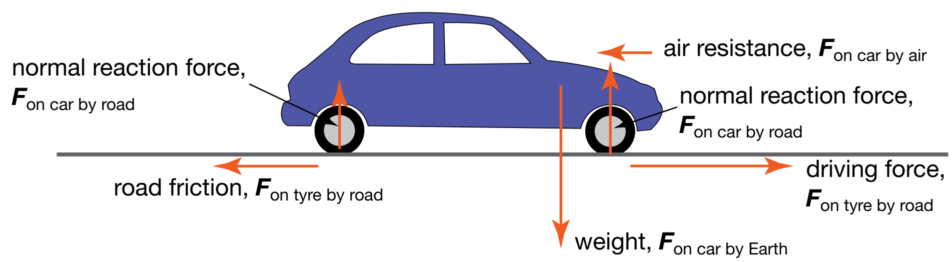
When Cambridge University was closed down in 1665 due to an outbreak of the plague, Newton went home and spent the next two years studying and writing. During this time, he developed the laws of gravity that explain the motion of the planets, and his three famous laws of motion. Over the same period, he put forward the view that white light consisted of many colours, and he invented calculus. Newton's laws of gravity and motion were not published until about 20 years later.

Newton later became a member of Parliament, a warden of the Mint and President of the Royal Society. After his death in 1727, he was buried in Westminster Abbey, London, alongside many English kings, queens, political leaders and poets.

Forces in two dimensions

The forces acting on a car being driven along a straight horizontal road are:

- *Weight*. The force applied by the Earth on the car. A medium-sized sedan containing a driver and passenger has a weight of about 1.5×10^4 N. The weight acts through the centre of mass, or balancing point, of the car. This is normally closer to the front of the car than the back.
- *The normal reaction force*. The force applied on the car by the road. This force is a reaction to the force applied on the road by the car. A normal reaction force pushes up on all four wheels. Its magnitude is normally greater at the front wheels than the rear wheels. On a horizontal road, the sum of these normal reaction forces has the same magnitude as the weight. What do you think would happen if this were not the case?



The state of motion of a front-wheel-drive car on a horizontal road depends on the net force acting on it.

- *The driving force*. This is provided by the road and is applied to the driving wheels. The driving wheels are turned by the motor. In most cars, either the front wheels or the rear wheels are the driving wheels. The motor of a four-wheel-drive vehicle turns all four wheels. As a tyre pushes back on the road, the road pushes forward on the tyre, propelling the car forward. The forward push of the road on the tyre is a type of friction commonly referred to as traction, or grip. If the tyres do not have enough tread, or the road is icy, there is not enough friction to push the car forward and the tyre slides on the road. The wheel spins and the car skids. The car cannot be propelled forward as effectively. Skidding also occurs if the motor turns the driving wheels too fast.
- *Road friction*. This is the retarding force applied by the road on the tyres of the non-driving wheels. The non-driving wheels of front-wheel-drive cars roll as they are pulled along the road by the moving car. In older cars, the non-driving wheels are usually at the front. They are pushed along the road by the moving car. Rolling friction acts on the non-driving wheels in a direction opposite to the direction of the car's movement. When the driving wheels are not being turned by the motor, rolling friction opposes the forward movement of all four wheels. When the brakes are applied, the wheels to which the brakes are attached are made to turn too slowly for the speed at which the car is moving. They are no longer rolling freely. This increases the road friction greatly and the car eventually stops. If the brakes are applied hard enough, the wheels stop completely, or lock, and the car goes into a skid. The sliding friction that exists when the car is skidding is less than the friction that exists when the wheels are rolling just a little.
- ***Air resistance***. The drag, or air resistance acting on the car, increases as the car moves faster. As a fluid friction force, air resistance can be reduced by streamlining the vehicle.

Air resistance is the force applied to an object, opposite to its direction of motion, by the air through which it is moving.

The net force acting on the car in the figure on the previous page is zero. It is therefore moving along the road at constant speed. We know that it is moving to the right because both the air resistance and road friction act in a direction opposite to that of motion. If the car were stationary, neither of these forces would be acting at all.

- If the driving force were to increase, the car would speed up until the sum of the air resistance and road friction grew large enough to balance the driving force. Then, once again, the car would be moving at a constant, although higher, speed.
- If the driver stopped pushing down on the accelerator, the motor would stop turning the driving wheels and the driving force would become zero. The net force would be to the left. As the car slowed down, the air resistance and road friction would gradually decrease until the car came to a stop. The net force on the car would then be zero until such time as the driving force was restored.

PHYSICS IN FOCUS

Anti-lock brake systems

When brakes in an older car without ABS are applied too hard, as they often are when a driver panics, the wheels lock. The resulting sliding friction is less than the friction acting when the wheels are still rolling. The car skids, steering control is lost and the car takes longer to stop than if the wheels were still rolling. Drivers are often advised to 'pump' the brakes in wet conditions to prevent locking. This involves pushing and releasing the brake pedal in quick succession until the car stops. This, however, is very difficult to do in an emergency situation.

An anti-lock brake system (ABS) allows the wheels to keep rolling no matter how hard the brakes are applied. A small computer attached to the braking system monitors the rotation of the wheels. If the wheels lock and rolling stops, the pressure on the brake pads (or shoes) that stops the rotation is reduced briefly. This action is repeated up to 15 times each second. Anti-lock brake systems are most effective on wet roads. However, even on a dry surface, braking distances can be reduced by up to 20%.

Rolling downhill

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Unit 2 | AOS 1 | Topic 3 | Concept 2

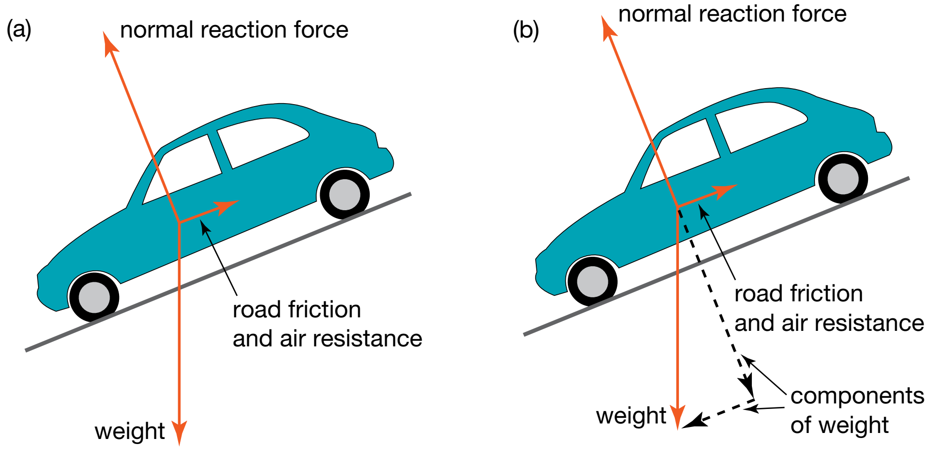
Force components — a box on a slope
Concept summary and practice questions

A car left parked on a hill will begin to roll down the hill with increasing speed if it is left out of gear and the handbrake is off. Figure (a) on the following page shows the forces acting on such a car. In order to simplify the diagram, all of the forces are drawn as if they were acting through the centre of mass of the car. The forces on the car can then be modelled as acting on a single point. The direction of net force acting on the car is down the hill. It is clear that the pull of gravity (the weight of the car) is a major contributor to the downhill motion of the car.

It is often useful to divide vectors into parts called **components**. Figure (b) on the opposite page shows how the weight can be broken up, or resolved, into two components — one parallel to the slope and one perpendicular to the slope. Notice that the vector sum of the components is the weight. By resolving the weight into these two components, two useful observations can be made:

Components are parts. Any vector can be resolved into a number of components. When all of the components are added together, the result is the original vector.

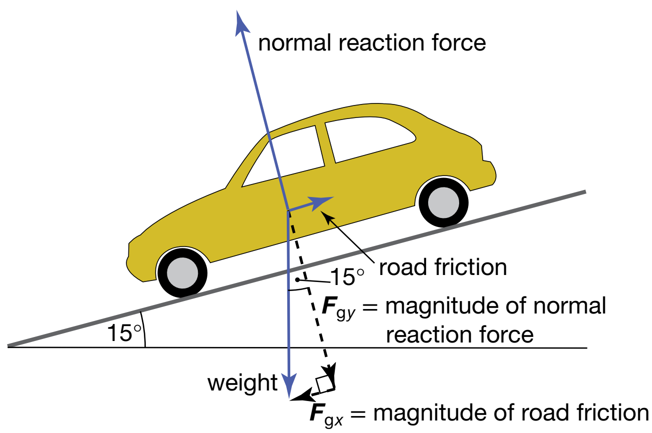
1. The normal reaction force is balanced by the component of weight that is perpendicular to the surface. The net force has no component perpendicular to the road surface. This must be the case because there is no change in motion perpendicular to the slope.
2. The magnitude of the net force is simply the difference between the magnitude of the component of weight that is parallel to the surface and the sum of the road friction and air resistance.



(a) A simplified diagram of the forces acting on a car rolling down a slope
(b) Vectors can be resolved into components. In this case, the weight has been resolved into two components. The net force is parallel to the slope.

Sample problem 11.4

A car of mass 1600 kg left parked on a steep but rough road begins to roll down the hill. After a short while it reaches a constant speed. The road is inclined at 15° to the horizontal. The car's speed is sufficiently slow that the air resistance is insignificant and can be ignored. Determine the magnitude of the road friction on the car while it is rolling at constant speed.



Solution: Because the car is rolling at constant speed, the net force acting on it is zero. The weight ($\boldsymbol{F}_g$) can be resolved into two components — one down the slope ($\boldsymbol{F}_{gx}$) and one perpendicular to it ($\boldsymbol{F}_{gy}$). The perpendicular component of the weight, $\boldsymbol{F}_{gy}$, is balanced by the normal reaction force. The magnitude of the road friction must be equal to the magnitude of the weight component down the slope, $\boldsymbol{F}_{gx}$.

$$\sin 15° = \frac{F_{gx}}{F_g}$$ (in the triangle formed by the weight and its components)

$$F_{gx} = F_g \sin 15°$$ (where F_g is the magnitude of the weight)

$$= mg \sin 15°$$

$$= 1600 \text{ kg} \times 9.8 \text{ N kg}^{-1} \times \sin 15°$$ (substituting data)

$$= 4.1 \times 10^3 \text{ N}$$

The magnitude of the road friction is therefore 4100 N while the car is rolling with a constant speed.

It is useful to consider the effect on the net force of the angle of the incline to the horizontal. If the angle is greater than 15°, the component of weight parallel to the slope increases and the net force will no longer be zero. The speed of the car will therefore increase. The component of weight perpendicular to the slope decreases and the normal reaction force decreases by the same amount.

Revision question 11.4

(a) **A 5000 kg truck is parked on a road surface inclined at an angle of 20° to the horizontal. Calculate the component of the truck's weight that is:**
 (i) down the slope of the road
 (ii) perpendicular to the slope of the road.

(b) **In the case of the car in sample problem 11.4, what is:**
 (i) the component down the road surface of the normal reaction force acting on it
 (ii) the normal reaction force?

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Unit 2 | AOS 1 | Topic 2 | Concept 4

Newton's Second Law
Concept summary and practice questions

Newton's Second Law of Motion

Casual observations indicate that the acceleration of a given object increases as the net force on the object increases. It is also clear that lighter objects change their velocity at a greater rate than heavier objects when the same force is applied.

It can be shown experimentally that the acceleration, $\boldsymbol{a}$, of an object is:

- proportional to the net force, $\boldsymbol{F}_{\text{net}}$, applied to it
- inversely proportional to its mass, m.

$$\boldsymbol{a} \propto \boldsymbol{F}_{\text{net}} \qquad \boldsymbol{a} \propto \frac{1}{m}$$

Thus,

$$\boldsymbol{a} \propto \frac{\boldsymbol{F}_{\text{net}}}{m}$$

$$\Rightarrow \boldsymbol{a} = \frac{\text{k}\boldsymbol{F}_{\text{net}}}{m}$$

where k = a constant of proportionality.

The SI unit of force, the newton (N), is defined such that a net force of 1 N causes a mass of 1 kg to accelerate at 1 m s^{-2}. The value of the constant, k, is 1. It has no units. Thus:

$$\boldsymbol{a} = \frac{\boldsymbol{F}_{\text{net}}}{m}$$

$$\boldsymbol{F}_{\text{net}} = m\boldsymbol{a}.$$

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Newton's second law
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The previous equation describes Newton's Second Law of Motion.

This statement of Newton's second law allows you to:

- determine the net force acting on an object without knowing any of the individual forces acting on it. The net force can be deduced as long as you can measure or calculate (using formulae or graphs) the acceleration of a known mass.
- determine the mass of an object. You can do this by measuring the acceleration of an object on which a known net force is exerted.
- predict the effect of a net force on the motion of an object of known mass.

Sample problem 11.5

A 65 kg physics teacher, starting from rest, glides gracefully down a slide in the local playground. The net force on her during the slide is a constant 350 N. How fast will she be travelling at the bottom of the 8.0 m slide?

Solution:

$$\boldsymbol{F}_{net} = m\boldsymbol{a}$$
$$\Rightarrow 350 \text{ N} = 65 \text{ kg} \times \boldsymbol{a} \quad \text{(substituting magnitudes)}$$
$$\Rightarrow \boldsymbol{a} = \frac{350 \text{ N}}{65 \text{ kg}}$$
$$= 5.4 \text{ m s}^{-2}$$

Thus, $u = 0$, $a = 5.4 \text{ m s}^{-2}$, $x = 8.0$ m and $v = ?$

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

$$\Rightarrow v^2 = 0 + 2 \times 5.4 \text{ m s}^{-2} \times 8.0 \text{ m}$$
$$= 86.4 \text{ m}^2 \text{ s}^{-2}$$
$$\Rightarrow v = 9.3 \text{ m s}^{-1}$$

Revision question 11.5

(a) What is the magnitude of the average force applied by a tennis racquet to a 58 g tennis ball during service if the average acceleration of the ball during contact with the racquet is 1.2×10^4 m s^{-2}?

(b) A toy car is pulled across a smooth, polished horizontal table with a spring balance. The reading on the spring balance is 2.0 N and the acceleration of the toy car is measured to be 2.5 m s^{-2}. What is the mass of the toy car? (Note that, because the table is described as smooth and polished, friction can be ignored.)

Applying Newton's second law in real life

Of course, the revision questions presented above do not reflect what really happens. When a tennis ball is served, the force applied by the tennis racquet is not the only force acting on the ball. However, the weight of the ball and the air resistance on the ball are **negligible**; that is, they are so small compared with the force of the racquet on the ball that they can be ignored while the racquet is in contact with the ball. The table surface in revision question 11.5(b) is smooth. This description was deliberately included so that you would know that the force of friction on the toy car was negligible. If the table were not described as smooth, you could not have answered the question without assuming that it was smooth. The event described in sample problem 11.5 was also simplified. It is unlikely that the net force on the teacher gliding down the slide would be constant.

A quantity that is **negligible** is so small that it can be ignored when modelling a phenomenon or an event.

The assumptions made to answer each of the questions asked in the sample problem and revision questions are called **idealisations**. However, caution is needed when making idealisations. For example, it would be unreasonable to ignore the air resistance on a tennis ball while it was soaring through the air at 150 km h^{-1} (42 m s^{-1}) after the serve was completed.

An **idealisation** makes modelling a phenomenon or event easier by assuming ideal conditions that don't exactly match the real situation.

Most applications of Newton's second law are not as simple as those given above. Some more typical examples are presented in the following sample problems.

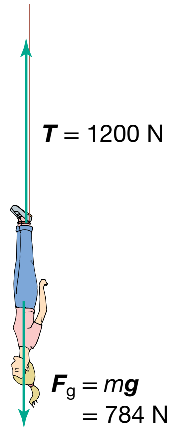
Sample problem 11.6

When the head of an 80 kg bungee jumper is 24 m from the surface of the water below, her velocity is 16 m s^{-1} downwards and the tension in the bungee cord is 1200 N. Air resistance can be assumed to be negligible.

(a) What is her acceleration at that instant?

(b) If her acceleration remained constant during the rest of her fall, would she stop before hitting the water?

Solution: Firstly, a diagram must be drawn to show the forces acting on the bungee jumper (see the figure on the top of the next page). The only two forces that need to be considered are the tension ($\boldsymbol{T}$) in the cord and the jumper's weight ($\boldsymbol{F}_g$).



The bungee jumper's weight, $F_g = mg$

$= 80 \text{ kg} \times 9.8 \text{ m s}^{-2}$ down

$= 784$ N down.

(a) Apply Newton's second law to determine the acceleration. Assign up as positive for this part of the question.

$$\boldsymbol{F}_{net} = m\boldsymbol{a}$$

$$\Rightarrow \boldsymbol{T} - \boldsymbol{F}_g = m\boldsymbol{a} \quad \text{(assigning up as positive)}$$

$$\Rightarrow 1200 \text{ N} - 784 \text{ N} = 80 \text{ kg} \times \boldsymbol{a} \quad \text{(substituting data)}$$

$$\Rightarrow 80 \text{ kg} \times \boldsymbol{a} = 416 \text{ N}$$

$$\Rightarrow \boldsymbol{a} = \frac{416 \text{ N}}{80 \text{ kg}}$$

$$\Rightarrow \boldsymbol{a} = 5.2 \text{ m s}^{-2} \text{ in an upwards direction}$$

(b) If the jumper's acceleration were constant, one of the constant acceleration formulae could be used to answer this question. Assign down as positive for this part of the question as the bungee jumper has a downwards initial velocity and displacement during the time period being considered.

$u = 16 \text{ m s}^{-1}$, $v = 0$, $a = -5.2 \text{ m s}^{-2}$, $s = ?$

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

$$\Rightarrow 0 = (16 \text{ m s}^{-1})^2 + 2\,(-5.2 \text{ m s}^{-2})s \quad \text{(substituting data)}$$

$$\Rightarrow 0 = 256 \text{ m}^2 \text{ s}^{-2} - 10.4 \text{ m s}^{-2} \times s$$

$$\Rightarrow 10.4 \text{ m s}^{-2}\, s = 256 \text{ m}^2 \text{ s}^{-2}$$

$$\Rightarrow s = 24.6 \text{ m} \quad \text{(dividing both sides by } 10.4 \text{ m s}^{-2}\text{)}$$

Alas, the bungee jumper would not stop in time. However, do not be upset! In practice, the acceleration of the bungee jumper would not be constant. The tension in the cord would increase as she fell. Therefore, the net force on her would increase and her upwards acceleration would be greater in magnitude than the calculated value. She will therefore almost certainly come to a stop in a distance considerably less than that calculated.

Sample problem 11.7

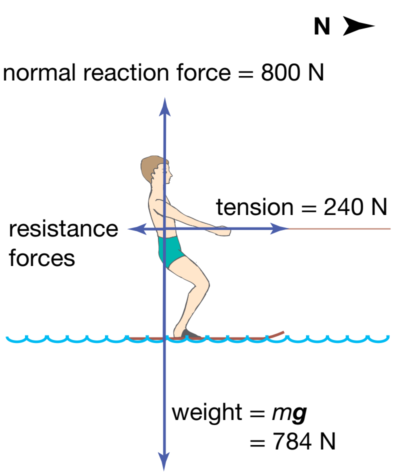
A waterskier of mass 80 kg, starting from rest, is pulled in a northerly direction by a horizontal rope with a constant tension of 240 N. After 6.0 s, he has reached a speed of 12 m s^{-1}.

(a) What is the net force on the skier?

(b) If the tension in the rope were the only horizontal force acting on the skier, what would his acceleration be?

(c) What is the sum of the resistance forces on the skier?

Solution: A diagram must be drawn to show the forces acting on the skier. Assign the positive direction as north as shown in the figure on the left.



(a) The net force cannot be determined by adding the individual force vectors because the resistance forces are not given, nor is there any information in the question to suggest that they can be ignored. It can, however, be calculated by applying Newton's second law if the acceleration is known.

$u = 0$, $v = 12 \text{ m s}^{-1}$, $t = 6.0$ s, $a = ?$

$$v = u + at$$

$$12 \text{ m s}^{-1} = 0 + a \times 6.0 \text{ s} \quad \text{(substituting data)}$$

$$\Rightarrow a \times 6.0 \text{ s} = 12 \text{ m s}^{-1} \quad \text{(dividing both sides by 6.0 s)}$$

$$\Rightarrow a = 2.0 \text{ m s}^{-2}$$

Thus,

$$\boldsymbol{F}_{net} = m\boldsymbol{a}$$

$$= 80 \text{ kg} \times 2.0 \text{ m s}^{-2} \text{ north}$$

$$= 160 \text{ N north.}$$

The net force on the skier is 160 N north.

(b) The net force on the skier is horizontal. If the tension were the only horizontal force acting on the skier, it would be equal to the net force since the vertical forces on the skier add to zero.

Thus, the acceleration would be given by:

$$\boldsymbol{a} = \frac{\boldsymbol{F}_{net}}{m}$$
$$= \frac{240\text{ N north}}{80\text{ kg}}$$
$$= 3.0\text{ m s}^{-2}\text{ north.}$$

(c) The sum of the resistance forces (friction caused by the water surface and air resistance) on the skier is the difference between the net force and the tension.

sum of resistance forces = $\boldsymbol{F}_{net}$ − tension
= 160 N north − 240 N north
= 80 N south

Sample problem 11.8

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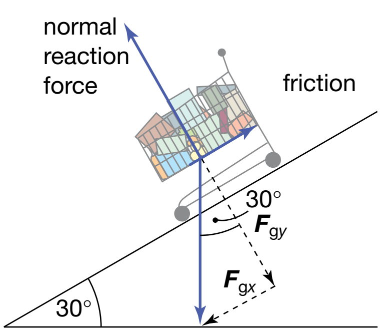
eLesson
Motion down an inclined plane
eles-0034

A loaded supermarket shopping trolley with a total mass of 60 kg is left standing on a footpath that is inclined at an angle of 30° to the horizontal. As the tired shopper searches for his car keys, he fails to notice that the trolley is beginning to roll away. It rolls in a straight line down the footpath for 9.0 s before it is stopped by an alert (and very strong) supermarket employee. Find:

(a) the speed of the shopping trolley at the end of its roll
(b) the distance covered by the trolley during its roll.

Assume that the footpath exerts a constant friction force of 270 N on the runaway trolley.

Solution:



Weight = mg
= 588 N

F_{gx} = component of weight parallel to slope

F_{gy} = component of weight perpendicular to slope

A diagram must be drawn to show the three forces acting on the shopping trolley. Air resistance is not included as it is negligible. The forces should be shown as acting through the centre of mass of the loaded trolley as in the figure on the left. The components of the weight, which are parallel and perpendicular to the footpath surface, should also be shown on the diagram.

The motion of the runaway shopping trolley, originally at rest, can be described by using the information provided, along with Newton's second law, which is used to determine its acceleration.

The net force can be found by 'breaking up' the weight into two components — one parallel to the footpath surface ($\boldsymbol{F}_{gx}$) and the other perpendicular to the surface ($\boldsymbol{F}_{gy}$). We know that $\boldsymbol{F}_{gy}$ is balanced by the normal reaction force because there is clearly no acceleration of the trolley perpendicular to the surface. The net force is therefore down the slope and has a magnitude of:

$$\boldsymbol{F}_{net} = \boldsymbol{F}_{gx} - \text{friction}$$
$$= mg\sin 30° - 270\text{ N}$$
$$= 588\text{ N}\sin 30° - 270\text{ N}$$
$$= 294\text{ N} - 270\text{ N}$$
$$= 24\text{ N.}$$

Newton's second law can now be applied to determine the acceleration of the trolley down the slope. Assign the positive direction as down the slope.

$$\boldsymbol{F}_{net} = m\boldsymbol{a}$$
$$\Rightarrow 24\text{ N down slope} = 60\text{ kg} \times \boldsymbol{a}$$
$$\boldsymbol{a} = \frac{24\text{ N down slope}}{60\text{ kg}}$$
$$= 0.40\text{ m s}^{-2}\text{ down slope}$$

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Weblink
Inclined plane

The final speed and distance travelled by the trolley can now be calculated.

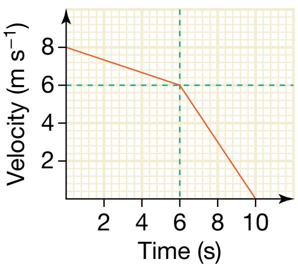
$u = 0$, $a = 0.40$ m s^{-2}, $t = 9.0$ s, $v = ?$, $s = ?$

$$\begin{aligned} v &= u + at \\ &= 0 + 0.40 \text{ m s}^{-2} \times 9.0 \text{ s} \\ &= 3.6 \text{ m s}^{-1} \end{aligned}$$

$$\begin{aligned} s &= ut + \tfrac{1}{2}at^2 \\ &= 0 \times 9.0 \text{ s} + \tfrac{1}{2} \times 0.40 \text{ m s}^{-2} \times (9.0 \text{ s})^2 \\ &= \tfrac{1}{2} \times 0.40 \text{ m s}^{-2} \times 81 \text{ s}^2 \\ &= 16.2 \text{ m} \end{aligned}$$

At the end of its roll, the trolley was travelling at a speed of 3.6 m s^{-1} and had moved a distance of 16.2 m down the slope.

Sample problem 11.9



The velocity-versus-time graph on the left describes the motion of a 45 kg girl on rollerblades as she rolls from a horizontal concrete path onto a rough horizontal gravel path.

(a) What was the magnitude of the net force on the girl on the concrete surface?

(b) If the only horizontal force acting on the blades is the friction force applied by the path, what is the value of the following ratio?

$$\frac{\text{friction force of gravel path on rollerblades}}{\text{friction force of concrete path on rollerblades}}$$

Solution: (a) The magnitude of acceleration of the girl while on the concrete surface can be determined from the first 6.0 s of the motion described by the graph. It is equal to the gradient of the graph.

$$\begin{aligned} a &= \frac{\text{rise}}{\text{run}}\left(= \frac{\Delta v}{\Delta t}\right) \\ &= \frac{-2.0 \text{ m s}^{-1}}{6.0 \text{ s}} \\ &= -0.33 \text{ m s}^{-2} \end{aligned}$$

The magnitude of the net force on the girl is therefore:

$$\begin{aligned} \boldsymbol{F}_{\text{net}} &= m\boldsymbol{a} \\ &= 45 \text{ kg} \times 0.33 \text{ m s}^{-2} \\ &= 15 \text{ N}. \end{aligned}$$

(b) If the only horizontal force acting on the rollerblades is friction, the net force on the girl is the same as the friction force on the blades. Thus:

$$\begin{aligned} \frac{\text{friction force of gravel path on rollerblades}}{\text{friction force of concrete path on rollerblades}} &= \frac{\boldsymbol{F}_{\text{net}} \text{ on girl while on gravel}}{\boldsymbol{F}_{\text{net}} \text{ on girl while on concrete}} \\ &= \frac{m\boldsymbol{a} \text{ on gravel}}{m\boldsymbol{a} \text{ on concrete}} \\ &= \frac{\boldsymbol{a} \text{ (during last 4.0 s)}}{\boldsymbol{a} \text{ (during first 6.0 s)}} \\ &= \frac{\text{gradient (for last 4.0 s)}}{\text{gradient (for first 6.0 s)}} \\ &= \frac{\dfrac{-6.0 \text{ m s}^{-1}}{4.0 \text{ s}}}{\dfrac{-2.0 \text{ m s}^{-1}}{6.0 \text{ s}}} \\ &= 4.5. \end{aligned}$$

Revision question 11.6

A loaded sled with a mass of 60 kg is being pulled across a level snow-covered field with a horizontal rope. It accelerates from rest over a distance of 9.0 m, reaching a speed of 6.0 m s^{-1}. The tension in the rope is a constant. The frictional force on the sled is 200 N. Air resistance is negligible.

(a) What is the acceleration of the sled?

(b) What is the magnitude of the tension in the rope?

Revision question 11.7

A cyclist rolls freely from rest down a slope inclined at 20° to the horizontal. The total mass of the bicycle and cyclist is 100 kg. The bicycle rolls for 12 seconds before reaching a horizontal surface. The surface exerts a constant friction force of 300 N on the bicycle.

(a) What is the net force on the bicycle (including the cyclist)?

(b) What is the acceleration of the bicycle?

(c) What is the speed of the bicycle when it reaches the horizontal surface?

Revision question 11.8

If the velocity-versus-time graph in sample problem 11.9 was applied to a car of mass 1200 kg on two road surfaces, what net force (in magnitude) acts on the car during:

(a) the first 6.0 seconds

(b) the final 4.0 seconds?

Falling down

Objects that are falling (or rising) through the air are subjected to two forces — weight and air resistance. The weight of the object is constant. The magnitude of the air resistance, however, is not constant. It depends on many factors, including the object's speed, surface area and density. It also depends on the density of the body of air through which the object is falling. The air resistance is always opposite to the direction of motion. The net force on a falling object of mass m and weight $\boldsymbol{F}_g$ can therefore be expressed as:

$$\boldsymbol{F}_{net} = m\boldsymbol{a} \qquad \text{(where } \boldsymbol{a} \text{ is the acceleration of the object)}$$
$$\Rightarrow \boldsymbol{F}_g - \text{air resistence} = m\boldsymbol{a}.$$

When dense objects fall through small distances near the surface of the Earth it is usually quite reasonable to assume that the air resistance is negligible. Thus:

$$\boldsymbol{F}_g = m\boldsymbol{a}$$
$$\Rightarrow m\boldsymbol{g} = m\boldsymbol{a} \qquad \text{(where } \boldsymbol{g} \text{ is the gravitational field strength)}$$
$$\Rightarrow \boldsymbol{g} = \boldsymbol{a}.$$

The acceleration of a body in free fall in a vacuum or where air resistance is negligible is equal to the gravitational field strength. At the Earth's surface, where $\boldsymbol{g}$ = 9.8 N kg^{-1}, this acceleration is 9.8 m s^{-2}. The units N kg^{-1} and m s^{-2} are equivalent.

$$1 \text{ N} = 1 \text{ kg m s}^{-2}$$
$$\Rightarrow 1 \text{ N kg}^{-1} = 1 \text{ kg m s}^{-2} \text{ kg}^{-1} \qquad \text{(multiplying both sides by kg}^{-1}\text{)}$$
$$\Rightarrow 1 \text{ N kg}^{-1} = 1 \text{ m s}^{-2}$$

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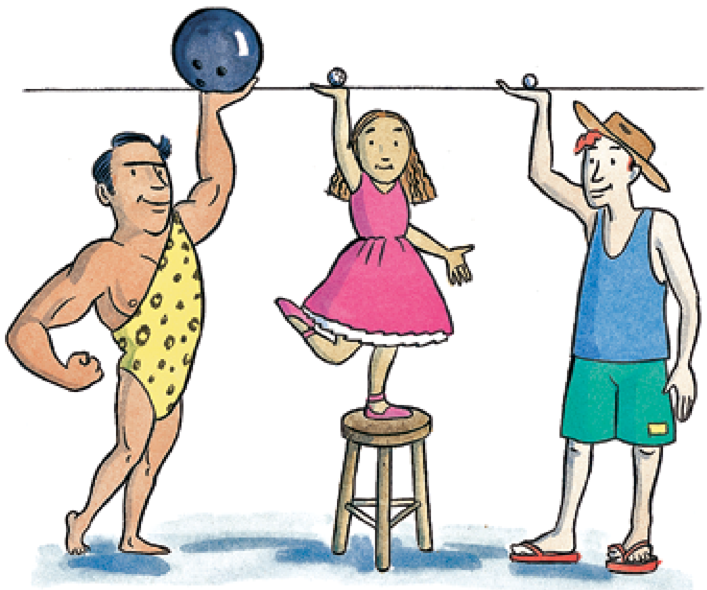
eModelling
Simulation of basketball throw
doc-0052
Analysing the fall of a bowling ball using a graphics calculator
doc-0053

If a bowling ball, a golf ball and a table-tennis ball were dropped at the same instant from a height of 2.0 m in a vacuum, they would all reach the ground at the same time. Each ball would have an initial velocity of zero, an acceleration of 9.8 m s^{-2} and a downward displacement of 2.0 m.



A bowling ball, a golf ball and a table-tennis ball dropped from a height of 2.0 m. Which one would you expect to reach the ground first?

If, however, the balls are dropped either in a classroom or outside, the table-tennis ball will reach the ground a moment later than the other two balls.

The acceleration of each of the balls is:

$$\boldsymbol{a} = \frac{\boldsymbol{F}_{\text{net}}}{m}$$

$$= \frac{m\boldsymbol{g} - \boldsymbol{A}}{m} \qquad \text{(where } \boldsymbol{A} \text{ is air resistance)}$$

$$= \frac{m\boldsymbol{g}}{m} - \frac{\boldsymbol{A}}{m}$$

$$= \boldsymbol{g} - \frac{\boldsymbol{A}}{m}.$$

The term $\frac{\boldsymbol{A}}{m}$ is very small for the bowling ball and the golf ball. Even though the air resistance on the table-tennis ball is small, its mass is also small and the term $\frac{\boldsymbol{A}}{m}$ is not as small as it is for the other two balls.

WARNING: Do not drop a bowling ball from a height of 2.0 m indoors. If you wish to try this experiment, replace the bowling ball with a medicine ball and keep your feet out of the way!

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eLesson
Air resistance
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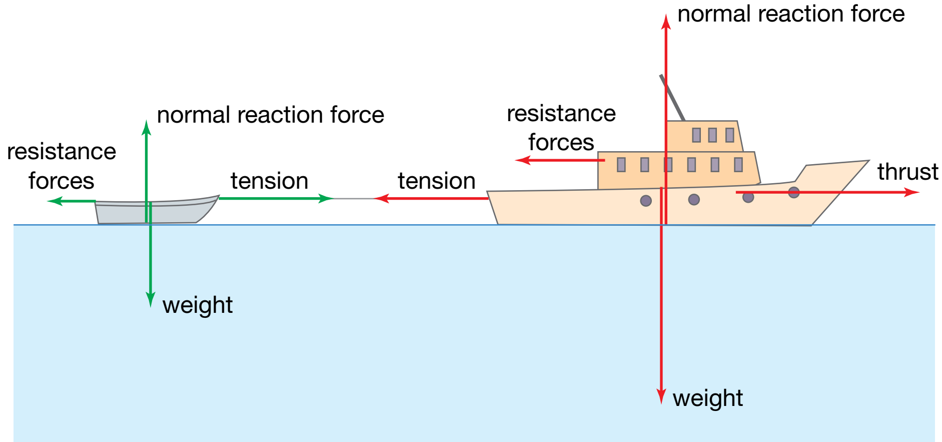
Newton's second law and tension between connected bodies

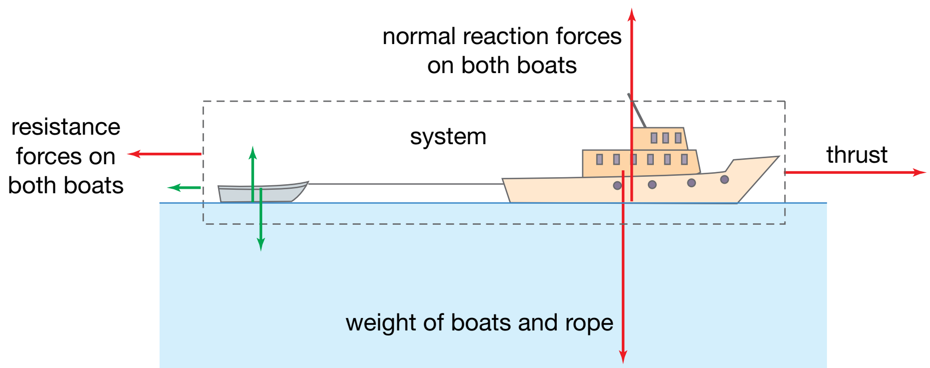
In many situations, Newton's second law needs to be applied to more than one body.

The following figure shows a small dinghy being pulled by a larger boat. The forces acting on the larger boat are labelled in red, while the forces acting on the small dinghy are labelled in green. Newton's second law can be applied to each of the two boats.



This diagram shows the forces acting on each of the two boats.

The following figure shows only the forces acting on the whole system of the two boats and the rope joining them. When Newton's second law is applied to the whole system, the system is considered to be a single object.



This diagram shows only the forces acting on the whole system. The system consists of the two boats and the rope joining them.

The thrust that acts on the larger boat and the system is provided by the water. The propeller of the larger boat pushes back on the water and the water pushes back on the propeller blades. The only force that can cause the small dinghy to accelerate forward is the tension in the rope.

If the tension in the rope is greater than the resistance forces on the dinghy, the dinghy will accelerate. If the tension in the rope is equal to the resistance forces on the dinghy, it will move with a constant velocity. If the tension in the rope is less than the resistance forces on the dinghy, it will slow down. That is, its acceleration will be negative.

The rope pulls back on the larger boat with the same tension that it applies in a forward direction on the small dinghy. This is consistent with Newton's third law. Through the rope, the larger boat pulls forward on the small dinghy with a force that is equal and opposite to the force with which the small dinghy pulls on the large boat.

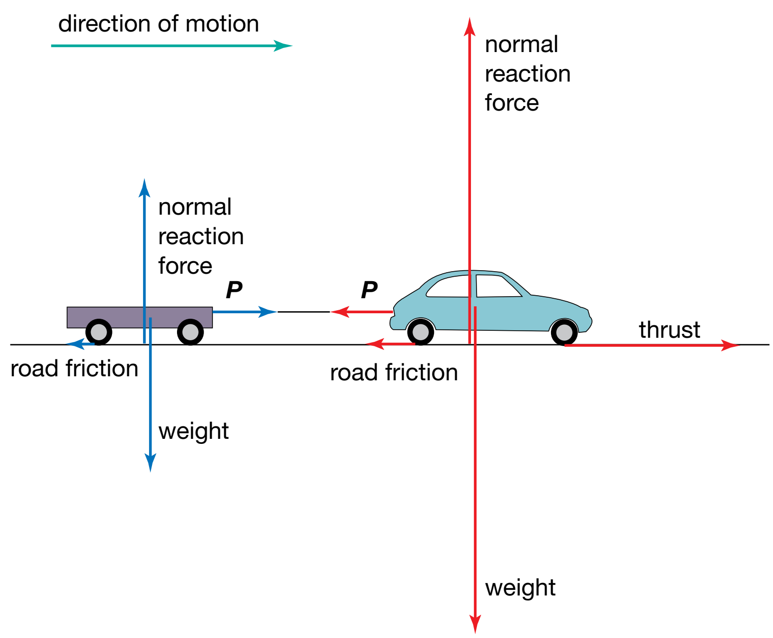
Sample problem 11.10

A car of mass 1400 kg towing a trailer of mass 700 kg accelerates at a constant rate on a horizontal road. A thrust of 5400 N is provided by the forward push of the road on the driving wheels of the car. The road friction on the car is 800 N, while that on the trailer is 400 N. The air resistance on both the car and the trailer is negligible. Determine:

(a) the acceleration of both the car and trailer

(b) the force with which the trailer is pulled by the car (labelled ***P*** in the figure below).

Solution: A diagram must be drawn to show the forces acting on the car and trailer. Assign the direction of motion as positive.



(a) Newton's second law cannot be successfully applied separately to either the car or the trailer to find the acceleration because the net force on each of them is not known. However, the acceleration of the whole system is the same as the acceleration of the car and the trailer.

The net force on the whole system is:

$$\begin{aligned} \boldsymbol{F}_{\text{net}} &= \text{thrust} - \text{road friction (car)} - \text{road friction (trailer)} \\ &= 5400 \text{ N} - 800 \text{ N} - 400 \text{ N} \\ &= 4200 \text{ N}. \end{aligned}$$

Apply Newton's second law to the system.

$$\begin{aligned} \boldsymbol{F}_{\text{net}} &= m\boldsymbol{a} \\ \Rightarrow 4200 \text{ N} &= 2100 \text{ kg} \times \boldsymbol{a} \\ \Rightarrow \boldsymbol{a} &= \frac{4200 \text{ N}}{2100 \text{ kg}} \\ &= 2.0 \text{ m s}^{-2} \text{ to the right} \end{aligned}$$

This result is very useful. The acceleration of each of the two separate objects that make up the system is also 2.0 m s^{-2}. That means that the net force acting on both the car and the trailer is known.

(b) Newton's second law can now be applied to the trailer to find the force $\boldsymbol{P}$ with which it is being pulled by the car.

$$\boldsymbol{F}_{\text{net}} = m\boldsymbol{a} \qquad (\boldsymbol{F}_{\text{net}} \text{ is the net force on the trailer.})$$

$$\Rightarrow \boldsymbol{P} - 400\ \text{N} = 700\ \text{kg} \times 2.0\ \text{m s}^{-2}$$

$$\Rightarrow \boldsymbol{P} - 400\ \text{N} = 1400\ \text{N}$$

$$\Rightarrow \boldsymbol{P} = 1800\ \text{N}$$

It is worth noting that the net force on the car can be determined by simply adding the individual forces acting on it.
The net force on the car is:

$$\begin{aligned}\boldsymbol{F}_{\text{net}} &= 5400\ \text{N} - 800\ \text{N} - \boldsymbol{P} \\ &= 5400\ \text{N} - 800\ \text{N} - 1800\ \text{N} \\ &= 2800\ \text{N to the right.}\end{aligned}$$

This is the same as the value that would be obtained by applying Newton's second law to the car.

Revision question 11.9

A boat of mass 2000 kg tows a small dinghy of mass 100 kg with a thick rope. The boat's propellers provide a forward thrust of 4700 N. The total resistance forces of air and water on the boat and dinghy system amount to 400 N and 100 N respectively.
(a) What is the acceleration of the boat and dinghy?
(b) What is the net force on the dinghy?
(c) What is the magnitude of the tension in the rope?

Using Newton's second law

1. Draw a diagram of the system.
2. Use clearly labelled arrows to represent the forces acting on each body in the system. The diagram can be simplified if necessary by drawing all forces as though they were acting through the centre of mass unless you are interested in the rotational motion.
3. Apply Newton's second law to the system and/or each individual body in the system until you have the information that you need.

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Unit 2 | AOS 1 | Topic 3 | Concept 5

Momentum and impulse
Concept summary and practice questions

Momentum and impulse

How difficult is it to stop a moving object? How difficult is it to make a stationary object move? The answer to both of these questions depends on two physical characteristics of the object:

- the object's mass
- how fast the object is moving, or how fast you want it to move.

The product of these two physical characteristics is called **momentum**. The momentum, $\boldsymbol{p}$, of an object of mass $\boldsymbol{m}$ with a velocity $\boldsymbol{v}$ is defined as: $\boldsymbol{p} = m\boldsymbol{v}$.

Momentum is a vector quantity and has SI units of kg m s^{-1}.

Momentum is the product of the mass of an object and its velocity. It is a vector quantity.

Sample problem 11.11

What is the momentum of a train of mass 8.0×10^6 kg that is travelling at a speed of 15 m s^{-1} in a northerly direction?

Solution:

$m = 8.0 \times 10^6$ kg, $\boldsymbol{v} = 15$ m s^{-1} north

$$\begin{aligned}\boldsymbol{p} &= m\boldsymbol{v} \\ &= 8.0 \times 10^6\ \text{kg} \times 15\ \text{m s}^{-1}\ \text{north} \\ &= 1.2 \times 10^7\ \text{kg m s}^{-1}\ \text{north}\end{aligned}$$

Revision question 11.10

A car of mass 1200 kg travels east with a constant speed of 15 m s^{-1}. It then undergoes a constant acceleration of 3.0 m s^{-2} for 2.0 seconds. What is the momentum of the car:
(a) before it accelerates
(b) at the end of the 2.0 s acceleration?

Making an object stop, or causing it to start moving, requires a non-zero net force. The relationship between the net force applied to an object and its momentum can be explored by applying Newton's second law to the object.

$$\boldsymbol{F}_{\text{net}} = m\boldsymbol{a}$$

$$\Rightarrow \boldsymbol{F}_{\text{net}} = m\left(\frac{\Delta \boldsymbol{v}}{\Delta t}\right)$$

$$\Rightarrow \boldsymbol{F}_{\text{net}}\Delta t = m\Delta \boldsymbol{v}$$

The **impulse** of a force is the product of the force and the time interval over which it acts. Impulse is a vector quantity.

The product $\boldsymbol{F}_{\text{net}}\Delta t$ is called the **impulse** of the net force. The impulse of any force is defined as the product of the force and the time interval over which it acts. Impulse is a vector quantity with SI units of N s.

$$m\Delta \boldsymbol{v} = m(\boldsymbol{v} - \boldsymbol{u})$$
$$= m\boldsymbol{v} - m\boldsymbol{u}$$
$$= \boldsymbol{p}_{\text{f}} - \boldsymbol{p}_{\text{i}}$$

where
$\boldsymbol{p}_{\text{f}}$ = the final momentum of the object
$\boldsymbol{p}_{\text{i}}$ = the initial momentum of the object.

Thus, the effect of a net force on the motion of an object can be summarised by the statement: impulse = change in momentum.
In fact, when translated from the original Latin, Newton's second law reads:

The rate of change of momentum is directly proportional to the magnitude of the net force and is in the direction of the net force.

This is expressed algebraically as:

$$\boldsymbol{F}_{\text{net}} \propto \frac{\Delta \boldsymbol{p}}{\Delta t}$$

$$\Rightarrow \boldsymbol{F}_{\text{net}} = \text{k}\frac{\Delta \boldsymbol{p}}{\Delta t}.$$

The SI unit of force, the newton, has been defined so that the constant of proportionality, k, equals 1.
Thus:

$$\Rightarrow \boldsymbol{F}_{\text{net}} = \frac{\Delta \boldsymbol{p}}{\Delta t}.$$

Sample problem 11.12

A 30 g squash ball hits a wall horizontally at a speed of 15 m s^{-1} and bounces back in the opposite direction at a speed of 12 m s^{-1}. It is in contact with the wall for an interval of 1.5×10^{-3} seconds.
(a) What is the change in momentum of the squash ball?
(b) What is the impulse on the squash ball?
(c) What is the magnitude of the force exerted by the wall on the squash ball?

Solution: Assign the initial direction of the ball as positive.

(a) $\Delta \boldsymbol{p} = m\boldsymbol{v} - m\boldsymbol{u}$

$= m(\boldsymbol{v} - \boldsymbol{u})$

$= 0.030 \text{ kg} (-12 \text{ m s}^{-1} - 15 \text{ m s}^{-1})$

$= 0.030 \text{ kg} \times -27 \text{ m s}^{-1}$

$= -0.81 \text{ kg m s}^{-1}$

(b) impulse of the net force on the squash ball

= change in momentum of the squash ball

$= -0.81 \text{ kg m s}^{-1}$

$= -0.81 \text{ N s}$

It can be shown that $1 \text{ N s} = 1 \text{ kg m s}^{-1}$.

We know that the net force on the squash ball is the force exerted by the wall since there is no change in the vertical motion of the ball. It is reasonable to ignore air resistance.

(c) magnitude of impulse $= \boldsymbol{F}\Delta t$

$$\Rightarrow 0.81 \text{ N s} = \boldsymbol{F} \times 1.5 \times 10^{-3} \text{ s}$$

$$\Rightarrow \boldsymbol{F} = \frac{0.81 \text{ N s}}{1.5 \times 10^{-3} \text{ s}}$$

$$\Rightarrow \boldsymbol{F} = 540 \text{ N}$$

Revision question 11.11

During a crash test a 1400 kg car travelling at 16 m s^{-1} collides with a steel barrier and rebounds with an initial speed of 4.0 m s^{-1} before coming to rest. The car is in contact with the barrier for 1.4 seconds. What is the magnitude of:

(a) the change in momentum of the car during contact with the barrier

(b) the impulse applied to the car by the barrier

(c) the force exerted by the barrier on the car?

Impulse from a graph

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Investigation 11.3:
Impulse, momentum and Newton's Second Law of Motion

doc-16185

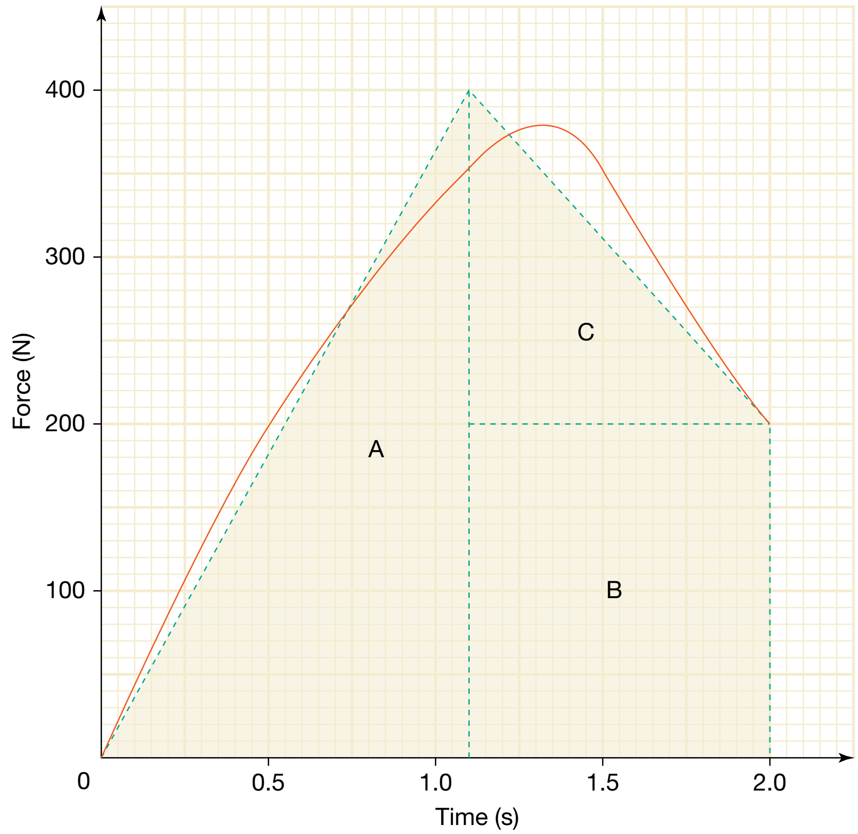
The force that was determined in sample problem 11.12 was actually the average force on the squash ball. In fact, the force acting on the squash ball changes, reaching its maximum magnitude when the centre of the squash ball is at its smallest distance from the wall. The impulse ($\boldsymbol{I}$) delivered by a changing force is given by:

$\boldsymbol{I} = \boldsymbol{F}_{av} \Delta t$.

If a graph of force versus time is available, the impulse can be determined from the area under the graph. (You might recall that the displacement of an object can be determined by calculating the area under its velocity-versus-time graph — and displacement = $\boldsymbol{v}_{av}\Delta t$. Similarly, the change in velocity of an object can be determined by calculating the area under its acceleration-versus-time graph — and change in velocity = $\boldsymbol{a}_{av} \Delta t$.)

Sample problem 11.13

The graph below describes the changing horizontal force on a 40 kg ice-skater as she begins to move from rest. Estimate her speed after 2.0 seconds.



Solution: The magnitude of the impulse on the skater can be determined by calculating the area under the graph. This can be determined either by counting squares or by finding the shaded area.

$$\begin{aligned}\text{magnitude of impulse} &= \text{area A} + \text{area B} + \text{area C}\\ &= \tfrac{1}{2} \times 1.1\text{ s} \times 400\text{ N} + 0.9\text{ s} \times 200\text{ N} + \tfrac{1}{2} \times 0.9\text{ s} \times 200\text{ N}\\ &= 220\text{ N s} + 180\text{ N s} + 90\text{ N s}\\ &= 490\text{ N s}\end{aligned}$$

$$\text{impulse} = \text{change in momentum} = m\Delta \boldsymbol{v}$$

$$\Rightarrow 490\text{ N s} = 40\text{ kg} \times \Delta \boldsymbol{v}$$

$$\Rightarrow \Delta \boldsymbol{v} = \frac{490\text{ N s}}{40\text{ kg}}$$

$$= 12\text{ m s}^{-1}$$

As her initial speed is zero (she started from rest), her speed after 2.0 seconds is 12 m s^{-1}.

Revision question 11.12

Consider the motion described in sample problem 11.13.
(a) Estimate the speed of the skater after 1.1 s.
(b) What is the acceleration of the skater during the first 1.1 s?
(c) What constant force would produce the same change in speed after 2.0 s?

Golfers are advised to 'follow through'. The force is applied to the ball for a longer time, giving it more momentum.

Follow through

Players of ball games are often advised to 'follow through.' The force is then applied to the ball by the bat, racquet, club, stick or arm for a larger time interval. The impulse, $\boldsymbol{F}\Delta t$, is larger and the change in momentum, $\Delta\boldsymbol{p}$, is therefore larger. Consequently, the change in velocity of the ball as a result of the applied force is greater.

Protecting that frail human body

The human body does not cope very well with sudden blows. The skeleton provides a fairly rigid frame that protects the vital organs inside and, with the help of your muscles, enables you to move. A sudden impact to your body, or part of your body, can:

- push or pull the bones hard enough to break them
- tear or strain the ligaments that hold the bones together
- tear or strain muscles or the tendons that join muscles to bones
- push bones into vital organs like the brain and lungs
- tear, puncture or crush vital organs like the kidneys, liver and spleen.

The damage that is done depends on the magnitude of the net force and the subsequent acceleration to which your body is subjected. In any collision, the net force acting on your body, or part of your body, can be expressed as:

$$\boldsymbol{F}_{\text{net}} = \frac{\Delta\boldsymbol{p}}{\Delta t}.$$

The symbol $\Delta\boldsymbol{p}$ represents the change in momentum of the part of your body directly affected by that net force. The magnitude of your change in momentum is usually beyond your control. For example, if you are sitting in a car travelling at 100 km h^{-1} when it hits a solid concrete wall, the magnitude of the change in momentum of your whole body during the collision will be your mass multiplied by your initial speed. When you land on a basketball court after a high jump, the magnitude of the change in momentum of each knee will be its mass multiplied by its speed just as your feet hit the floor. You have no control over your momentum.

You do, however, have control over the time interval during which the momentum changes. If Δt can be increased, the magnitude of the net force applied to you will be decreased. You can do this by:

- bending your knees when you land after jumping in sports such as netball and basketball. This increases the time interval over which your knees change their momentum, and decreases the likelihood of ligament damage.
- moving your hand back when you catch a fast-moving ball in sports such as cricket. The ball changes its momentum over a longer time interval, reducing the force applied to it by your hand. In turn, the equal and opposite force on your hand is less.

Gloves make it possible for wicketkeepers to catch a solid cricket ball travelling at high speed without severe pain and bruising.

Helmets save lives and prevent serious injury in many activities.

- wearing gloves and padding in sports such as baseball, softball and gridiron. Thick gloves are essential for wicketkeepers in cricket, who catch the solid cricket ball while it is travelling at speeds up to 150 km h^{-1}.
- wearing footwear that increases the time interval during which your feet stop when they hit the ground. This is particularly important for people who run on footpaths and other hard surfaces. Indoor basketball and netball courts have floors that, although hard, bend a little, increasing the period of impact of running feet.

Don't be an egghead

After bicycle helmets became compulsory in Victoria in July 1990, the number of head injuries sustained by cyclists decreased dramatically. Bicycle helmets typically consist of an expanded polystyrene liner about 2 cm thick, covered in a thin, hard, polymer shell. They are designed to crush on impact.

In a serious bicycle accident, the head is likely to collide at high speed with the road or another vehicle. Even a simple fall from a bike can result in the head hitting the road at a speed of about 20 km h^{-1}. Without the protection of a helmet, concussion is likely as the skull decelerates and collides with the brain because of the large net force on it. If the net force and subsequent deceleration is large enough, the brain can be severely bruised or torn, resulting in permanent brain damage or death. The effect is not unlike that of dropping a soft-boiled egg onto a hard floor.

Although a helmet does not guarantee survival in a serious bicycle accident, it does reduce the net force applied to the skull, and therefore increases the chances of survival dramatically. The polystyrene liner of the helmet increases the time interval during which the skull changes its momentum.

Helmets used by motorcyclists, as well as in horse riding, motor racing, cricket and many other sports, all serve the same purpose — to increase the time interval over which a change in momentum takes place.

Newton's second law and seatbelts

In a high-speed head-on car collision, each car comes to a stop rapidly. An occupant not wearing a seatbelt continues at the original speed of the car (as described by Newton's first law) until acted on by a non-zero net force. An unrestrained occupant therefore moves at high speed until:

- colliding with part of the interior of the car, stopping even more rapidly than the car itself, usually over a distance of only several centimetres
- crashing through the stationary, or almost stationary, windscreen into the object collided with, or onto the road
- crashing into another occupant closer to the front of the car.

An occupant properly restrained with a seatbelt stops with the car. In a typical suburban crash, the acceleration takes place over a distance of about 50 cm. The rate of change of the momentum of a restrained occupant is much less. Therefore, the net force on the occupant is less. As well as increasing the time interval over which the occupant comes to a stop, a properly fitted seatbelt:

- spreads the force over a larger area of the body
- reduces the likelihood of a collision between the body and the interior of the vehicle
- protects the occupant from crashing through the windscreen or a door.

PHYSICS IN FOCUS

Computer crash modelling

Automotive engineers use computer modelling during the design and development of new vehicles to investigate the effectiveness of safety features. This sort of crash modelling takes place long before the first prototype is built and the first physical crash tests take place.

Computer crash modelling has resulted in improvements to front and side structural design and to internal safety features such as seatbelt and airbag systems. Modelling crashes allows the investigation of a wide range of collision types, including full frontal, offset frontal, angled frontal and pole or barrier; collisions between trucks and cars; and rear impacts. The possibilities are endless. The computer models are then verified with the crash testing of real vehicles.

During side-impact modelling, the computer is used to test thousands of combinations of seatbelt, cushioning and airbag designs. For each test, the computer calculates the forces acting on occupants, estimates the severity and even the costs of injuries, and compares results with other design solutions.

One aspect of design that can be tested is the sensor that triggers airbags to inflate. Complex calculations and comparisons are performed by a microprocessor within the sensing module before it 'decides' whether or not to trigger the airbags. The crash events that are modelled to develop the airbag sensors include high- and low-speed collisions, full-frontal and angled-frontal impacts and pole- or tree-type collisions.

Engineers use computers to model collisions to design and develop features that improve the safety characteristics of cars. Computer modelling takes place long before the real crash tests are performed.

A vehicle that has undergone a roof crush test

Cars that crumple

Modern cars are designed to crumple at the front and rear. This provision increases the time interval during which the momentum of the car changes in a collision, further protecting its occupants from death or serious injury. Even though the front and rear of the car crumple, the passenger compartment is protected by a rigid frame. The engine is also surrounded by rigid structures that prevent it from being pushed into the passenger compartment. The tendency of the roof to crush is currently being reduced by increasing the thickness of the windscreen and side windows, using stronger adhesives and strengthening the roof panel.

The inside of the passenger compartment is also designed to protect occupants. Padded dashboards, collapsible steering wheels and airbags are designed to reduce the rate of change of momentum of occupants in the event of a collision. Interior fittings like switches, door knobs and handbrakes are sunk so that the occupants do not collide with them.

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Unit 2 | AOS 1 | Topic 3 | Concept 3

Torque
Concept summary and practice questions

Torque or turning effect of a force

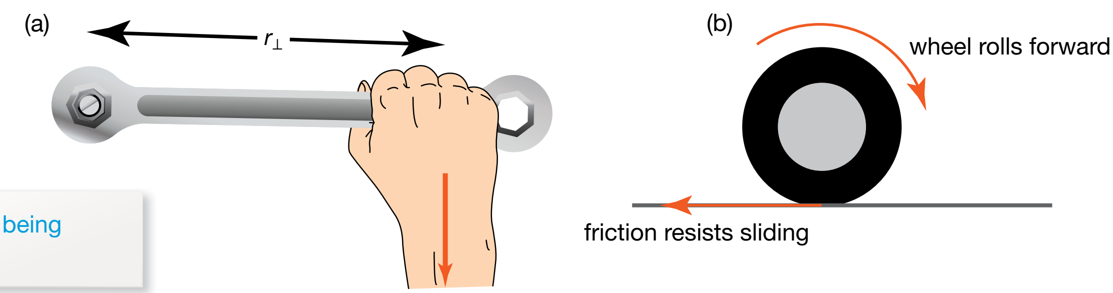
So far the explanation of forces and motion has treated objects as if they are a single point, or as if the force acts through the middle of the object; that is, its centre of mass. However, nature is more complicated than this. Friction acts at the rim of the front tyre of a bike to make it roll, the thigh muscle straightens the leg, a billiard cue hits the bottom edge of a ball to make it spin backwards, the wind blows over a tree, a pull on a handle opens the door. All these actions involve rotation, and a force has made the object turn.

The turning effect of a force is called a torque. The symbol for torque is τ, the Greek letter *tau*. The size of a torque about a point or pivot is determined by the product of two factors:

- the size of the force, $\boldsymbol{F}$, and
- the perpendicular distance between the line of action of the force and the pivot, $r_\perp$.

$$\tau = r_\perp \boldsymbol{F}$$

As a product of force and distance, torque has the units of Newton metre (Nm). It is also a vector, but because its effect is rotation, the direction of the vector is set by a rule. The rule is: 'If the rotation in the plane of the page is clockwise, the direction of the vector is into the page.'



Examples of torque being applied

Sample problem 11.14

A torque wrench is used to tighten nuts onto their bolts to a specific tightness or force. A torque wrench has a handle (black in the photo below) on one end and a socket that fits over a nut on the other end. In between is a scale that gives a reading in Newton metres.

The scale on a torque wrench has a reading of 30 Newton metres. If the hand applying the force is 30 cm from the end, what is the size of the force by the hand on the wrench?

Solution:

torque, $\tau = 30$ Nm

distance, $r_\perp = 0.30$ m

So force, $\boldsymbol{F} = \tau / r_\perp$

$= 30 \text{ Nm} / 0.30 \text{ m}$

$= 100$ N

Revision question 11.13

The handle of a torque wrench is hollow so an extension rod can be inserted. If you can exert only 30 N of force, how far along the extension rod from the handle should you place your hand to achieve a torque of 30 Nm?

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Unit 2	Rotational equilibrium
AOS 1	Concept summary and practice questions
Topic 3	
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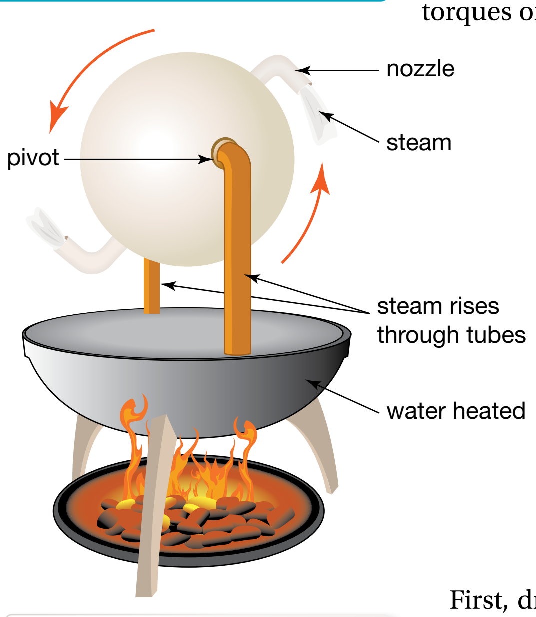
Equilibrium or keeping still

Earlier in this chapter, 'keeping still' meant not moving. If the net force was zero and the object was at rest, it would stay still. The forces were considered as acting on a single point. However, if the forces act at different points on the object, it is possible to have a net force of zero, but the object can still spin. In the diagram on the left, the force upwards equals the force downwards, so the net force is zero, but the sphere rotates. In this case there is a net torque. The torques of the two forces about the centre add together.



A zero net force can cause rotation.

In cases such as car engines and electric motors, the production of a torque is essential for rotation and movement. But torque, and the rotation and movement it causes, can be detrimental. In bridges and buildings, the torque effect of a force can't be avoided, but needs to be controlled if the structure is to remain standing. Such structures need to be designed so that not only is the net force equal to zero, but the net torque is also zero, and importantly this is true about every point in the structure.

For a structure to be stable, two conditions need to apply:

1. net force = zero
2. net torque about any point = zero.

Strategy for solving problems involving torque

Questions regarding torque will often involve determining the value of two forces, so the solution will require generating two equations, which can then be solved simultaneously.

First, draw a diagram with all the forces acting on the structure. Label each force. If its size is given in the question, write the value, e.g. 10 N. If the size of the force is unknown, use a symbol such as ***F*** or ***R***.

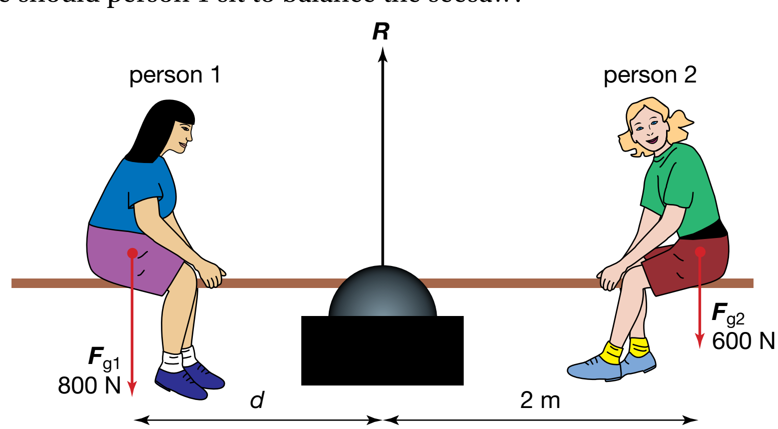
1. Net force = zero. It is easier to break this up into two simpler tasks:
   (a) Sum of forces up = Sum of forces down and
   (b) Sum of forces left = Sum of forces right.
2. Net torque about any point = zero. Choose a point about which to calculate the torques. Any point will do, but it makes solving the problem easier if you choose a point through which an unknown force acts. The torque of this force about that point will be zero as its line of action passes through the point.

   Sum of clockwise torques = Sum of anticlockwise torques.

Now you will have two equations with two unknowns; one equation from 2, above and one from 1.

Sample problem 11.15

Where should person 1 sit to balance the seesaw?



Solution: To satisfy equilibrium, both the sum of the forces acting on the seesaw and the sum of the torques must equal zero.

From net force = zero:

Sum of forces up = sum of forces down

$$R = 800\text{ N} + 600\text{ N}$$
$$R = 1400\text{ N upwards.}$$

Taking torques about the fulcrum at the centre:

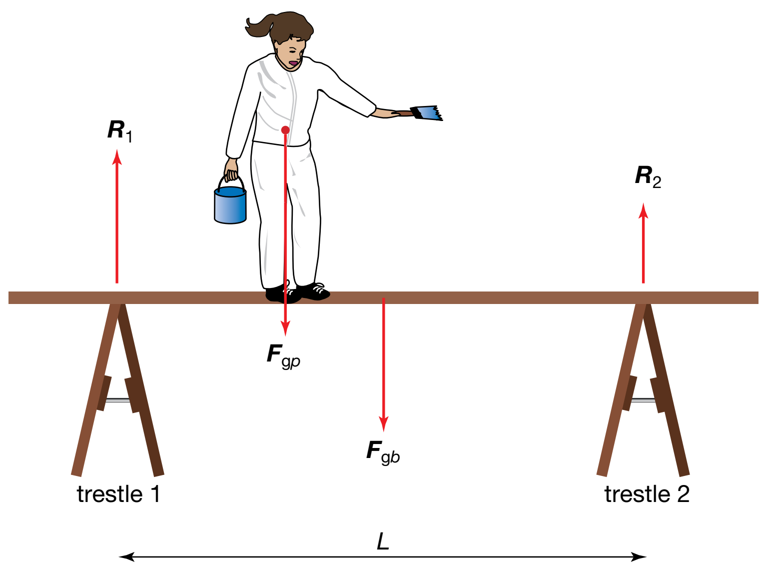
Sum of clockwise torques = sum of anticlockwise torques

$$600\text{ N} \times 2\text{ m} = 800\text{ N} \times d\text{ m}$$
$$d = 1.5\text{ m.}$$

Taking torques about person 1 gives the same answer as when torques are taken about the fulcrum but uses the calculated value of R. Take torques about person 2 and see if you get the same answer. Was the calculation as simple as when the torques were taken about the fulcrum?

Sample problem 11.16

Consider the painter's plank supported between two trestles shown below. The plank behaves as a simple bridge or beam, and the weight of the painter must be transferred through the plank to the two trestles. The mass of the beam is 40 kg, the mass of the painter is 60 kg and she is a quarter of the distance from trestle 1. What is the magnitude of the reaction forces R_1 and R_2?



Solution: If the structure is stable, both the sum of forces and the sum of torques must equal zero.

From net force = zero:

Sum of forces up = sum of forces down

$$R_1 + R_2 = 40 \times 9.8\text{ N} + 60 \times 9.8\text{ N} \quad (1)$$
$$= 980\text{ N}$$

Taking torques about trestle 1:

Sum of clockwise torques = sum of anticlockwise torques

$$40 \times 9.8 \times \frac{1}{4} L + 60 \times 9.8 \times \frac{1}{2} L = R_2 \times L$$

Cancel L gives:

$$98 + 294 = R_2 \quad (2)$$
$$R_2 = 392\text{ N}$$

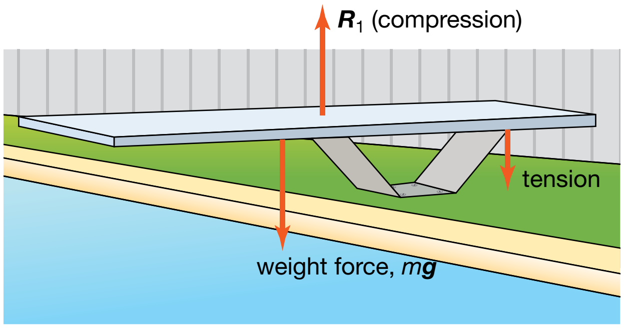
Substituting into (1) gives $R_1 + 392 = 980$ N

$$R_1 = 588\text{ N}$$

Types of structures: cantilevers

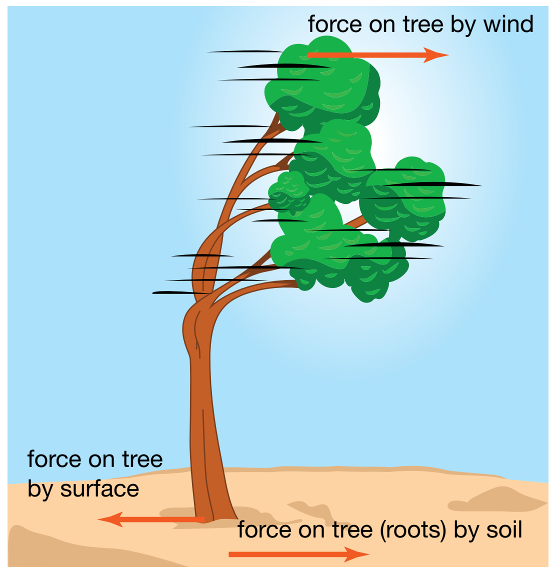
A cantilever is a beam with one end free to move. A diving board, flagpole and a tree are examples of cantilevers.

The diving board shown at left is supported by an upward force, R_1, from the bracket. The weight force acts down through the middle of the board at a point further out. If these were the only forces on the diving board, the board would rotate anticlockwise. To prevent this rotation, the other end of the bracket pulls down on the diving board. The board is bolted to each end of the bracket. At which end are the bolts not needed?



A diving board is an example of a cantilever.

The tree shown below is buffeted by winds from the left. The soil on the right at the base of the tree is compressed and pushes back to the left. The combination of these two forces pushes the roots of the tree to the left, and the soil to the left of the roots pushes back to the right.



A tree buffeted by winds is a cantilever.

Revision question 11.14

A eucalyptus tree, 15 m high and with a 200 cm diameter, was pulled over until it failed. The applied load was 6 kN m about the base of the tree.

(a) If the root ball of the tree has an average depth of 0.80 m, what is the size of the force by the soil on the root ball at the point of failure?

(b) If the rope pulling on the tree was attached halfway up the tree, calculate at the point of failure:

(i) the size of the force in the rope (assuming the rope is horizontal) and

(ii) the size of the force by the ground at the base of the tree.

Practical investigations

- Compare the accuracy of different methods of determining ***g***.
- Investigate the friction of running shoes or of a towel falling off a rack.
- Investigate the compression and tension behaviour of plasticine.
- A wet rag is hard to drag when it is spread out and pulled across the floor. What does the resistive force depend on?
- Design and test a safety helmet for a papier mâché 'egg'.

Chapter review

Summary

- Force is a vector quantity.
- Weight is a measure of the force on an object due to the pull of gravity.
- The weight of an object is directly proportional to its mass.
- The vector sum of the forces acting on an object is called the net force.
- The velocity of an object can change only if a non-zero net force acts on it. This statement is an expression of Newton's First Law of Motion.
- When a non-zero net force acts on an object, the object accelerates in the direction of the net force.
- The forces acting on a moving vehicle are:
  - weight, acting down through the centre of mass
  - the normal reaction force, applied perpendicular to the surface of the road
  - the driving force, applied in the direction of motion by the road
  - road friction, applied to the non-driving wheels opposite to the direction of motion
  - air resistance, applied opposite to the direction of motion.
- The motion of a vehicle depends on the net force acting on the vehicle.
- Newton's Second Law of Motion describes the relationship between the acceleration of an object, the net force acting on it, and the object's mass. It can be expressed as $\boldsymbol{F}_{net} = m\boldsymbol{a}$.
- Newton's second law can be applied to a single object or a system of multiple bodies that are in contact or connected together.
- When an object applies a force to a second object, the second object applies an equal and opposite force to the first object. This statement is an expression of Newton's Third Law of Motion.
- The momentum of an object is the product of its mass and its velocity.
- The impulse delivered to an object by a force is the product of the force and the time interval during which the force acts on the object.
- The impulse delivered by the net force on an object is equal to the change in momentum of the object. This can be expressed as $\boldsymbol{F}_{net}\Delta t = m\Delta\boldsymbol{v}$.
- The impulse delivered by a force can be found by determining the area under a graph of force versus time.
- The damage done to the human body during a collision depends on the magnitude of the net force and subsequent acceleration the body is subjected to.
- The net force on a human body during a collision can be decreased by increasing the time interval during which the body's momentum changes. Increasing the time interval to reduce the net force, and hence damage, to the human body is used to advantage in many sports and in road safety.

Questions

In answering the questions that follow, assume that the magnitude of the gravitational field strength near the Earth's surface is 9.8 N kg^{-1}.

An attraction to the Earth

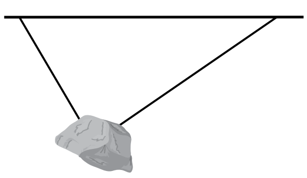
1. A slightly overweight physics teacher steps off the bathroom scales and proudly remarks, 'My weight is down to 75 kg!'. The physics teacher clearly should have known better! Rewrite the remark in two different ways so that it is correct.
2. Describe the difference between a vector quantity and a scalar quantity.
3. Which of the following are vector quantities?
   (a) Mass
   (b) Weight
   (c) Gravitational field strength
   (d) Time
   (e) Energy
   (f) Temperature
4. Take a quick look at questions 5 and 6. Why are you being asked to determine the magnitude of the weight rather than the weight?
5. A car has a mass of 1400 kg with a full petrol tank.
   (a) What is the magnitude of its weight at the surface of the Earth?
   (b) What would be the magnitude of the weight of the car on the surface of Mars where the magnitude of the gravitational field strength is 3.6 N kg^{-1}?
   (c) What is the mass of the car on the surface of Mars?
6. Estimate the magnitude of the weight at the surface of the Earth of:
   (a) an apple
   (b) this book
   (c) your physics teacher.
7. Estimate your own mass in kilograms and determine:
   (a) the magnitude of your weight at the surface of the Earth
   (b) the magnitude of your weight on the surface of Mars where the magnitude of the gravitational field strength is 3.6 N kg^{-1}
   (c) your mass on the planet Mars.

Force diagrams

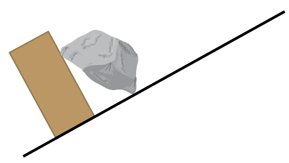
8. Draw force diagrams for the following:
- (a) an open parachute falling slowly to the ground. Consider air resistance.
- (b) a thrown basketball approaching its maximum height before coming down into the basket
- (c) a car approaching a red light rolling slowly to a stop
- (d) a rocket at lift off.

9. Draw force diagrams for the following:

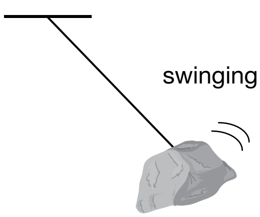
(a)



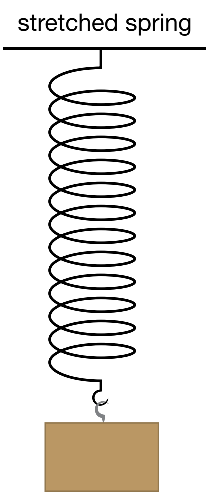
(b)



(c)



(d)

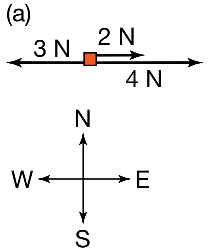


The net force

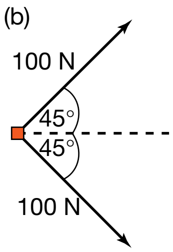
10. A person is standing on a horizontal floor. Draw and label in the form $\boldsymbol{F}_{\text{on A by B}}$ all of the forces acting on the person, the floor and the Earth.

11. Determine the net force in the situations illustrated in diagrams (a) and (b) below.

(a)

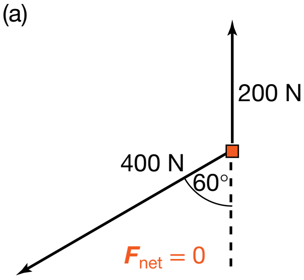


(b)

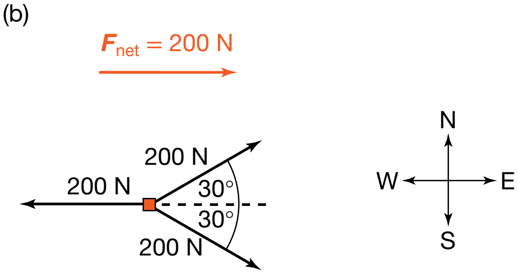


12. In the illustrations below, the net force is shown along with all but one of the contributing forces. Determine the magnitude and direction of the missing force.

(a)



(b)



13. A car is moving north on a horizontal road at a constant speed of 60 km h^{-1}.
- (a) Draw a diagram showing all of the significant forces acting on the car. Show all of the forces as if they were acting through the centre of mass.
- (b) What is the net force on the car?

Newton's First Law of Motion

14. When you are standing on a bus, train or tram that stops suddenly, you lurch forwards. Explain why this happens in terms of Newton's first law.

15. If the bicycle that you are riding runs into an obstacle such as a large rock, you may be flung forwards over the handlebars. Explain in terms of Newton's first law why this happens.

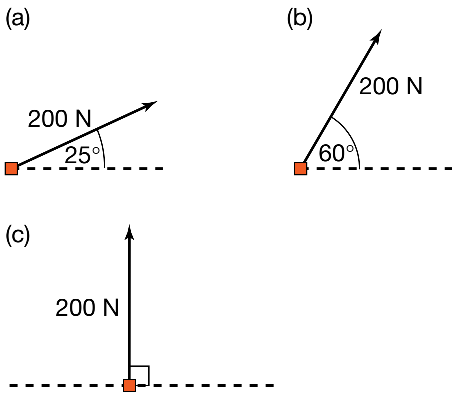
Forces in two dimensions

16. A ball rolls down a hill with an increasing speed.
- (a) Draw a diagram to show all of the forces acting on the ball.
- (b) What is the direction of the net force on the ball?
- (c) What is the largest single force acting on the ball?
- (d) When the ball reaches a horizontal surface, it slows, eventually coming to a stop. Explain, with the aid of a diagram, why this happens.

17. When you try to push a broken-down car with its handbrake still on, it does not move. What other forces are acting on the car to produce a net force of zero?

18. Redraw the figure on page 189 for a car with rear-wheel drive.

19. Determine the magnitude of the horizontal components of each of the forces shown in the illustrations below.



Newton's Second Law of Motion

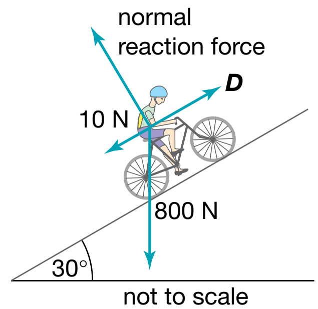
20. What is an idealisation? Illustrate your answer with an example.

21. When a space shuttle takes off, its initial acceleration is 3.0 m s^{-2}. It has an initial mass of about 2.2×10^6 kg.
- (a) Determine the magnitude of the net force on the space shuttle as it takes off.
- (b) What is the magnitude of the upward thrust as it takes off?

22. A 6 kg bowling ball and a 60 kg gold bar are dropped at the same instant from the third floor of the Leaning Tower of Pisa. Use Newton's second law to explain why:
- (a) they both reach the ground at the same time
- (b) a 6 kg doormat dropped from the same location at the same time takes significantly longer to reach the ground.

23. A bungee jumper of mass 70 kg leaps from a bridge.
- (a) What is the weight of the bungee jumper?
- (b) During which part of the jump is:
  - (i) the upwards force on the jumper due to the tension in the bungee cord greater than the jumper's weight
  - (ii) the weight of the jumper greater than the upward pull of the bungee cord?
- (c) What tension in the bungee cord is needed for the jumper to travel at a constant speed? Does this occur at any time during the jump? Explain.

24. A cyclist of mass 60 kg is riding up a hill inclined at 30° to the horizontal at a constant speed. The mass of the bicycle is 20 kg. The figure that follows shows the forces acting on the bicycle–cyclist system.



- (a) What is the net force on the bicycle–cyclist system?
- (b) The sum of the magnitudes of the road friction and air resistance on the system is 10 N. What is the magnitude of the component of the weight of the system that is parallel to the road surface?
- (c) What is the magnitude of the driving force ***D***?
- (d) What is the magnitude of the normal reaction force on the bicycle–cyclist system?

25. An experienced downhill skier with a mass of 60 kg (including skis) is moving down a slope inclined at 30° with increasing speed. She is moving in a straight line down the slope.
- (a) What is the direction of the net force on the skier?
- (b) Draw a diagram showing the forces acting on the skier. Show all of the forces as if they were acting through her centre of mass.
- (c) What is the magnitude of the component of the skier's weight that is parallel to the slope?
- (d) If the sum of the forces resisting the movement of the skier down the slope is 8.0 N, what is the magnitude of the net force on her?

26. A car of mass 1200 kg starts from rest on a horizontal road with a forward thrust of 10 000 N. The resistance to motion due to road friction and air resistance totals 2500 N.
- (a) What is the magnitude of the net force on the car?
- (b) What is the magnitude of the acceleration of the car?
- (c) What is the speed of the car after 5.0 s?
- (d) How far has the car travelled after 5.0 s?

27. A train of mass 8.0×10^6 kg travelling at a speed of 25 m s^{-1} is required to stop over a maximum distance of 360 m. What frictional force must act on the train when the brakes are applied if the train is to do this?

28. A short-sighted skier of mass 70 kg suddenly realises while travelling at a speed of 12 m s^{-1} that there is a steep cliff 50 m straight ahead. What frictional force is required on the skier if he is to stop just before he skis off the edge of the cliff?

29. A physics teacher decides, just for fun, to stand on some bathroom scales (calibrated in newtons) in a lift. The scales provide a measure of the force with which they push up on the teacher. When the lift is stationary, the reading on the bathroom scales is 700 N. What will be the reading on the scales when the lift is:

(a) moving upwards at a constant speed of 2.0 m s^{-1}

(b) accelerating downwards at 2.0 m s^{-2}

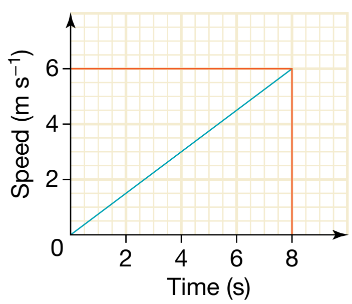
(c) accelerating upwards at 2.0 m s^{-2}?

30. The cable holding a lift would break if the tension in it were to exceed 25 000 N. If the 480 kg lift has a load limit of 24 passengers whose average mass is 70 kg, what is the maximum possible upwards acceleration of the lift without breaking the cable?

31. A downhill skier of mass 60 kg accelerates down a slope inclined at an angle of 30° to the horizontal. Her acceleration is a constant 2.0 m s^{-2}. What is the magnitude of the friction force resisting her motion?

32. A roller-coaster carriage (and occupants) with a total mass of 400 kg rolls freely down a straight track inclined at 40° to the horizontal with a constant acceleration. The frictional force on the carriage is a constant 180 N. What is the magnitude of the acceleration of the carriage?

33. A skateboarder of mass 56 kg is rolling freely down a straight incline. The motion of the skateboarder is described in the graph below.



(a) What is the magnitude of the net force on the skateboarder?

(b) If the friction force resisting the motion of the skateboarder is a constant 140 N, at what angle is the slope inclined to the horizontal?

34. What force provides the forward thrust that gets you moving when you are:

(a) ice-skating

(b) downhill skiing

(c) waterskiing

(d) skateboarding

(e) swimming

(f) rowing?

35. Front-wheel-drive cars have a number of advantages over rear-wheel-drive cars. Compare and comment on the forces acting on the tyres in the two different types of car while being driven at a constant speed on a horizontal road.

36. The magnitude of the air resistance (R) on a car can be approximated by the formula:

$$R = 1.2\ v^2$$

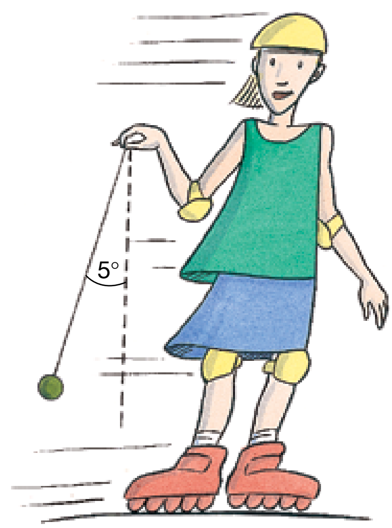
where R is measured in newtons and v is the speed of the car in m s^{-1}.

(a) Design a spreadsheet to calculate the magnitude of the force of air resistance and the net force on a car for a range of speeds as it accelerates from 20 km h^{-1} to 60 km h^{-1} on a horizontal road. Assume that, while accelerating, the driving force is a constant 1800 N and the road friction on the non-driving wheels is a constant 300 N.

(b) Use your spreadsheet to plot a graph of the net force versus speed for the car.

(c) Modify your spreadsheet to show how the net force on the car changes when the same acceleration from 20 km h^{-1} to 60 km h^{-1} is undertaken while driving up a road inclined at 10° to the horizontal.

37. A well-coordinated rollerblader is playing with a yoyo while accelerating on a horizontal surface. When the yoyo is at its lowest point for several seconds, it makes an angle of 5° with the vertical. Determine the acceleration of the rollerblader.



38. A ball of mass 0.50 kg is thrown vertically upwards.

(a) What is the velocity of the ball at the top of its flight?

(b) What is the magnitude of the ball's acceleration at the top of its flight?

(c) What is the net force on the ball at the top of its flight?

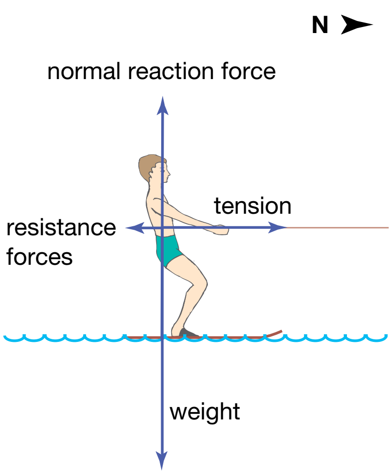
39. A student argues that since there are friction forces on the front and back wheels of a bike that act in opposite directions, the bike cannot move. Explain how the bike moves.

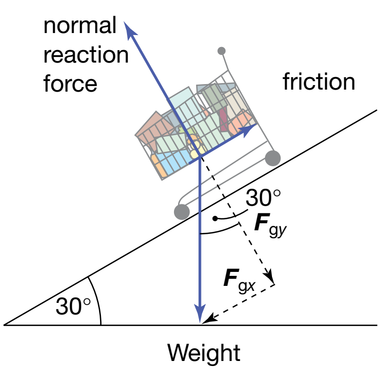
Newton's Third Law of Motion

40. Copy the following table into your workbook. Describe fully the missing half of the following force pairs.

You push on a wall with the palm of your hand.	
Your foot pushes down on a bicycle pedal.	
The ground pushes up on your feet while you are standing.	
The Earth pulls down on your body.	
You push on a broken-down car to try to get it moving.	
A hammer pushes down on a nail.	

41. Label all of the forces in the figures shown below in the form $\boldsymbol{F}_{\text{on A by B}}$.





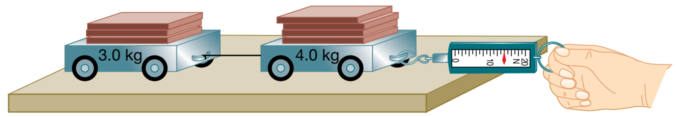
42. Identify the force pair(s) in the upper figure on page 199.

43. Explain, in terms of Newton's first and third laws, why a freestyle swimmer moves faster through the water than a breaststroke swimmer.

44. A student says that the friction forces on the front and back tyres of a car are an example of Newton's Third Law of Motion. Is the student correct? Explain.

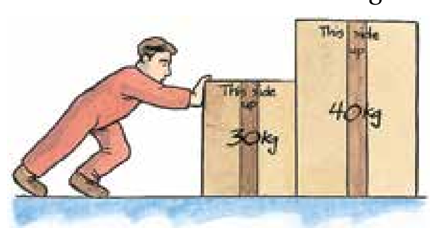
Newton's second law and tension between connected bodies

45. Two loaded trolleys of masses 3.0 kg and 4.0 kg, which are joined by a light string, are pulled by a spring balance along a smooth, horizontal laboratory bench as shown in the figure below. The reading on the spring balance is 14 N.



(a) What is the acceleration of the trolleys?
(b) What is the magnitude of the tension in the light string joining the two trolleys?
(c) What is the net force on the 4.0 kg trolley?
(d) What would be the acceleration of the 4.0 kg trolley if the string was cut?

46. A warehouse worker applies a force of 420 N to push two crates across the floor as shown in the following figure. The friction force opposing the motion of the crates is a constant 2.0 N for each kilogram.



(a) What is the acceleration of the crates?
(b) What is the net force on the 40 kg crate?
(c) What is the force exerted by the 40 kg crate on the 30 kg crate?
(d) What is the force exerted by the 30 kg crate on the 40 kg crate?
(e) Would the worker find it any easier to give the crates the same acceleration if the positions of the two blocks were reversed? Support your answer with calculations.

Momentum and impulse

47. Make an estimate to one significant figure of the magnitude of each of the following:
(a) The average net force on a car while it is accelerating from 0 to 40 km h^{-1} in 3.2 s
(b) The magnitude of the air resistance on an 80 kg skydiver who has reached a terminal velocity of 200 km h^{-1}

(c) The momentum of an Olympic class athlete participating in the 100 m sprint event
(d) The momentum of a family car travelling at the speed limit along a suburban street
(e) The impulse that causes a 70 kg football player who is running at top speed to stop abruptly as he collides with a goal post that he didn't see
(f) The impulse applied to a netball by a goal shooter as she pushes it up towards the goal at a speed of 5 m s^{-1}
(g) The change in momentum of a tennis ball as it is returned to the server in a Wimbledon final.

48. A 60 g tennis ball is bounced vertically onto the ground. After reaching the ground with a downwards velocity of 8.0 m s^{-1}, the ball rebounds with a velocity of 6.0 m s^{-1} vertically upwards.
(a) What is the change in momentum of the tennis ball?
(b) What is the impulse applied by the tennis ball to the ground? Explain how you obtained your answer without any information about the change in momentum of the ground.
(c) Does the ground actually move as a result of the impulse applied by the tennis ball? Explain your answer.
(d) If the tennis ball is in contact with the ground for 2.0×10^{-3} s, what is the average net force on the tennis ball during this interval?
(e) What is the average normal reaction force during this time interval?

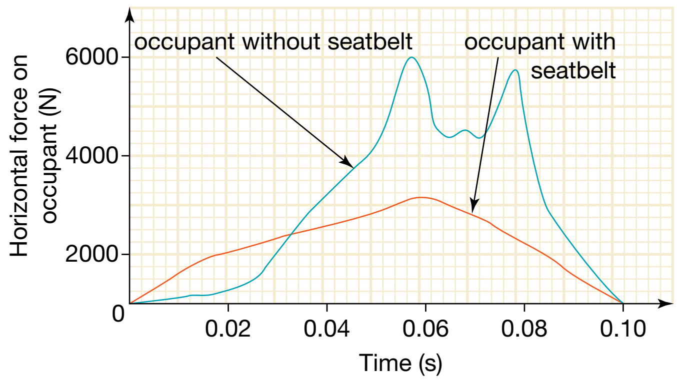
49. A 75 kg basketballer lands vertically on the court with a speed of 3.2 m s^{-1}.
(a) What total impulse is applied to his feet by the ground?
(b) If the basketballer's speed changes from 3.2 m s^{-1} to zero in 0.10 s, what total force does the ground apply to his feet?
(c) Estimate the height from which the basketballer fell to the court.

50. A car with a total mass of 1400 kg (including occupants) travelling at 60 km h^{-1} hits a large tree and stops in 0.080 s.
(a) What impulse is applied to the car by the tree?
(b) What force is exerted by the tree on the car?
(c) What is the magnitude of the deceleration of the 70 kg driver of the car if he is wearing a properly fitted seatbelt?

51. Airbags are fitted to the centre of the steering wheel of many new cars. In the event of a sudden deceleration, the airbag inflates rapidly, providing extra protection for a driver restrained by a seatbelt. Explain how airbags reduce the likelihood of serious injury or death.

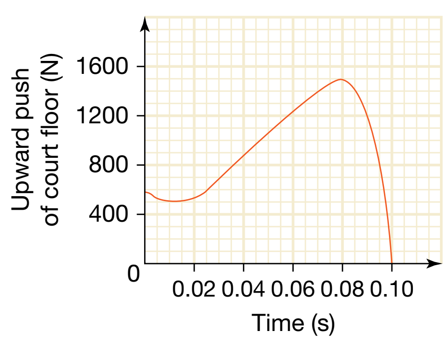
52. Joggers are advised to run on grass or other soft surfaces rather than concrete paths or bitumen roads to reduce the risk of knee and other leg injuries. Explain why this is so.

53. The figure below shows how the horizontal force on the upper body of each of two occupants of a car changes as a result of a head-on collision. One occupant is wearing a seatbelt while the other is not. Both occupants are stationary 0.10 s after the initial impact.



(a) What is the horizontal impulse on the occupant wearing the seatbelt?
(b) If the mass of the occupant wearing the seatbelt is 60 kg, determine the speed of the car just before the initial impact.
(c) Is the occupant who is not wearing the seatbelt heavier or lighter than the other (more sensible) occupant?
(d) Write a paragraph explaining the difference in shape between the two curves on the graph.

54. The following figure shows how the upward push of the court floor changes as a 60 kg basketballer jumps vertically upwards to complete a slam dunk.
(a) What is the impulse applied to the basketballer by the floor?
(b) With what speed did the basketballer leave the ground?
(c) What was the average force exerted on the basketballer by the floor during the 0.10 s interval?
(d) Explain why the initial upward push of the floor is not zero.



55. A well-known politician makes the suggestion that if cars were completely surrounded by rubber 'bumpers' like those on dodgem cars, they would simply bounce off each other in a collision, and passengers would be safer. Discuss the merits of this suggestion in terms of Newton's laws of motion.

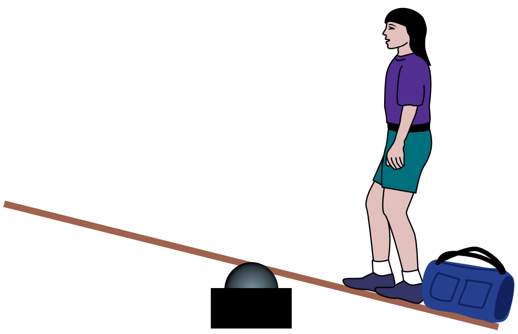
56. Choose one of the statements below and discuss its accuracy in a paragraph. Make estimates of the physical characteristics of the colliding objects so that you can support your arguments with calculations.

(a) When you bounce a basketball onto the ground, there is a collision between the Earth and the basketball. The total momentum of the system of the Earth and the basketball is conserved. Therefore, the Earth moves as a result of the collision.

(b) When a car collides with a solid concrete wall firmly embedded into the ground, the total momentum of the system is conserved. Therefore, the concrete wall moves, but not quickly or far enough to allow any measurement of the movement to be made.

Torque

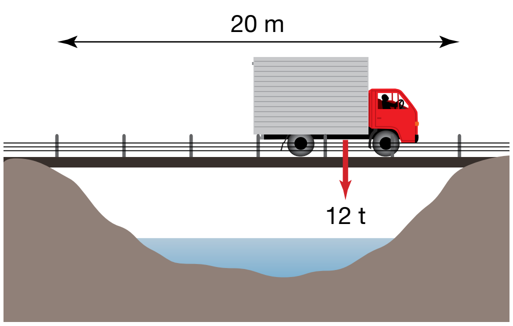
57. Sam is standing at the right-hand end of the seesaw shown in the figure below. He places a bag on the seesaw and then begins walking up the plank to the left. Describe what happens as he walks towards, and then beyond, the fulcrum.



58. A truck crosses a concrete girder bridge (as shown in the figure below). The bridge spans 20 m and is supported at each end on concrete abutments.

(a) Describe what happens to the reaction at each abutment as the truck moves across the bridge from left to right.

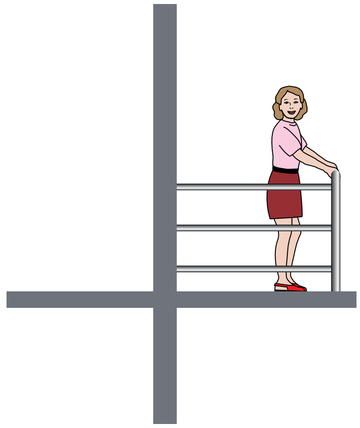
(b) The truck weighs 12 tonne. Calculate the reaction at each support when the centre of gravity of the truck is 4 m from the right abutment.



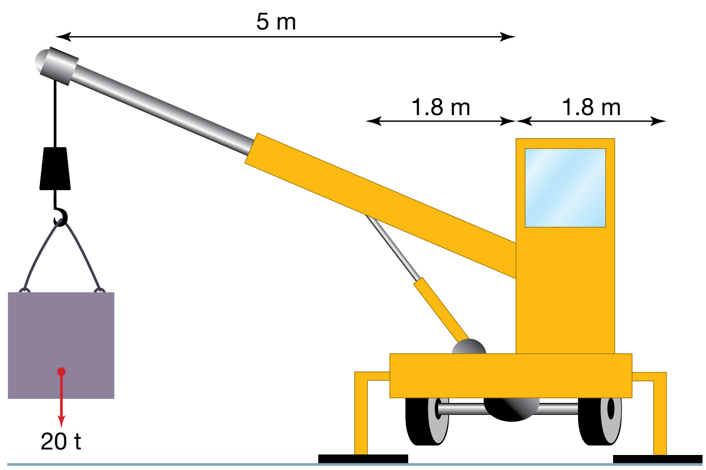
59. A person standing on the outside edge of the cantilevered balcony shown in the following figure walks inside.

(a) Explain what forces are necessary to support the balcony.

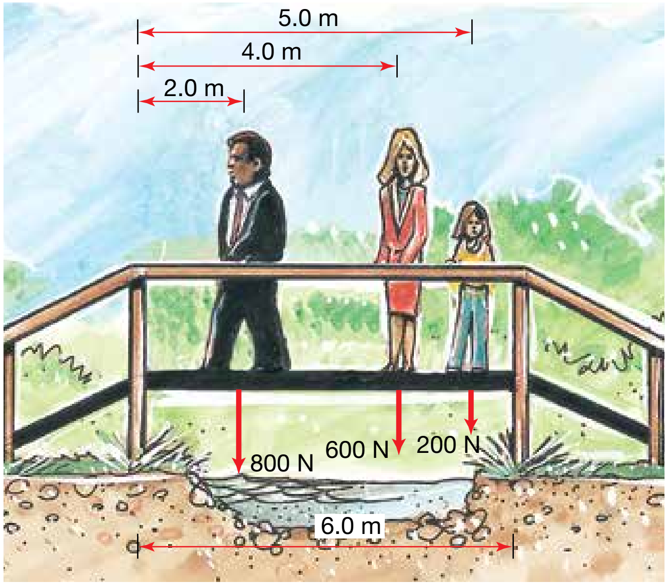
(b) As the person walks across the balcony, describe what happens to the reaction at the support.



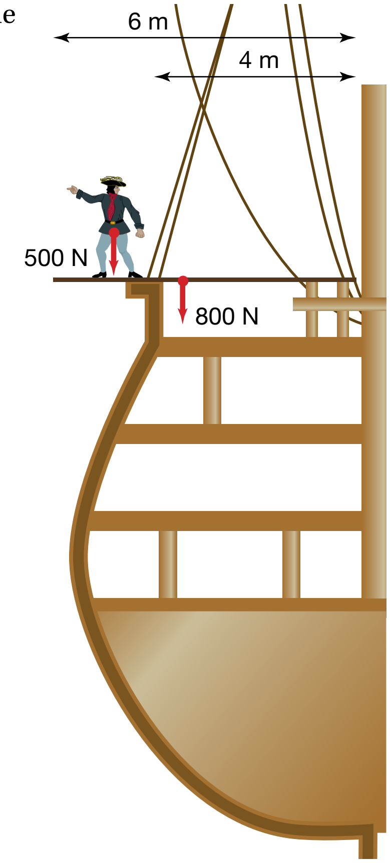
60. The truck crane in the figure below is able to lift a 20 tonne load at a radius of 5 m. If the weight of the truck is evenly distributed, how heavy must the truck be if it is not to tip over? Assume the weight of the truck is uniformly distributed.



61. The pedestrian bridge spanning the creek in the figure below weighs 2 kN. Calculate the reaction at each end when the three people are in the positions shown.



62. How far beyond the edge of the boat can Pirate Bill walk along the plank before it tips and he falls into the water? The 6 m long plank weighs 800 N and Pirate Bill weighs 500 N.



CHAPTER

12 Mechanical interactions

REMEMBER

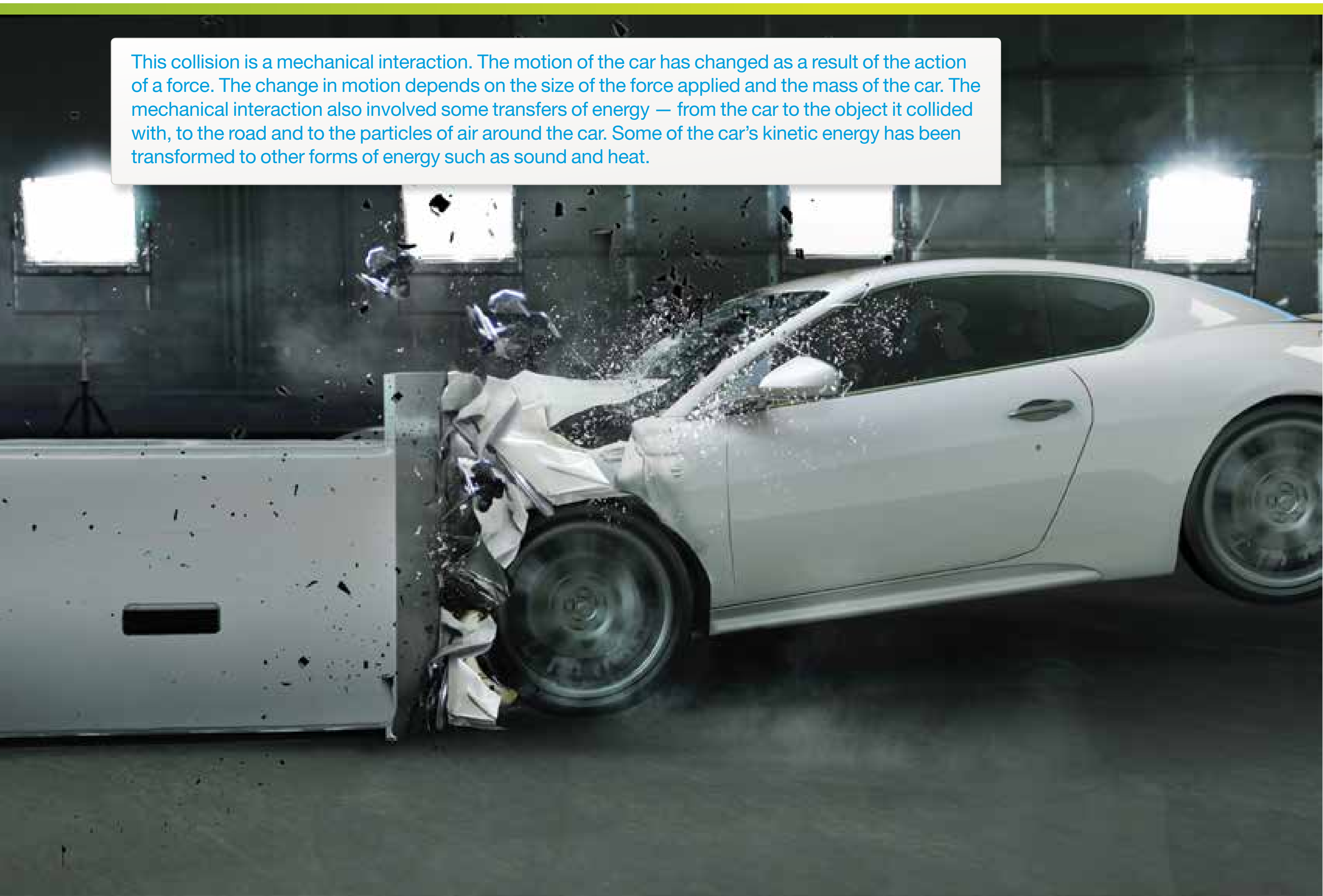
Before beginning this chapter, you should be able to:

- identify and describe energy transfers and transformations in a wide range of common situations
- qualitatively account for the total energy when energy transfers and transformations take place.

KEY IDEAS

After completing this chapter, you should be able to:

- analyse collisions between objects moving in a straight line in terms of impulse and momentum transfer
- analyse work in terms of force and distance travelled in the direction of the force
- use the area under a force-versus-distance (or displacement) graph to determine work done by a force with changing magnitude
- apply the energy conservation model to energy transfers and transformations
- analyse mechanical energy transfers and transformations in terms of work, energy and power
- apply Hooke's Law for an ideal spring
- solve problems involving transfers between gravitational potential energy, potential energy in ideal springs and kinetic energy near the Earth's surface
- describe and analyse power as the rate of energy transfer
- analyse momentum transfer (impulse) in an isolated system for collisions between objects moving along a straight line



This collision is a mechanical interaction. The motion of the car has changed as a result of the action of a force. The change in motion depends on the size of the force applied and the mass of the car. The mechanical interaction also involved some transfers of energy — from the car to the object it collided with, to the road and to the particles of air around the car. Some of the car's kinetic energy has been transformed to other forms of energy such as sound and heat.

Impulse and momentum in collisions

When two objects, A and B, collide with each other, each object exerts a force on the other. These two forces are an example of Newton's Third Law of Motion. The two forces act on different objects, are equal in magnitude and act in opposite directions.

The collision starts at some point in time and finishes at another point in time. The symbol Δt represents the duration of the collision. From Newton's point of view, both objects measure the same duration. Multiplying $\boldsymbol{F}_{\text{on B by A}}$ by Δt gives $\boldsymbol{F}_{\text{on B by A}}\,\Delta t$, which, from the previous chapter, is the impulse on B by A. This impulse produces a change in momentum, but whose momentum? A or B? Because it is the impulse by A on B, it is B's momentum that is changed.

$$\boldsymbol{F}_{\text{on B by A}}\,\Delta t = \boldsymbol{I}_{\text{on B by A}} = \Delta \boldsymbol{p}_{\text{B}}$$

Similarly, the force on A by B produces a change in A's momentum.

$$\boldsymbol{F}_{\text{on A by B}}\,\Delta t = \boldsymbol{I}_{\text{on A by B}} = \Delta \boldsymbol{p}_{\text{A}}.$$

Forces are actions by one object on another, but momentum can be said to be a quantity an object has, even if it is a vector. So a force acting for a time changes how much momentum an object has.

In a collision, the two forces are equal in magnitude and opposite in direction. So the changes in momentum of A and B are also equal in magnitude and opposite in direction. This can be written as:

$$\Delta \boldsymbol{p}_{\text{B}} = -\Delta \boldsymbol{p}_{\text{A}}$$

Because momentum is a quantity, this statement can be interpreted as 'the momentum that B gains equals the momentum that A loses'. This is the basis of a conservation principle. Total momentum is conserved.

The 'change' in something is always the 'final' value minus the 'initial' value, or what is added to the 'initial' value to get the 'final'.

$$\Delta \boldsymbol{p} = \boldsymbol{p}_{\text{final}} - \boldsymbol{p}_{\text{initial}} \text{ or } \boldsymbol{p}_{\text{final}} = \boldsymbol{p}_{\text{initial}} + \Delta \boldsymbol{p}$$

For object B, $\Delta \boldsymbol{p}_{\text{B}} = \boldsymbol{p}_{\text{Bfinal}} - \boldsymbol{p}_{\text{Binitial.}}$
For object A, $\Delta \boldsymbol{p}_{\text{A}} = \boldsymbol{p}_{\text{Afinal}} - \boldsymbol{p}_{\text{Ainitial.}}$

So, from the above relationship:

$$\Delta \boldsymbol{p}_{\text{B}} = -\Delta \boldsymbol{p}_{\text{A}}$$
$$\boldsymbol{p}_{\text{Bfinal}} - \boldsymbol{p}_{\text{Binitial}} = -(\boldsymbol{p}_{\text{Afinal}} - \boldsymbol{p}_{\text{Ainitial}}).$$

Putting the initial momenta together gives:

$$\boldsymbol{p}_{\text{Afinal}} + \boldsymbol{p}_{\text{Bfinal}} = \boldsymbol{p}_{\text{Ainitial}} + \boldsymbol{p}_{\text{Binitial}}$$

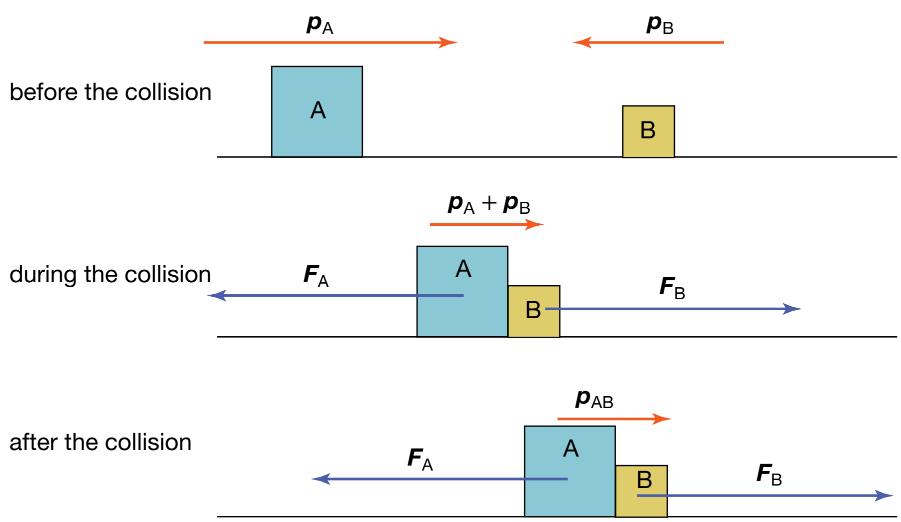
sum of momentum after = sum of the momentum before

Total momentum is conserved.

From this analysis it can be seen that the conservation of momentum is a logical consequence of Newton's third law.

The interaction between objects A and B can be summarised as follows:

- The total momentum of the system remains constant.
- The change in momentum of the system is zero.
- The change in momentum of object A is equal and opposite to the change in momentum of object B.



The total momentum of the system $\boldsymbol{p}_{AB}$ after the collision is the same as the total momentum of the system before and during the collision.

The net force on this system of two blocks is zero.

Sample problem 12.1

Consider the collision illustrated in the figure above. Block A has a mass of 5.0 kg; block B has a mass of 3.0 kg; and each block has a speed of 4.0 m s^{-1} before the collision. After the collision, the blocks move off together. Friction may be ignored.

(a) Determine the velocity of the blocks after the collision.
(b) What is the change in momentum of each of the blocks?
(c) What is the impulse on block A during the collision?
(d) Determine the final velocity of block B if, instead of moving off together, block A rebounds to the left with a speed of 0.50 m s^{-1}.

Solution: (a) Assign the direction to the right as positive. The expressions $\boldsymbol{v}_A$ and $\boldsymbol{v}_B$ are the velocities of blocks A and B respectively before the collision, and m_A and m_B are the respective masses of blocks A and B.

The total momentum of the system before the collision is:

$$\begin{aligned}\boldsymbol{p}_A + \boldsymbol{p}_B &= m_A\boldsymbol{v}_A + m_B\boldsymbol{v}_B \\ &= 5.0 \text{ kg} \times 4.0 \text{ m s}^{-1} + 3.0 \text{ kg} \times -4.0 \text{ m s}^{-1} \\ &= 20 \text{ kg m s}^{-1} - 12 \text{ kg m s}^{-1} \\ &= 8.0 \text{ kg m s}^{-1}.\end{aligned}$$

The total momentum of the system before the collision is the same as the total momentum of the system after the collision as the net force on the system is zero. After the collision, blocks A and B can be considered to be a single body of mass m_{AB}, velocity $\boldsymbol{v}_{AB}$ and momentum $\boldsymbol{p}_{AB}$. Thus:

$$\begin{aligned}\boldsymbol{p}_{AB} &= 8.0 \text{ kg m s}^{-1} \\ \Rightarrow m_{AB}\boldsymbol{v}_{AB} &= 8.0 \text{ kg m s}^{-1} \\ \Rightarrow (5.0 + 3.0) \text{ kg} \times \boldsymbol{v}_{AB} = 8.0 \text{ kg} \times \boldsymbol{v}_{AB} &= 8.0 \text{ kg m s}^{-1} \\ \Rightarrow \boldsymbol{v}_{AB} &= 1.0 \text{ m s}^{-1}.\end{aligned}$$

The velocity of the blocks after the collision is 1.0 m s^{-1} to the right.

(b) Considering block A alone,

$$\Delta \boldsymbol{p}_A = m_A \Delta \boldsymbol{v}_A$$
$$= 5.0 \text{ kg } (1.0 \text{ m s}^{-1} - 4.0 \text{ m s}^{-1})$$
$$= 5.0 \text{ kg} \times -3.0 \text{ m s}^{-1}$$
$$= -15 \text{ kg m s}^{-1}, \text{ or } 15 \text{ kg m s}^{-1} \text{ to the left.}$$

$\Delta \boldsymbol{p}_B$ should be 15 kg m s^{-1} to the right since the change in momentum of the whole system is zero. To confirm this, consider block B alone.

$$\boldsymbol{p}\Delta_B = m_B \Delta \boldsymbol{v}_B$$
$$= 3.0 \text{ kg } (1.0 \text{ m s}^{-1} - (-4.0 \text{ m s}^{-1}))$$
$$= 3.0 \text{ kg} \times 5.0 \text{ m s}^{-1}$$
$$= 15 \text{ kg m s}^{-1}, \text{ or } 15 \text{ kg m s}^{-1} \text{ to the right.}$$

(c) The impulse on block A during the collision is equal to its change in momentum, that is, −15 kg m s^{-1} or 15 N s to the left. (The impulse on block B is equal and opposite to this.)

(d) Let the final momenta and velocities of blocks A and B be $\boldsymbol{p}_{Af}$, $\boldsymbol{p}_{Bf}$, $\boldsymbol{v}_{Af}$ and $\boldsymbol{v}_{Bf}$ respectively.

$$\boldsymbol{p}_{Af} + \boldsymbol{p}_{Bf} = 8.0 \text{ kg m s}^{-1} \text{ (since momentum is conserved here)}$$
$$\Rightarrow 5.0 \text{ kg} \times -0.50 \text{ m s}^{-1} + 3.0 \text{ kg} \times \boldsymbol{v}_{Bf} \text{ m s}^{-1} = 8.0 \text{ kg m s}^{-1}$$
$$\Rightarrow -2.5 \text{ kg m s}^{-1} + 3.0 \text{ kg} \times \boldsymbol{v}_{Bf} = 8.0 \text{ kg m s}^{-1}$$
$$\Rightarrow 3.0\ \boldsymbol{v}_{Bf} = 10.5 \text{ kg m s}^{-1}$$
$$\Rightarrow \boldsymbol{v}_{Bf} = 3.5 \text{ m s}^{-1}, \text{ or } 3.5 \text{ m s}^{-1} \text{ to the right}$$

Revision question 12.1

Consider a collision in which a model car of mass 5.0 kg travelling at 2.0 m s^{-1} in an easterly direction catches up to and collides with an identical model car travelling at 1.0 m s^{-1} in the same direction. The cars lock together after the collision. Friction can be assumed to be negligible.

(a) **What was the total momentum of the two-car system before the collision?**
(b) **Calculate the velocity of the model cars as they move off together after the collision.**
(c) **What is the change in momentum of the car that was travelling faster before the collision?**
(d) **What is the change in momentum of the car that was travelling slower before the collision?**
(e) **What was the magnitude of impulse on both cars during the collision?**
(f) **How are the impulses on the two cars different from each other?**

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Modelling real collisions

The Law of Conservation of Momentum makes it possible to predict the consequences of collisions between two cars or between two people on a sporting field. For example, if a 2000 kg delivery van travelling at 30 m s^{-1} (108 km h^{-1}) collided with a small, stationary car of mass 1000 kg, the speed of the tangled wreck (the two vehicles locked together) could be predicted. However, you would need to assume that the frictional forces and driving force acting on both cars were zero after the collision. A reasonably good estimate can be made of the speed of the tangled wreck immediately after the collision in this way.

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Unit 2 | AOS 1 | Topic 4 | Concept 7

Conservation of momentum in collisions
Concept summary and practice questions

The initial momentum $\boldsymbol{p}_i$ of the system is given by:

$$\boldsymbol{p}_{van} + \boldsymbol{p}_{car} = 2000 \text{ kg} \times 30 \text{ m s}^{-1} + 0 \text{ kg m s}^{-1}$$
$$= 60\,000 \text{ kg m s}^{-1}$$

where the initial direction of the van is taken to be positive.

The momentum of the system after the collision $\boldsymbol{p}_f$ is the momentum of just one object — the tangled wreck.

$$\boldsymbol{p}_f = 3000 \text{ kg} \times \boldsymbol{v}$$

where $\boldsymbol{v}$ is the velocity of the tangled wreck after the collision.

But since $\boldsymbol{p}_f = \boldsymbol{p}_i$,

$$3000 \text{ kg} \times \boldsymbol{v} = 60\,000 \text{ kg m s}^{-1}$$
$$\Rightarrow \boldsymbol{v} = \frac{60\,000 \text{ kg m s}^{-1}}{3000 \text{ kg}}$$
$$= 20 \text{ m s}^{-1}.$$

The speed of the small car changes a lot more than the speed of the large van. However, the change in the momentum of the car is equal and opposite to that of the van.

$$\Delta\boldsymbol{p}_{car} = 1000 \text{ kg} \times 20 \text{ m s}^{-1} - 0 \text{ kg m s}^{-1}$$
$$= 20\,000 \text{ kg m s}^{-1}$$
$$\Delta\boldsymbol{p}_{van} = 2000 \text{ kg} \times 20 \text{ m s}^{-1} - 2000 \text{ kg} \times 30 \text{ m s}^{-1}$$
$$= 40\,000 \text{ kg m s}^{-1} - 60\,000 \text{ kg m s}^{-1}$$
$$= -20\,000 \text{ kg m s}^{-1}.$$

If the small car hit the stationary van at a speed of 30 m s^{-1}, and the two vehicles locked together, the speed of the tangled wreck would be less than 20 m s^{-1}. Apply the Law of Conservation of Momentum to predict the speed of the tangled wreck immediately after this collision.

The concept of energy

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Unit 2	**Law of Conservation of Energy**
AOS 1	Concept summary and practice questions
Topic 4	
Concept 5	

A lot has already been said about energy in previous chapters of this book. The word *energy* is used often in everyday language. Try writing down your own definition of energy. Look up a dictionary — any dictionary — to find out what it means. Most dictionaries and some physics textbooks define energy as the capacity to do work. The term *work* is defined as the quantity of energy transferred when an object moves in the direction of a force applied to it. These definitions do not, however, provide a clear understanding of what energy actually is.

Energy is a concept — an idea — that is used to describe and explain change. The following list of some of the characteristics of energy provides some clues as to what it really is.

- All matter possesses energy.
- Energy takes many different forms. It can therefore be classified. Light, internal energy, kinetic energy, gravitational potential energy, chemical energy and nuclear energy are some of the different forms of energy. The names given to different forms of energy sometimes overlap. For example, light is an example of radiant energy. Gamma radiation could be described as nuclear energy or radiant energy. Sound energy and electrical energy involve kinetic energy of particles.
- Energy cannot be created or destroyed. This statement is known as the Law of Conservation of Energy. The quantity of energy in the universe is a constant. However, nobody knows how much energy there is in the universe.
- Energy can be stored, transferred to other matter or transformed from one form into another.

- Some energy transfers and transformations can be seen, heard, felt, smelt or tasted.
- It is possible to measure the quantity of energy transferred or transformed. However, many energy transfers and transformations are not observable and therefore cannot be measured.

The concept of energy allows us to keep track of the changes that take place in a system. The system could be the universe, Earth, your home, the room you are in, your body or a car.

Getting down to work

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Unit 2 — Work, force and displacement
AOS 1 — Concept summary and practice questions
Topic 4
Concept 1

A **mechanical interaction** is one in which energy is transferred from one object to another by the action of a force.

Work is done when energy is transferred to or from an object by the action of a force. Work is a scalar quantity.

Energy can be transferred to or from matter in several different ways. It can be transferred by:
- emission or absorption of electromagnetic radiation or nuclear radiation
- heating or cooling as the result of a temperature difference
- the action of a force on an object resulting in movement.

An interaction that involves the transfer of energy by the action of a force is called a **mechanical interaction**.

When mechanical energy is transferred to or from an object, the amount of mechanical energy transferred is called **work**.

The work (W) done when a force ($\boldsymbol{F}$) causes a displacement ($\boldsymbol{s}$) in the direction of the force is defined as:

work = magnitude of the force × magnitude of displacement in the direction of the force

$$W = F \times s.$$

Work is a scalar quantity. The SI unit of work is the joule. One joule of work is done when a force of magnitude of 1 newton (N) causes a displacement of 1 metre in the same direction of the force. That is:

$$1\text{ J} = 1\text{ N} \times 1\text{ m}$$
$$= 1\text{ N m}.$$

It is important to remember that work is always done *by* a force acting *on* something.

Sample problem 12.2

A shopper pushes horizontally on a loaded supermarket trolley of mass 30 kg with a force of 150 N to move it a distance of 5.0 metres along a horizontal, straight path. The friction force opposing the motion of the trolley is a constant 120 N. How much work is done on the trolley by:
(a) the force applied by the shopper
(b) the net force
(c) the shopper to oppose the friction force?

Solution:

(a) $W = Fs$
$= 150\text{ N} \times 5.0\text{ m}$
$= 750\text{ J}$

(b) $W = F_{net}\, s$
$= 30\text{ N} \times 5.0\text{ m}$
$= 150\text{ J}$

(c) $W = Fs$
$= 120\text{ N} \times 5.0\text{ m}$
$= 600\text{ J}$

Revision question 12.2

A warehouse worker pushes a heavy crate a distance of 2.0 m across a horizontal concrete floor against a constant friction force of 240 N. He applies a horizontal force of 300 N on the crate. How much work is done on the crate by:
(a) the warehouse worker **(b) the net force?**

Kinetic energy

Kinetic energy is the energy associated with the movement of an object. Like all forms of energy, kinetic energy is a scalar quantity.

Kinetic energy is the energy associated with the movement of an object. By imagining how much energy it would take to stop a moving object, it can be deduced that kinetic energy depends on the mass and speed of the object.

A formula for kinetic energy can be deduced by recalling Newton's First Law of Motion:

> *Every object continues in its state of rest or uniform motion unless made to change by a non-zero net force.*

The kinetic energy of an object can change only as a result of a non-zero net force acting on it in the direction of motion. It follows that the change in kinetic energy of an object is equal to the work done on it by the net force acting on it. If an object initially at rest is acted on by a net force of magnitude F_{net} and moves a distance s (which will necessarily be in the direction of the net force), its change in kinetic energy ΔE_k can be expressed as:

$$\Delta E_k = F_{net}\, s.$$

The quantity of kinetic energy it possesses is:

$$E_k = F_{net}\, s$$

because the initial kinetic energy was zero.

Applying Newton's second law ($F_{net} = ma$) to this expression:

$$E_k = mas$$

where m is the mass of the object.

The movement of the object can also be described in terms of its initial velocity v and its final velocity u. The magnitudes of the quantities a, s, v and u are related to each other by the equation:

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

If the object acquires a speed v as a result of the work done by the net force:

$$v^2 = 2as \qquad \text{since } u = 0$$

$$\Rightarrow as = \frac{v^2}{2}.$$

Substituting this into the expression for kinetic energy:

$$E_k = mas$$

$$\Rightarrow E_k = \frac{mv^2}{2}.$$

The kinetic energy of an object of mass m and speed v can therefore be expressed as:

$$E_k = \tfrac{1}{2}mv^2.$$

Note that the momentum ($p = mv$) is a vector quantity, whereas kinetic energy $E_k = \tfrac{1}{2}mv^2$ is a scalar quantity.

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Unit 2	Kinetic energy
AOS 1	Concept summary and practice questions
Topic 4	
Concept 2	

Sample problem 12.3

Compare the kinetic energy of an Olympic track athlete running the 100 m sprint with that of a family car travelling through the suburbs.

Solution: Estimate the mass of the athlete to be 70 kg and the speed of the athlete to be 10 m s^{-1}.

$$\begin{aligned} E_k &= \tfrac{1}{2}mv^2 \\ &= \tfrac{1}{2} \times 70\text{ kg} \times (10\text{ m s}^{-1})^2 \\ &= 3.5 \times 10^3\text{ J} \end{aligned}$$

Estimate the total mass of the car and its passengers to be 1500 kg and the speed of the car to be about 60 km h^{-1} (17 m s^{-1}).

$$E_k = \frac{1}{2}mv^2$$
$$= \frac{1}{2} \times 1500\,\text{kg} \times (17\,\text{m s}^{-1})^2$$
$$= 2.2 \times 10^5\,\text{J}$$

The value of the ratio $\frac{E_k\,(\text{car})}{E_k\,(\text{athlete})} = \frac{2.2 \times 10^5\,\text{J}}{3.5 \times 10^3\,\text{J}} = 63.$

Thus the car has about 60 times as much kinetic energy as the athlete.

Revision question 12.3

(a) Calculate the kinetic energy of a 2000 kg elephant charging at a speed of 8.0 m s^{-1}.
(b) Estimate the kinetic energy of:
(i) a cyclist riding to work
(ii) a snail crawling across a footpath.

Sample problem 12.4

If the supermarket trolley in sample problem 12.2 starts from rest, what is its final speed?

Solution: The change in kinetic energy of the trolley is equal to the work done on it by the net force acting on it.

$$\Delta E_k = F_{net}\, s$$
$$\Rightarrow E_k = F_{net}\, s \quad \text{(since the initial kinetic energy is zero)}$$
$$= 30\text{ N} \times 5.0\text{ m}$$
$$= 150\text{ J}$$
$$\Rightarrow \frac{1}{2}mv^2 = 150\text{ J}$$
$$\Rightarrow \frac{1}{2} \times 30\text{ kg} \times v^2 = 150\text{ J} \quad \text{(substituting data)}$$
$$\Rightarrow v^2 = \frac{150\,\text{J}}{15\,\text{kg}}$$
$$\Rightarrow v = 3.2\text{ m s}^{-1}$$

Revision question 12.4

A gardener pushes a loaded wheelbarrow with a mass of 60 kg a distance of 4.0 m along a straight horizontal path against a constant friction force of 120 N. He applies a horizontal force of 150 N on the wheelbarrow. If the wheelbarrow is initially at rest, what is its final speed?

If the net force is in the opposite direction to that in which the object is moving, the object slows down. For example, the work done by the net force to stop a 70 kg athlete running at a speed of 10 m s^{-1} is given by:

$$\text{work done by net force} = \Delta E_k$$
$$= 0 - \frac{1}{2}mv^2$$
$$= -\frac{1}{2} \times 70\text{ kg} \times (10\text{ m s}^{-1})^2$$
$$= -3500\text{ J}.$$

The negative sign indicates that the direction of the net force is opposite to the direction of the displacement.

AS A MATTER OF FACT

The truth of the slogan 'Speed kills' can be appreciated by comparing the kinetic energy of a 1500 kg car travelling at 60 km h^{-1} (16.7 m s^{-1}) with that of the same car travelling at 120 km h^{-1} (33.3 m s^{-1}).

At 60 km h^{-1}, the car's kinetic energy is:

$$E_k = \frac{1}{2} mv^2$$
$$= \frac{1}{2} \times 1500 \text{ kg} \times (16.7 \text{ m s}^{-1})^2$$
$$= 2.1 \times 10^5 \text{ J.}$$

At 120 km h^{-1}, its kinetic energy is:

$$E_k = \frac{1}{2} mv^2$$
$$= \frac{1}{2} \times 1500 \text{ kg} \times (33.3 \text{ m s}^{-1})^2$$
$$= 8.3 \times 10^5 \text{ J.}$$

In other words, a 100% increase in speed produces a 400% increase in the kinetic energy and therefore a four-fold increase in the work that needs to be done on the car to stop it during a crash with a solid object.

Potential energy

Energy that is stored is called potential energy. Objects that have potential energy have the capacity to apply forces and do work. Potential energy takes many forms.

- The food that you eat contains potential energy. Under certain conditions, the energy stored in food can be transformed into other forms of energy. Your body is able to transform the potential energy in food into internal energy so that you can maintain a constant body temperature. Your body transforms some of the food's potential energy into the kinetic energy of blood, muscles and bones so that you can stay alive and move. Some of it is transformed into electrochemical energy to operate your nervous system.
- Batteries contain potential energy. In the next chapter, you will see how the energy stored by 'separating' charges that are attracted to each other can be transformed into other forms of energy by completing a circuit.
- An object that is in a position from which it could potentially fall has **gravitational potential energy**. The gravitational potential energy of an object is 'hidden' until the object is allowed to fall. Gravitational potential energy exists because of the gravitational attraction of masses towards each other. All objects with mass near the Earth's surface are attracted towards the centre of the Earth. The further away from the Earth's surface an object is, the more gravitational potential energy it has.
- Energy can be stored in objects by compressing them, stretching them, bending them or twisting them. If the change in shape can be reversed, energy stored in this way is called **strain potential energy**. Strain potential energy can be transformed into other forms of energy by allowing the object to reverse its change in shape.

Gravitational potential energy is the energy stored in an object as a result of its position relative to another object to which it is attracted by the force of gravity.

Strain potential energy is the energy stored in an object as a result of a reversible change in shape. It is also known as elastic potential energy.

studyon

Unit 2 | AOS 1 | Topic 4 | Concept 3

Gravitational potential energy
Concept summary and practice questions

Gravitational potential energy

When an object is in free fall, work is done on it by the force of gravity, transforming gravitational potential energy into kinetic energy. When you lift an object, you do work on it by applying an upwards force on it greater than or equal to its weight. Although the gravitational field strength, $\boldsymbol{g}$, decreases with distance from the Earth's surface, it can be assumed to be constant near the surface. The increase in gravitational potential energy ΔE_{gp} by an object of mass m lifted through a height Δh can be found by determining how much work is done on it by the force (or forces) opposing the force of gravity.

$$W = Fs$$
$$= mg\Delta h \quad (\text{substituting } F = mg \text{ and } s = \Delta h)$$
$$\Rightarrow \Delta E_{gp} = mg\Delta h$$

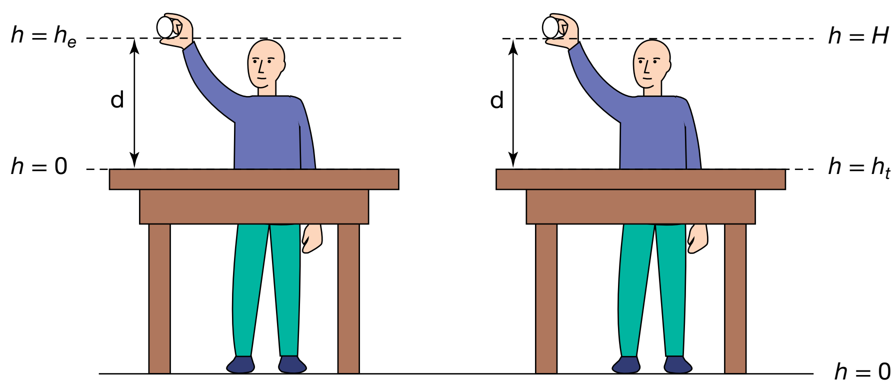
This formula only provides a way of calculating *changes* in gravitational potential energy. If the gravitational potential energy of an object is defined to be zero at a reference height, a formula for the quantity of gravitational potential energy can be found for an object at height h above the reference height.

$$\Delta E_{gp} = mg\Delta h$$
$$\Rightarrow E_{gp} - 0 = mg\,(h - 0)$$
$$\Rightarrow E_{gp} = mgh$$

Usually the reference height is ground or floor level. Sometimes it might be more convenient to choose another reference height. However, it is the change in gravitational potential energy that is most important in investigating energy transformations. The figure below shows that the gain in gravitational potential energy as a raw egg is lifted from the surface of a table is mgd. When the raw egg is dropped to the table, the result will be the same whether you use the height of the table or ground level as your reference height. The gravitational potential energy gained will be transformed into kinetic energy as work is done on the egg by the force of gravity.

$$\Delta E_{gp} = mg\Delta h = mg(h_e - 0) = mgd$$

$$\Delta E_{gp} = mg\Delta h = mg(H - h_t) = mgd$$



The choice of reference height does not have any effect on the change in gravitational potential energy.

AS A MATTER OF FACT

High jumpers use a technique called the Fosbury Flop which allows them to clear the bar while keeping their centre of mass as low as possible. The gravitational potential energy needed to clear the bar is minimised. Thus, with their maximum kinetic energy at take-off, high jumpers can clear those extra few centimetres.

Incidentally, you might like to estimate just how much energy is needed to clear the bar in the high jump. Start by working out the change in height of an athlete's centre of mass during a jump of about 2.0 m.

The Fosbury Flop can place a high jumper's centre of mass below the bar during the jump.

Strain potential energy

Work must be done on an object by a force in order to change its strain potential energy. However, when objects are compressed, stretched, bent or twisted, the force needed to change their shape is not constant. For example, the more you stretch a rubber band, the harder it is to stretch it further. The more you compress the sole of a running shoe, the harder it is to compress it further. The amount of strain potential energy gained by stretching a rubber band or by compressing the sole of a running shoe can be determined by calculating the amount of work done on it.

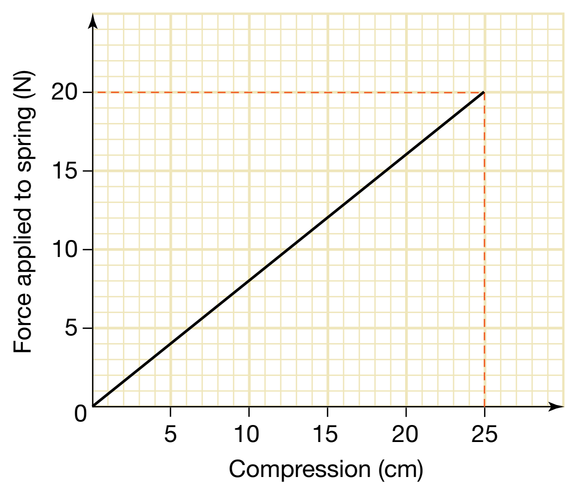
The amount of work done by a changing force is given by:

$$W = F_{av}\, s.$$

It can be determined by calculating the area under a graph of force versus displacement in the direction of the force. In the case of a simple spring, a rubber band or the sole of a running shoe, the work done (and hence the change in strain potential energy) can be calculated by determining the area under a graph of force versus extension, or force versus compression.

Sample problem 12.5

The following figure shows how the force required to compress a spring changes as the spring is compressed. How much strain potential energy is stored in the spring when it is compressed by 25 cm?



Solution: The amount of strain potential energy added to the spring when it is compressed is equal to the amount of work done to compress it (which is equal to the area under the force-versus-compression graph).

W = area under graph

$= \frac{1}{2} \times 0.25\text{ m} \times 20\text{ N}$ (converting units of compression from cm to m)

$= 2.5\text{ J}$

Revision question 12.5

How much strain potential energy is stored in the spring described in sample problem 12.5 when it is compressed by a distance of:

(a) **10 cm**

(b) **20 cm?**

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Unit 2 | AOS 1 | Topic 4 | Concept 4

Hooke's Law and elastic potential energy
Concept summary and practice questions

Hooke's Law

The spring in sample problem 12.5 is an example of an ideal spring. For an ideal spring, the force required to compress (or extend) the spring is directly proportional to the compression (or extension):

$$\boldsymbol{F} \propto \Delta \boldsymbol{x}$$

where

$\boldsymbol{F}$ is the force exerted by the spring

$\Delta \boldsymbol{x}$ is the displacement of the spring.

This relationship is expressed fully by Hooke's Law, which states:

$$\boldsymbol{F} = -k\Delta \boldsymbol{x}$$

where k is known as the spring constant.

The negative sign in Hooke's Law is necessary because the direction of the force applied by the spring is always opposite to the direction of the spring's displacement. For example, if the spring is compressed, it pushes back in the opposite direction. If the spring is extended, it pulls back in the opposite direction.

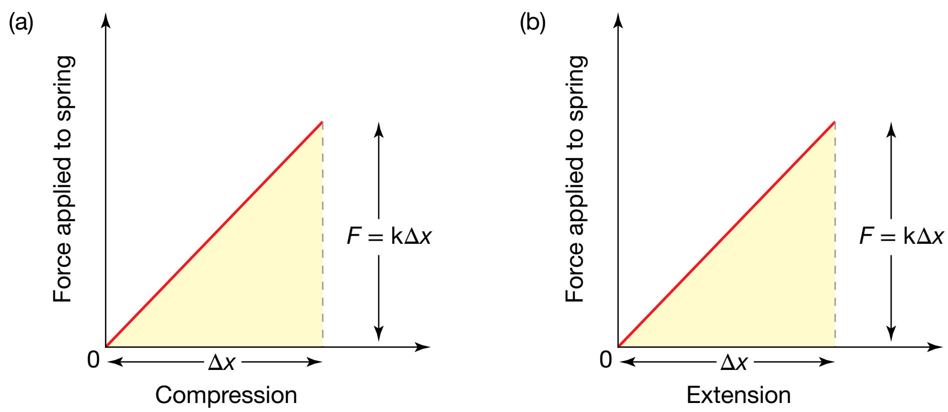
Hooke's Law is more conveniently expressed without vector notation as:

$$F = k\Delta x$$

where

F is the magnitude of the force applied by the spring

Δx is the magnitude of the extension or compression of the spring.



Graphs showing the force applied by an ideal spring versus (a) compression and (b) extension

The strain energy stored in a spring that is changed in length by Δx, whether it is compressed or extended, is equal to the area under the force-versus-compression graph or the force-versus-extension graph. That is:

$$\begin{aligned}\text{strain potential energy} &= \tfrac{1}{2} \times k\Delta x \times \Delta x \\ &= \tfrac{1}{2}k(\Delta x)^2\end{aligned}$$

Sample problem 12.6

A wooden block is pushed against an ideal spring of length 30 cm until its length is reduced to 20 cm. The spring constant of the spring is 50 N m^{-1}.

(a) What is the magnitude of the force applied on the wooden block by the compressed spring?

(b) How much strain potential energy is stored in the compressed spring?

(c) How much work was done on the spring by the wooden block?

Solution: (a) $F = k\Delta x$

$= 50\text{ N m}^{-1} \times 0.10\text{ m}$ (spring compression is 10 cm)

$= 5.0\text{ N}$

(b) strain potential energy $= \frac{1}{2}k(\Delta x)^2$

$= \frac{1}{2} \times 50\text{ N m}^{-1} \times (0.10\text{ m})^2$

$= 0.25\text{ J}$

(c) Work done on spring = elastic potential energy

$= 0.25\text{ J}$

Revision question 12.6

(a) An object hanging from the end of a spring extends the spring by 20 cm. The spring constant is 60 N m^{-1}.

(i) What upwards force is applied to the object by the spring?

(ii) How much strain potential energy is stored in the spring when it is extended by 20 cm?

(iii) What is the mass of the object?

(b) What is the spring constant of the spring described in sample problem 12.5?

Conservation of total mechanical energy and efficiency

Along with kinetic energy, gravitational potential energy and strain potential energy are referred to as forms of mechanical energy. Transformation to or from each of these forms of energy requires the action of a force. A single bounce of a tennis ball onto a hard surface involves the following mechanical energy transformations.

- As the ball falls, the force of gravity does work on the ball, transforming gravitational potential energy into kinetic energy.
- As soon as the bottom of the tennis ball touches the ground, the upwards push of the ground does work on the tennis ball, transforming kinetic energy into strain potential energy. A small amount of gravitational potential energy is also transformed into strain potential energy. This continues until the kinetic energy of the ball is zero.
- As the ball begins to rise and remains in contact with the ground, the upwards push of the ground does work on the tennis ball, transforming strain potential energy into kinetic energy and a small amount of gravitational potential energy until the ball loses contact with the ground.
- As the ball gains height, the force of gravity does work on the ball, transforming kinetic energy into gravitational potential energy.

Of course, if mechanical energy were conserved, the ball would return to the same height from which it was dropped. In fact, mechanical energy is not conserved. During each of the mechanical transformations that occur during the bounce, some of the mechanical energy of the ball is transformed. Some of the ball's mechanical energy is transformed to thermal energy of the air, ground and ball, resulting in a small temperature increase. Some mechanical energy can be lost as sound, while permanent deformation through the breaking on bonds between atoms can also lead to a loss of such energy.

Mechanical energy losses to thermal energy, sound etc. are largely permanent. It is very difficult to convert this lost energy back into mechanical energy and so it is not considered useful. The efficiency, η, of an energy transfer is calculated from the ratio:

$$\eta = \frac{\text{useful energy out}}{\text{total energy in}}$$

where η is the Greek letter eta.

Sample problem 12.7

A ball dropped from 1.50 m rebounds to 1.20 m. What is the efficiency?

Solution:

$$\eta = \frac{\text{useful energy out}}{\text{total energy in}}$$

The 'total energy in' is the gravitational potential energy of the ball at rest at a height of 1.50 m.

$$\begin{aligned} E_{gp} &= mgh_1 \\ &= mg \times 1.50\text{ m} \end{aligned}$$

The 'useful energy out' is the gravitational potential of the ball at its rebound height of 1.20 m.

$$\begin{aligned} E_{gp} &= mgh_2 \\ &= mg \times 1.20\text{ m} \\ \eta &= \frac{1.2mg}{1.5mg} \\ &= 80\% \end{aligned}$$

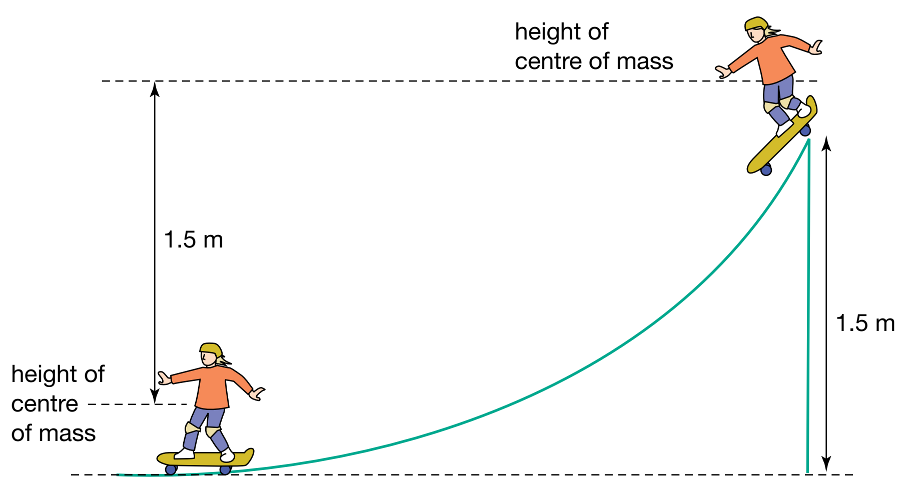
Revision question 12.7

A basketball is pumped up to give an efficiency of 80% when dropped. If this basketball is dropped from a height of 2.0 m, to what height does it rebound after the fourth bounce?

Sample problem 12.8

A skateboarder of mass 50 kg, starting from rest, rolls from the top of a curved ramp, a vertical drop of 1.5 m (see the figure below). What is the speed of the skateboarder at the bottom of the ramp?

The frictional force applied to the skateboarder by the ramp is negligible.



Solution: It can be assumed in this case that the total mechanical energy is conserved. The only transformation that takes place is that from gravitational potential energy to kinetic energy. The gain in kinetic energy of the skateboarder is therefore equal to the magnitude of the loss of gravitational potential energy.

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Conservation of mechanical energy app

$$\Delta E_k = \Delta E_{gp}$$

$$\Rightarrow \tfrac{1}{2} mv^2 = mg\Delta h$$

$$\Rightarrow \tfrac{1}{2} \times 50 \text{ kg} \times v^2 = 50 \text{ kg} \times 10 \text{ N kg}^{-1} \times 1.5 \text{ m} \quad \text{(substituting data)}$$

$$\Rightarrow v^2 = \frac{50 \text{kg} \times 10 \text{ N kg}^{-1} \times 1.5 \text{ m}}{\tfrac{1}{2} \times 50 \text{ kg}}$$

$$\Rightarrow v = 5.5 \text{ m s}^{-1} \quad \text{(evaluating)}$$

The speed of the skateboarder at the bottom of the ramp is 5.5 m s^{-1}.

Revision question 12.8

A toy car of mass 0.50 kg is pushed against an ideal spring so that the spring is compressed by 0.10 m. The spring constant of the spring is 80 N m^{-1}.

(a) How much strain potential energy is stored in the spring when it is compressed?

(b) After the toy car is released, what will be its speed at the instant that the spring returns to its natural length?

AS A MATTER OF FACT

Kangaroos have huge tendons in their hind legs that store and return elastic potential energy much more efficiently than do those of other mammals of comparable size. This allows them to hop for very large distances without tiring. A young 50 kg kangaroo is capable of storing about 360 J of energy in each of its hind legs. A typical four-legged animal of the same mass stores about 55 J in each of its hind legs while running.

An adult red kangaroo can jump over obstacles up to 2 m in height.

Power

Power is the rate at which energy is transferred or transformed.

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Unit 2 | AOS 1 | Topic 4 | Concept 6

Power and energy efficiency
Concept summary and practice questions

Power is the rate at which energy is transferred or transformed. In the case of conversions to or from mechanical energy or between different forms of mechanical energy, power, P, can be defined as the rate at which work is done.

$$P = \frac{W}{\Delta t}$$

where

W = the work done

Δt = the time interval during which the work is done.

The SI unit of power is the watt (W), which is defined as 1 J s^{-1}.

The power delivered when a force, F, is applied to an object can also be expressed in terms of the object's speed v.

$$\begin{aligned} P &= \frac{W}{\Delta t} = \frac{Fx}{\Delta t} \\ &= F \times \frac{x}{\Delta t} \\ &= Fv \end{aligned}$$

Sample problem 12.9

A student of mass 40 kg walks briskly up a flight of stairs to climb four floors of a building, a vertical distance of 12 m in a time interval of 40 s.

(a) At what rate is the student doing work against the force of gravity?

(b) If energy is transformed by the leg muscles of the student at the rate of 30 kJ every minute, what is the student's power output?

Solution:

(a) The work done by the student against the force of gravity is equal to the gain in gravitational potential energy.

$W = mg\Delta h$

The rate at which the work is done, or power (P), is:

$$\begin{aligned} P &= \frac{W}{\Delta t} = \frac{40\ \text{kg} \times 10\ \text{N kg}^{-1} \times 12\ \text{m}}{40\ \text{s}} \\ &= 120\ \text{W} \end{aligned}$$

(b) $$\begin{aligned} P &= \frac{\text{energy transferred}}{\text{time taken}} \\ &= 30\ \text{kJ min}^{-1} \\ &= \frac{30\,000\ \text{J}}{60\ \text{s}} \\ &= 500\ \text{W} \end{aligned}$$

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Climbing to the top
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Revision question 12.9

(a) If all of the 720 J of energy stored in the hind legs of a young 50 kg kangaroo were used to jump vertically, how high could it jump?

(b) What is the kangaroo's power output if the 720 J of stored energy is transformed into kinetic energy during a 1.2 second interval?

AS A MATTER OF FACT

Which is easier — riding a bike or running?

A normal bicycle being ridden at a constant speed of 4.0 m s^{-1} on a horizontal road is subjected to a rolling friction force of about 7 N and air resistance of about 6 N. The forward force applied to the bicycle by the ground must therefore be about 13 N. The mechanical power output required to push the bicycle along at this speed is:

$$P = Fv$$
$$= 13\ \text{N} \times 4.0\ \text{m s}^{-1}$$
$$= 52\ \text{W}.$$

Running at a speed of 4.0 m s^{-1} requires a mechanical power output of about 300 W. Even walking at a speed of 2.0 m s^{-1} requires a mechanical power output of about 75 W.

Riding a bicycle on a horizontal surface is less tiring than walking or running for two reasons.

1. Less mechanical energy is needed. The body of the rider does not rise and fall as it does while walking or running, eliminating the changes in gravitational potential energy.
2. Because the rider is seated, the muscles need to transform much less chemical energy to support body weight. The strongest muscles in the body can be used almost exclusively to turn the pedals.

Once you start riding uphill or against the wind, the mechanical power requirement increases significantly. For example, in riding along an incline that rose 1 m for every 10 m of road distance covered, the additional power needed by a 50 kg rider travelling at 4.0 m s^{-1} would be:

$$P = \frac{\Delta E_{gp}}{\Delta t}$$
$$= \frac{mg\Delta h}{\Delta t}.$$

In a time interval of 1.0 s, the vertical climb is $\frac{1}{10}$ of 4.0 m = 0.4 m.

$$\Rightarrow P = \frac{50\ \text{kg} \times 10\ \text{N kg}^{-1} \times 0.4\ \text{m}}{1.0\ \text{s}}$$
$$= 200\ \text{W}$$

Practical investigations

- Investigate the magnetic collision between two air track gliders. *Hint:* Use an ultrasound motion detector or a high-speed digital camera.
- Investigate the force of impact on a bouncing ball.

Chapter review

studyon
Unit 2 — Energy and motion
AOS 1
Topic 4 — Sit Topic test

Summary

- If the net force acting on a system is zero, the total momentum of the system does not change. This statement is an expression of the Law of Conservation of Momentum.
- If there are no external forces acting on a system of two objects when they collide, the change in momentum of the first object is equal and opposite to the change in momentum of the second object.
- The Law of Conservation of Energy states that energy cannot be created or destroyed.
- Work is done when energy is transferred to or from an object by the action of a force. The work done on an object by a force is the product of the magnitude of the force and the magnitude of the displacement in the direction of the force.
- All moving objects possess kinetic energy. The kinetic energy of an object can be expressed as $E_k = \frac{1}{2}mv^2$.
- The work done on an object by the net force is equal to the object's change in kinetic energy.
- The change in gravitational potential energy of an object near the Earth's surface can be expressed as $\Delta E_{gp} = mg\Delta h$ where Δh is the object's change in height.
- The change in the strain potential energy stored in an object can be found by determining the area under a force-versus-compression or force-versus-extension graph.
- The force $\boldsymbol{F}$ applied by an ideal spring when it is compressed or extended is proportional to its displacement $\Delta \boldsymbol{x}$. This relationship is expressed by Hooke's Law: $\boldsymbol{F} = -\mathrm{k}\Delta \boldsymbol{x}$, where k is known as the spring constant.
- The strain potential energy stored in an ideal spring is equal to $\frac{1}{2}\mathrm{k}(\Delta x)^2$.
- Kinetic energy, gravitational potential energy and strain potential energy are referred to as forms of mechanical energy. During a mechanical interaction, it is usually reasonable to assume that total mechanical energy is conserved.
- The efficiency of an energy transfer is calculated from the ratio:

$$\text{efficiency, } \eta = \frac{\text{useful energy out}}{\text{total energy in}}$$

- Power is the rate at which energy is transferred or transformed. In mechanical interactions, power is also equal to the rate at which work is done.
- The power delivered by a force is the product of the magnitude of the force and the velocity of the object on which the force acts.

Questions

Impulse and momentum in collisions

1. Explain in terms of the Law of Conservation of Momentum how astronauts walking in space can change their speed or direction.

2. A physics student is experimenting with a low-friction trolley on a smooth horizontal surface. Predict the final velocity of the 2.0 kg trolley in each of the following two experiments.
   (a) The trolley is travelling at a constant speed of 0.60 m s^{-1}. A suspended 2.0 kg mass is dropped onto it as it passes.
   (b) The trolley is loaded with 2.0 kg of sand. As the trolley moves with an initial speed of 0.60 m s^{-1}, the sand is allowed to pour out through a hole behind the rear wheels.
3. Two stationary ice-skaters, Catherine and Lauren, are facing each other and use the palms of their hands to push each other in opposite directions. Catherine, with a mass of 50 kg, moves off in a

straight line with a speed of 1.2 m s^{-1}. Lauren moves off in the opposite direction with a speed of 1.5 m s^{-1}.

(a) What is Lauren's mass?
(b) What is the magnitude of the impulse that results in Catherine's gain in speed?
(c) What is the magnitude of the impulse on Lauren while the girls are pushing each other away?
(d) What is the total momentum of the system of Catherine and Lauren just after they push each other away?
(e) Would it make any difference to their final velocities if they pushed each other harder? Explain.

4. Nick and his brother Luke are keen rollerbladers. Nick approaches his stationary brother at a speed of 2.0 m s^{-1} and bumps into him. As a result of the collision Nick, who has a mass of 60 kg, stops moving, and Luke, who has a mass of 70 kg, moves off in a straight line. The surface on which they are 'blading' is smooth enough that friction can be ignored.

(a) With what speed does Luke move off?
(b) What is the magnitude of the impulse on Nick as a result of the bump?
(c) What is the magnitude of Nick's change in momentum?
(d) What is the magnitude of Luke's change in momentum?
(e) How would the motion of each of the brothers after their interaction be different if they pushed each other instead of just bumping?
(f) If Nick held onto Luke so that they moved off together, what would be their final velocity?

5. An unfortunate driver of mass 50 kg travelling on an icy road in her 1200 kg car collides with a stationary police car of total mass 1500 kg (including occupants). The tangled wreck moves off after the collision with a speed of 7.0 m s^{-1}. The frictional force on both cars can be assumed to be negligible.
(a) At what speed was the unfortunate driver travelling before her car hit the police car?
(b) What was the impulse on the police car due to the collision?
(c) What was the impulse on the driver of the offending car (who was wearing a properly fitted seatbelt) due to the impact with the police car?
(d) If the duration of the collision was 0.10 s, what average net force was applied to the police car?

6. The Law of Conservation of Momentum can be written as $\Delta \boldsymbol{p}_B = -\Delta \boldsymbol{p}_A$, which equates the change in momentum of two different objects, A and B.
Some textbooks express Newton's third law as $\boldsymbol{F}_{\text{on B by A}} = -\boldsymbol{F}_{\text{on A by B}}$. What is it about the nature of a force that makes this statement misleading? Why is there no 'Law of Conservation of Force'?

7. Design a spreadsheet to model head-on collisions between two cars on an icy road or between two ice-skaters. Assume that the cars or skaters are locked together after impact. Use your spreadsheet to predict the speed of the cars or skaters after the collision for a range of masses and initial speeds.

Getting down to work

8. How much work is done on a 4.0 kg brick as it is lifted through a vertical distance of 1.5 m?

9. Imagine that you are trying to push-start a 2000 kg truck with its handbrake on. How much work are you doing on the truck?

10. A toddler swings her fluffy toy by a string around in circles at a constant speed. How much work does she do on the toy in completing:
(a) one full revolution
(b) half of a full revolution?

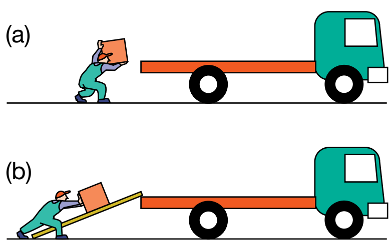
Kinetic energy

11. Use the formulae for work and kinetic energy to show that their units are equivalent.

12. Estimate the kinetic energy of:
   (a) a car travelling at 60 km h^{-1} on a suburban street
   (b) a tennis ball as it is returned to the server in a Wimbledon final.
13. Estimate the amount of work done on a 58 g tennis ball by the racquet when the ball is served at a speed of 200 km h^{-1}.

Potential energy

14. Estimate the change in gravitational potential energy of:
   (a) a skateboarder riding down a half-pipe
   (b) a child sliding from the top to the bottom of a playground slide
   (c) you at your maximum height as you jump up from rest.
15. A truck driver wants to lift a heavy crate of books with a mass of 20 kg onto the back of a truck through a vertical distance of 1 m. The driver needs to decide whether to lift the crate straight up, or push it up along a ramp.

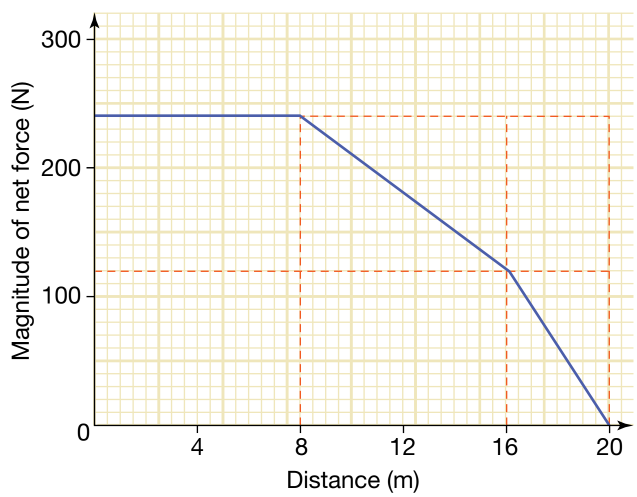


   (a) What is the change in gravitational potential energy of the crate of books in each case?
   (b) How much work must be done against the force of gravity in each case?
   (c) If the ramp is perfectly smooth, how much work must be done by the truck driver to push the crate of books onto the back of the truck?
   (d) In view of your answers to (b) and (c), which of the two methods is the best way to get the crate of books onto the back of the truck? Explain your answer.
16. World-class hurdlers raise their centre of mass as little as possible when they jump over the hurdles. Why?

Conservation of total mechanical energy

17. If a 160 g cricket ball is dropped from a height of 2.0 m onto a hard surface, calculate:
   (a) the kinetic energy of the ball as it hits the ground
   (b) the maximum amount of elastic potential energy stored in the ball
   (c) the height to which it will rebound.

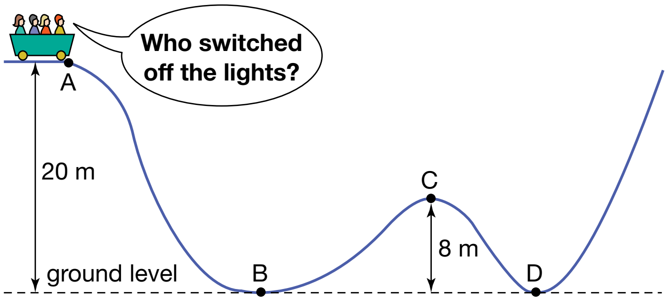
   Assume that 32% of the kinetic energy of the cricket ball is stored in it as it bounces on a hard surface.
18. Two ideal springs, X and Y, have spring constants of 200 N m^{-1} and 100 N m^{-1} respectively. They are each extended by 20 cm by pulling with a hook. For each of the springs, determine:
   (a) the magnitude of the force applied to the hook
   (b) the strain potential energy.
19. A tourist on an observation tower accidentally drops her 1.2 kg camera to the ground 20 m below.
   (a) What kinetic energy does the camera gain before shattering on the ground?
   (b) What is the speed of the camera as it hits the ground?
20. A car of mass 1500 kg travelling at 50 km h^{-1} collides with a concrete barrier. The car comes to a stop over a distance of 60 cm as the front end crumples.
   (a) What is the average net force on the car as it stops?
   (b) What is the average acceleration of the car and its occupants? Assume that the occupants are wearing properly fitted seatbelts.
   (c) What would be the average acceleration of properly restrained passengers in a very old car with no crumple zone if it stopped over a distance of only 10 cm? (The maximum magnitude of acceleration that humans can survive is about 600 m s^{-2}.)
   (d) Explain in terms of mechanical energy transformations why the front and rear ends of cars are designed to crumple.
   (e) In a collision with a rigid barrier, would you feel safer in a large or a small car? Use some sample calculations to illustrate your answer.
21. A girl of mass 50 kg rollerblades freely from rest down a path inclined at 30° to the horizontal. The following graph shows how the magnitude of the net force on the girl changes as she progresses down the path.



   (a) What is the kinetic energy of the girl after rolling a distance of 8.0 m?
   (b) What is the sum of the friction force and air resistance on the girl over the first 8.0 m?

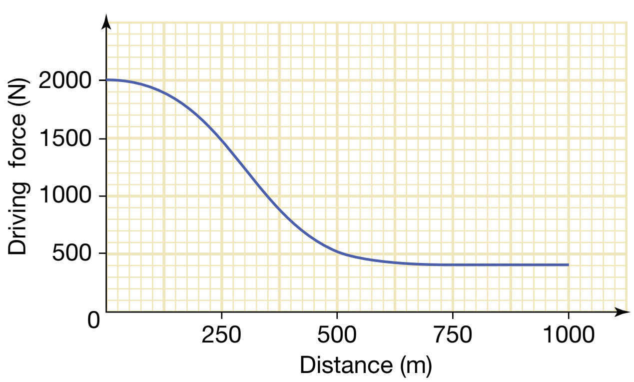
(c) What is the kinetic energy of the girl at the end of her 20 m roll?
(d) How much gravitational potential energy has been lost by the girl during her 20 m roll?
(e) Account for the difference between your answers to (c) and (d).

22. The following figure shows part of a roller-coaster track. As a fully loaded roller-coaster car of total mass 450 kg approaches point A with a speed of 12 m s^{-1}, the power fails and it rolls freely down the track. The friction force on the car can be assumed to be negligible.



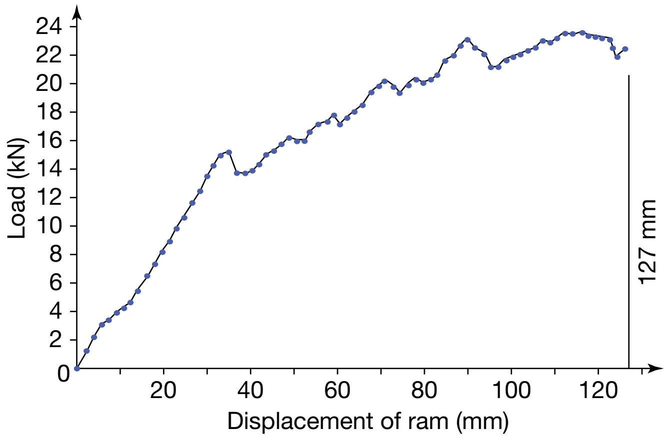
(a) What is the kinetic energy of the loaded car at point A?
(b) Determine the speed of the loaded car at each of points B and C.
(c) What maximum height will the car reach after passing point D?

23. The following graph shows how the driving force on a 1200 kg car changes as it accelerates from rest over a distance of 1 km on a horizontal road. The average force opposing the motion of the car due to air resistance and road friction is 360 N.



(a) How much work has been done by the forward push (the driving force) on the car?
(b) How much work has been done on the car to overcome both air resistance and road friction?
(c) What is the speed of the car when it has travelled 1 km?

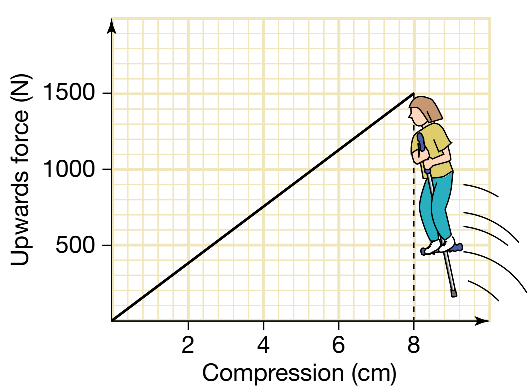
24. The following graph shows the results of a roof crush test conducted in the laboratories of the Department of Civil Engineering at Monash University.



(a) How much work has been done on the roof when the ram has reached its maximum displacement?
(b) If the car has a mass of 1400 kg, from what height would it need to be dropped on its roof to crush it by 127 mm?

25. A toy truck of mass 0.50 kg is pushed against a spring so that it is compressed by 0.10 m. The spring obeys Hooke's Law and has a spring constant of 50 N m^{-1}. When the toy truck is released, what will be its speed at the instant that the spring returns to its natural length? Assume that there is no frictional force resisting the motion of the toy truck.

26. A pogo stick contains a spring that stores energy when it is compressed. The following graph shows how the upwards force of a pogo stick on a 30 kg child jumping on it changes as the spring is compressed. The maximum compression of the spring is 8.0 cm. Assume that all of the energy stored in the spring is transformed to the mechanical energy of the child. The mass of the pogo stick itself can be ignored.



(a) How do you know that the spring in the pogo stick is an ideal spring?
(b) What is the spring constant of the spring?
(c) How much work is done on the child by the pogo stick as the spring expands?
(d) What is the kinetic energy of the child at the instant that the compression of the pogo stick spring is zero?
(e) How high does the child rise from the ground? Assume that the child leaves the ground at the instant that the compression of the pogo stick spring is zero.

27. Describe the mechanical energy transformations that take place when a child jumps up and down on a trampoline.

28. Discuss the mechanical energy transformations that take place when a diver uses a springboard to dive into the water, from the time that the diver is standing motionless on the springboard until the time she reaches her lowest point in the water. Use a graph describing the energy transformations in both the springboard and the diver to illustrate your answer.

29. Discuss the mechanical energy transformations that take place when a skateboard rider gets airborne off the end of a ramp (see the figure below).
(a) Use a graph to describe the energy transformations that occur during the time interval between starting at one end of the ramp, getting airborne at the other end, and returning to the starting point.
(b) Explain in terms of the energy transformations how it is possible for the rider's feet to remain in contact with the skateboard while in the air.

30. Jo and Bill are conducting an experimental investigation into the bounce of a basketball. Bill drops the ball from various heights and Jo measures the rebound height. They also use an electronic timer with thin and very light wires attached to the ball and to alfoil on the floor to measure the impact time. A top-loading balance measures the mass of the ball. What physical quantities can they calculate using these four measurements?

Efficiency

31. A tractor engine has a power output of 80 kW. The tractor is able to travel to the top of a 500 m hill in 4 minutes and 30 seconds. The mass of the tractor is 2.2 tonnes. What is the efficiency of the engine?

32. Human muscle has an efficiency of about 20%. Take a heavy mass, about 1–2 kg, in your hand. With your hand at your shoulder, raise and lower the mass 10 times as fast as you can. Measure the mass, your arm extension and the time taken, and calculate the amount of energy expended, your power output and your power input.

33. A pile driver has an efficiency of 80%. The hammer has a mass 500 kg and the pile a mass of 200 kg. The hammer falls through a distance of 5.0 m and drives the pile 50 mm into the ground. Calculate the average resistance force exerted by the ground.

Power

34. Estimate the average power delivered to a 58 g tennis ball by a racquet when the ball is served at a speed of 200 km h^{-1} and the ball is in contact with the racquet for 4.0 ms.

35. At what average rate is work done on a 4.0 kg brick as it is lifted through a vertical distance of 1.5 m in 1.2 s?

36. In the sport of weightlifting, the clean-and-jerk involves bending down to grasp the barbell, lifting it to the shoulders while squatting and then jerking it above the head while straightening to a standing position. In 1983, Bulgarian weightlifter Stefan Topurov became the first man to clean and jerk three times his own body mass when he lifted 180 kg. Assume that he raised the barbell through a distance of 1.8 m in a time of 3.0 s.
(a) How much work did Stefan do in overcoming the force of gravity acting on the barbell?
(b) How much power was supplied to the barbell to raise it against the force of gravity?
(c) How much work did Stefan do on the barbell while he was holding it stationary above his head?

37. A small car travelling at a constant speed of 20 m s^{-1} on a horizontal road is subjected to air resistance of 570 N and road friction of 150 N. What power provided by the engine of a car is used to keep it in motion at this speed?

38. While a 60 kg man is walking at a speed of 2.0 m s^{-1}, his centre of mass rises and falls 3.0 cm with each stride. At what rate is he doing work against the force of gravity if his stride length is 1.0 m?

39. A bicycle is subjected to a rolling friction force of 6.5 N and an air resistance of 5.7 N. The total mass of the bicycle and its rider is 75 kg. Its mechanical power output while being ridden at a constant speed along a horizontal road is 56 W.
(a) At what speed is it being ridden?
(b) If the bicycle was ridden at the same speed up a slope inclined at 30° to the horizontal, what additional mechanical power would need to be supplied to maintain the same speed? Assume that the rolling friction and air resistance are the same as on the horizontal road.

CHAPTER

13 Practical investigations

KEY IDEAS

At the end of this chapter you should be able to:

- explain why we do investigations
- consider and select a topic to investigate
- submit a research proposal to your teacher
- keep a logbook
- investigate different types of variables, such as independent, continuous and discrete variables
- select suitable measuring instruments to use in an investigation
- find patterns in the relationships between quantities under investigation
- use software programs
- handle difficulties
- work safely
- write a report.

As part of Unit 2, you will do a practical investigation on an aspect of the Motion Area of Study or one of the 12 options.

What is the benefit to you?

The practical investigation lets you follow your own interests. Enjoy creating solutions to questions that are important to you, managing your work and telling others about what you have done. Your study of Physics should help you to be more scientific.

Reflect on what it means to be 'scientific', and the characteristics of scientific ways of doing things compared to non-scientific ways. You will improve your ability to solve problems, use resources and communicate ideas. These attributes are useful in everyday life and highly valued in the workplace.

Being scientific means making use of observations, experiments and logical thinking to test ideas.

What is involved?

Many of the experiments you have done as part of this course were designed with clear instructions and specific questions to answer. In this investigation, there is more responsibility on you to plan and carry out the task. It gives you the opportunity to show your skill and imagination in experimental design, commitment to a task and your communication ability in explaining your results.

The topic can be one of your choosing and you can work individually or with another student. It is a rare topic that requires three pairs of hands and eyes.

The investigation will require a significant amount of class time. Your teacher will set aside two to three weeks for the activity, so some planning and organisation on your part will be needed to achieve a personally satisfying outcome. The table below will assist with your planning.

TABLE 13.1 Investigation planning with sample schedule

Task	Due date
Your teacher spends some class time to: • introduce the task • explain what is expected of you • suggest some possible topics or brainstorm others with the class • outline the timeline • distribute a form for you write down one or more topics you would like to investigate.	Fri. 25 Aug
Return your list of possible topics for approval.	Wed. 30 Aug
Submit a detailed research proposal for your approved topic.	Mon. 5 Sept
Requested equipment is assembled by the teacher and lab technician.	Fri. 9 Sept
Investigation begins.	Mon. 12 Sept
Cycle of measurements and data analysis leading to a review of progress and further, more detailed measurements.	Tues. 13 Sept
Use some holiday time to refine graphs and plan write-up of report, etc.	Fri. 30 Sept
Cycle continues.	Mon. 3 Oct
Pack up equipment.	Tues. 11 Oct
Write sections of report and place them into a poster template.	Wed. 12 Oct
Submit finished report.	Fri. 14 Oct

Selecting a topic

Coming up with a topic is not something that happens straight away. You need to take some time to consider it. You want to investigate a topic that interests you, that provides opportunity for some challenge, yet can be done in the time available and with the resources available within the school.

Brainstorming a list of possible topics is a good way to start:

- Form a group of three to five and appoint a leader.
- Draw a grid on a large sheet of paper with headings across the top such as: Hobbies and interests, Sports, Science in the news, Investigations you did in previous years, and Course topics. Down the side have types of investigations such as: Investigating the operation of a device or technology, Solving a technological problem, Investigating a physical phenomenon.
- Pick a box from the grid and brainstorm some topics for that box, then move onto another one.
- If other groups have done the same task, combine your entries with theirs.

Hints for brainstorming:

- Concentrate on quantity, not quality. Get down as many ideas as you can, as fast as you can. Resist the temptation to evaluate as you go — do that later.
- Be prepared to be outlandish. Humour is creative. Ideas that are preposterous might trigger ideas that are not.

Practical investigations have been a popular feature of physics courses in many countries for several decades, so there are thousands of possible topics if you search around. Some are listed below, and a document that contains weblinks and many more additional topics can be found in your eBookPLUS. You should check through these lists and see what sparks your interest because choosing a topic that intrigues you will ensure a high level of commitment and a sense of pride in the finished work. Avoid seemingly sophisticated topics, everyday topics are not only readily accessible and initially straightforward to investigate, but they often have hidden subtleties.

Turning the topic into a good question

Turning the topic into a question focuses your mind on what you want to find out. The question needs to be:

- one that experimenting can answer
- one worth investigating to you
- practicable, given your knowledge, time and the school resources
- asked in a way that indicates what you will do.

Submitting a research proposal

Once your teacher has approved your topic, the real work begins. On the next page is a typical proposal sheet that you could be asked to complete.

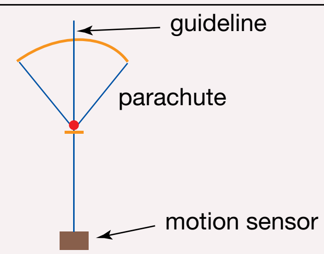
Keep a log

Use a separate, bound exercise book. Use it for thinking, calculating, drawing, leaving messages and preparing your report. You can use it to record your data if you don't want to use a computer. You can use the logbook to show your teacher how your work is progressing. Your logbook will also be assessed by your teacher.

Your logbook can include:

- your initial ideas
- notes from brainstorming
- notes from background reading
- equipment set up and plan
- your observations, measurements, data analysis and graphs
- difficulties you experience.

Practical investigation protocol

Name:	Jac
Partner's name (optional):	Jill
Title of your investigation:	Performance of a parachute
Investigation's purpose: (A brief sentence, but needs to be precise)	To investigate how the initial acceleration and terminal velocity of a parachute depend on the falling mass and the diameter of the air vent
Write down three starting questions you want to answer. (These are to help focus your planning.)	How quickly does a parachute reach terminal velocity? Does the air vent make a difference? Is the mass on the end a significant factor in determining the terminal velocity?
List independent variables; indicate which are continuous and which are discrete; list dependent variables. (Shows if you have thought of all the obvious variables)	Independent: falling mass, diameter of air vent, diameter of open canopy, number of strings supporting the mass, mass and type of canopy material Dependent: final terminal velocity, initial acceleration, distance and time to reach terminal velocity.
List the physics concepts and relationships you expect to use in your investigation. (Gives an indication of the extent of your understanding of the topic)	Air resistance increases with speed until the upward force balances the downward weight force, at which point the net force is zero and the parachute does not accelerate. The raw data is position of the parachute against time. From this, the speed in each interval can be calculated using $v = \frac{\Delta x}{\Delta t}$, and the acceleration between intervals can be calculated from $a = \frac{\Delta v}{\Delta t}$.
List the equipment and measuring instruments that you plan to use. (For your teacher to see whether you have the right tools for the task.)	Parachute: cloth, light string, scissors, plasticine, cardboard to reflect ultrasound, small disc with hole to attach strings, mass and cardboard Ruler, light cotton or fishing line to prevent swaying and parachute going off line Ultrasound motion sensor connected to computer, top-loading balance, protection for motion sensor from falling parachute
Sketch your experimental set up. (This will make your first day of investigating smoother and your teacher may be able to suggest refinements.)	
List the steps in your experimental design. (An important stage in your planning that lets your teacher to see if you have forgotten anything.)	1. Assemble parachute, set up equipment and do trial run. Release parachute in open position. 2. Start with a small air vent of 1 cm diameter. 3. Do at least three drops with each mass. Look at graph each time to see if the drop should be retained and if five good drops are needed. 4. Increase the mass and repeat drops. Do this for at least seven masses. Check graphs to see if pattern suggests more smaller, larger or in between mass values are needed. 5. Increase (possibly double) diameter of air vent and repeat drops for same mass values at least initially, but may need to use other values. 6. Repeat for another much larger air vent diameter. Do a fourth diameter if we have the time.
Any special requests (e.g. equipment may need to be left set up between classes, or access needed outside class time)	It would be handy if we could leave the guideline attached to the ceiling between classes or possibly stay on at lunchtime on Wednesdays.

Variables

Variables are the physical quantities that you measure. You set the value of some variables at the start of each experiment; other variables are determined by your experiment, and sometimes there are variables that you calculate using your measurements.

Independent variables are changed in an investigation to observe their effect on another variable.

Continuous variables take a numerical value. They can be represented as a line graph.

Discrete variables may include different types of categories such as colour. They can only be presented as a column graph, not as line graphs.

Dependent variables are determined by the independent variables.

Independent variables are variables whose value you determine. You would not investigate all independent variables, you would choose just two that interest you. Your report should still mention all independent variables to show your deep understanding of the problem you are investigating. The variables you don't investigate will have constant values during your experiment, so they could be called *fixed* or *controlled variables*.

There are two types of independent variables:

1. **Continuous variables** are variables that can take any numerical value, such as the release height of a parachute. This means they can be graphed using *x*–*y* axes. A graph can reveal a relationship between two quantities.
2. **Discrete variables** are variables that allow for different types, like different material for parachutes, rather than different numbers. These can only be presented as a column graph that enables comparison.

Dependent variables are variables that come from your experiment. Their values are determined by the independent variables. You would not analyse all dependent variables; normally just one would suffice.

Sample problem 13.1

Jac and Jill were considering investigating the impact and rebound of a bouncing basketball. The variables they considered were: drop height, air pressure in the ball, temperature of the ball, different surfaces, different brands of basketball, the age of the basketball and the height the ball achieved on first bounce. Which of these are dependent variables?

Solution: The height the ball achieved on first bounce is the dependent variable, all the other variables are independent as they can be changed to alter the outcome of the experiment.

Sample problem 13.2

Which of the examples below are continuous variables?

(a) Weight of a basketball
(b) Number of basketballs used in an investigation
(c) Type of material of which the basketball is constructed
(d) Age of students in a class

Solution: (a) and (d). The continuous variables are the weight of a basketball and the age of students in a class.

Revision question 13.1

Consider the variables that Jac and Jill were considering in sample problem 13.1. Classify these variables into the two categories: continuous and discrete.

Revision question 13.2

A student wishes to investigate the impact and rebound height of a bouncing basketball. List as many dependent variables as you can think of, including ones that can be calculated from others.

Selecting your measuring instruments

Your school will have a range of measuring instruments. They will vary in precision and ease of use.

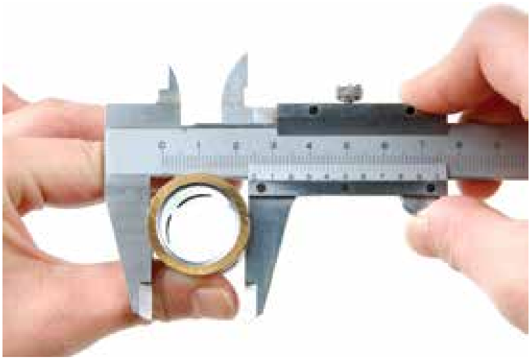
You won't always need to use the most accurate instrument. A simple instrument that allows for quick measurements will be enough more often than not. Sometimes a simple stopwatch is just as good as an electronic timer, and a beam balance may compare well to a very accurate top loading balance.

Some instruments that you might to consider are listed below based on what they measure.

Mass

- Slotted masses of known mass. Simple to use; accurate; comes only in multiples of a set weight, e.g. 50 g.
- Beam balance. Accurate with a large range of values; can be time consuming to measure several masses.

- Spring balance. Quick to use; covers a large range of masses; not very accurate.
- Top loading balance. Very accurate; very good for small masses; simple to use.



Length

- Metre ruler. Accurate; good for a range of distances; can be read to about 0.5 mm.
- Vernier calliper. For precision measurement of short distances; takes some time to learn how to use.
- Micrometer. For precision measurement of thicknesses; takes some time to learn how to use and can be easily damaged.

Time

- Stopwatch. Simple to use; accurate down to your response time; not reliable for short time intervals.
- Electronic timer. Requires some instruction; very accurate; best suited for short time intervals; can be used with electrical contacts and photogates.

Motion

- Ticker timer. Simple to use; limited in accuracy; best with objects moving over a short distance; can be time consuming to analyse.
- Air track. Very accurate, particularly if used with photogates; very effective in studying collisions; takes some time to set up, but data collection is very efficient once done.

- Ultrasound motion detector. Quite accurate; useful with real motions; lots of data which means data analysis in Excel can be time consuming.
- Video with analysis software. Quite accurate; requires some setting up; data obtained from software; data analysis in Excel can be time consuming. Free video motion analysis software are Tracker and PhysMo. Digital cameras with high-speed video are useful for measurement of short, fast events.

Electrical

- Meters: Voltmeters, ammeters, galvanometers. Easy to set up, but care is needed to ensure the meter is wired into the circuit correctly, otherwise the meter can be damaged; large range of values; usually analogue displays.
- Multimeters. Easy to set up; more tolerant of incorrect use, but can be damaged if incorrectly connected to a high current; large range of values; usually digital displays.

Specialist equipment

- Cathode-ray oscilloscope (CRO). Even though the CRO is basically a visual voltmeter, it is a versatile instrument. It can measure both constant and varying voltages. The sweep of the trace across the screen can be used to measure time intervals of the order of millionths of a second. Many transducers, such as microphones, produce a voltage that can be displayed on the screen, either for analysis or measurement of very short time intervals. There are also computer versions of CROs that can be freely downloaded.
- Data loggers. There are sensors now available for most physical quantities, such as temperature, pressure, light intensity, motion, force, voltage, current, magnetic field, ionising radiation. The recording of data by these sensors for later analysis greatly facilitates practical investigations.
- Apps. There are increasing numbers of apps that perform measurement functions. The accuracy of each needs to be confirmed before being used in a formal investigation, but it is an area worth exploring. Some sources include Physics Toolbox and Sensor Kinetics

Making the most of a measurement

Limits to precision and uncertainty

Every instrument has a limit to how precisely it measures. The scale or digital display imposes a constraint on how many digits you can record. The scale or display also reveals the tolerance of the measurement.

A metre ruler has lines to mark each millimetre, but there is space between these lines. You could measure a length to the nearest millimetre, but because of the space between the lines, if you look carefully, you can measure to a higher precision. You can measure to the nearest 0.5 mm.

The best estimate for the length of the red line in the figure above is 2.35 cm. The actual length is closer to 2.35 cm than it is to either 2.30 cm or 2.40 cm. The measurement of 2.35 cm says the actual length is somewhere between 2.325 cm and 2.375 cm.

The way to write this is:

The length of the red line = 2.35 ± 0.025 cm

The 0.025 represents the tolerance or uncertainty in the measurement.

In this case, with well-spaced millimetre lines, the tolerance is $\frac{1}{4}$ of the smallest division. For a dense scale where measurement lines are close together, the tolerance would be $\frac{1}{2}$ of the smallest division.

The reading on a digital scale is 8.94 grams. This means the mass is not 8.93 g nor 8.95 g. The actual mass is somewhere between 8.935 and 8.945 grams. The way to write this is:

The mass = 8.94 ± 0.005 g.

Sample problem 13.3

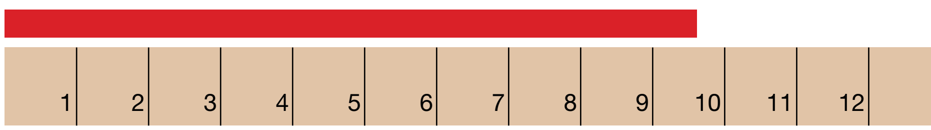
Record the reading on the scales below, including the tolerance.

Solution: The scale shows 0.250 g, so the actual weight may be between 0.2495 g and 0.2505 g. The mass is written as 0.250 ± 0.0005 g.

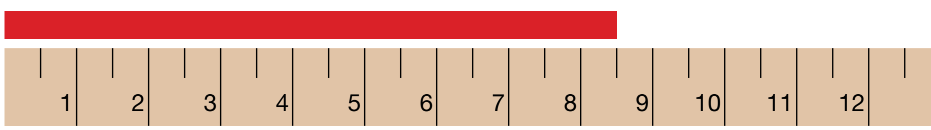
Revision question 13.3

(a) **Determine the length of each line in the diagram below, showing the tolerance in each case.**

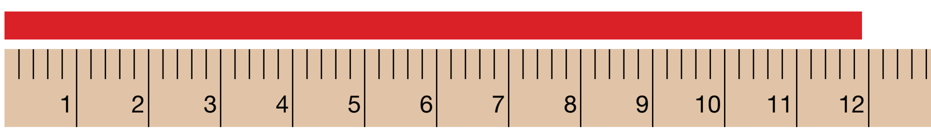
(i)



(ii)



(iii)



(b) **Record the reading on the scales at left, including the tolerance.**

Repeated measurements

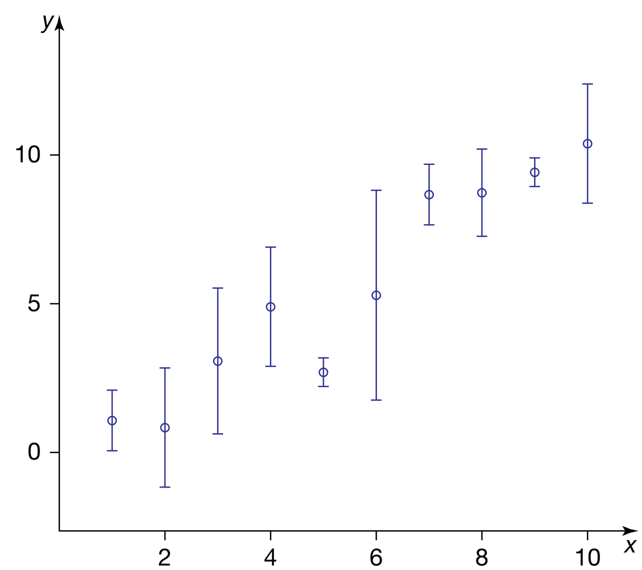
Measurements of independent variables are usually precise and careful, so one measurement should be enough. However, measurements of the dependent variables are often prone to some variation.

Whether the variation is caused by the human reaction time when using a stopwatch, judging the rebound height of a basketball or in the case of the parachute, the unpredictable way the canopy will open each time, each reading may be different. So it is sensible to take several readings to obtain an average. You would expect that at least three measurements would be needed, and possibly five, but more than five is generally unnecessary.

In some instances the variation between different readings will exceed the precision of the instrument. To determine which value you plot, you would use the average as well as the spread of the readings. For example, if your partner dropped the basketball from a height of 80.0 cm, and you judged the rebound height of the ball for five trials as: 68 cm, 69.5 cm, 68.5 cm, 68.5 cm and 69.5 cm. The average is 68.8 cm, which you would round to the nearest 0.5 cm because of the difficulty of judging a moving ball, giving an average of 69 cm. The full range of your measurements is from 68 cm to 69.5 cm, so your uncertainty would need to be 1 cm to cover the full range. This set of measurements would then be written as 69 ± 1 cm.

This format is useful in two ways: graphing and calculating.

When you graph your results, the number you will plot is 69 cm. To represent the '±1 cm', you can draw a line through the point, up 1 cm and down 1 cm, with a short line across the top and bottom of the line to make the ends evident.



Example of error bars

Rather than graphing rebound height against drop height, it is more revealing of the physics of the situation to calculate and graph the ratio of the rebound height to drop height against drop height. The ratio is a measure of how much of the original gravitational potential energy is restored.

In this case the ratio would be $\frac{69}{80.0} = 0.8625$, but how many digits are we entitled to use and how big should the error bar be? The first question is reasonably straightforward. The number of digits in your answer should equal the smallest number of digits in the data you used in the calculation. In this instance the average height has two digits, so the answer would be written as 0.86. You are not justified in including more digits because you don't know the original data accurately enough.

Working out the size of an error bar takes more effort. If the two pieces of data are 69 ± 1 cm and 80.0 ± 0.3 cm, we can just add the uncertainties to get ±1.3 cm, but that doesn't make sense when the calculated value is 0.86. Dividing the uncertainties would produce another unusual result.

The method used is to first express the uncertainty for each data value as a percentage. For example:

$$\text{Percentage error of } 69 \pm 1 \text{ cm} = \left(\frac{1}{69}\right) \times 100 = 1.4\%$$

$$\text{Percentage error of } 80.0 \pm 0.3 \text{ cm} = \left(\frac{0.3}{80}\right) \times 100 = 0.4\%$$

Now add the two percentage errors together:

Total percentage error = 1.4% + 0.4% = 1.8%

Next use this total percentage error to find the error in the calculated answer.

Error = 0.86 × 1.8% = 0.016, which would be rounded to one digit as 0.02.

The full calculated answer would now be 0.86 ± 0.02.

The percentage errors are added together regardless of whether the data values are divided, multiplied, added or subtracted. For example:

- Calculating speed using $v = \frac{\Delta x}{\Delta t}$, the percentage errors of displacement and time would be added together.
- Calculating momentum using $p = mv$, the percentage errors of mass and velocity would be added together.
- Calculating the change in momentum using $\Delta p = p_{\text{final}} - p_{\text{initial}}$, the actual uncertainties of each are added together.

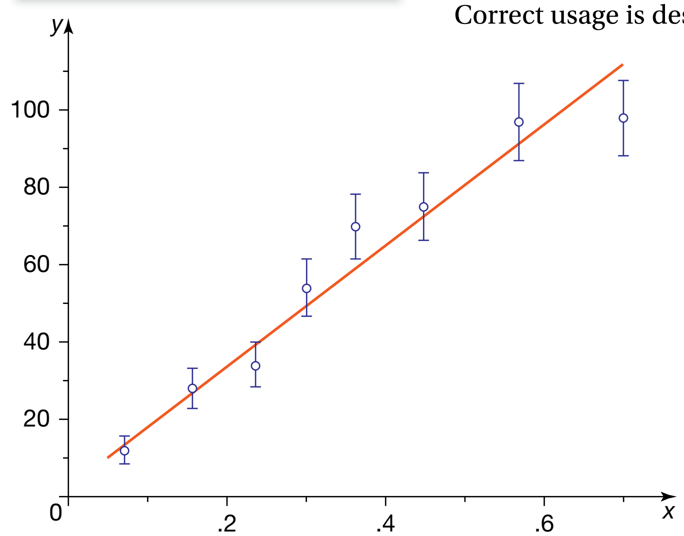
Finding patterns

Graphs are an effective way of summarising your data and looking for a physical relationship between the quantities you are investigating.

To present your data clearly, your graph should have the following features:

- Each axis labelled with the physical quantity it represents. It is convention to put the independent variable on the *x*-axis and the dependent variable on the *y*-axis. You want to find out how '*y*' depends on '*x*'. So, you might graph terminal velocity on the *y*-axis and mass on the *x*-axis.
- A scale with the units displayed.
- Include the origin, the zero value for the variables, on both axes. Sometimes the origin is a data point, even though you did not technically measure it. For example, if the drop height is zero, the rebound height would also be zero, and so the origin is a data point, but the energy lost cannot be determined and is not a data point. The inclusion of the origin on the axes makes any relationship more apparent. Truncating the values on either the *y*- or *x*-axis exaggerates the variation in the data, and may disguise any relationship between the variables.
- Error bar for each data point. Sometimes, given your scale, the error bars will be too small to be seen and so would not be worth including. If you are using Excel to generate your graphs, be careful when using the error bar facility. Correct usage is described below.

Graph showing a line of best fit



Drawing a line of best fit

A line of best fit summarises your graph. The line can be used to find the gradient of your graph and also a *y*-intercept.

The line of best fit doesn't need to pass through each data point, although you should try to draw the line through each error bar if possible, but you may not be able to go through all of them. As a general rule, try to have as many data points above your line as you have below. Don't assume your line must pass through the origin.

Of course, not all graphs can be summarised by a straight line. A gentle curve may be more appropriate, which can be analysed further.

Using Microsoft Excel

The Excel spreadsheet is a very useful tool to the experimenter. It can:

- store your measurements. Make sure you save your data every few minutes and do a backup every day.
- calculate any derived physical quantities, such as speed and acceleration of a parachute or the percentage of energy lost by a bouncing ball. The 'Fill down' command is a time saver.
- be a powerful graphing tool, but it must be used wisely. Because you are looking for a relationship between the variables, you must choose 'X Y (Scatter)' as your type of graph. This has the key scientific features of a proper scale and the presence of the origin. It is also preferable to choose a graph of unconnected data points as your sub-type. You don't want a line, straight or curved, going from data point to data point; some of your data points may be a touch out. A better choice is a 'line of best fit', which Excel can do for you.
- generate a line of best fit. If you right-click on any data point, a window pops up with the option 'Add Trendline'. This is the Excel command to create a line of best fit. Once selected, you have several choices. If your graph looks like a straight line, choose 'Linear'. If the graph looks like a curve passing through the origin, choose 'Power'. Students often think any curve is exponential, but unless the phenomenon involves growth or decay, it is very unlikely that a graph from a physics experiment would generate an exponential graph.
- create error bars. Excel can add in errors bars, but this is best avoided in most instances. It is likely that the size of your error bars will vary from data point to data point. Excel can't handle that. It assigns a fixed-size error bar to each data point. Error bars can be added by clicking on any part of the chart and going to the 'Layout' tab.

Note: These instructions may vary depending on the version of Excel you are using.

Note: In the 'Add Trendline' window, you can select to display the equation of the line of best fit on your graph. Care needs to be shown with numbers in the equation. The numbers of digits may not be justified by your data.

Handling difficulties

There will be times when:

- your results show no pattern
- your results aren't what you expected
- the equipment doesn't work
- you don't know what to do next
- you don't understand the references you have been reading.

How you handle such problems is important.

- Go back to basics. Check your logic, understanding and planning. Clarify the issue. Draw diagrams and concept maps if they help. Look for options. Go to a textbook.
- Talk to other students or members of your family. Sometimes just talking through a situation can help you see a solution.
- Seek help from your teacher.

Record in your logbook how you tackled the problem, what solution you found and where you got it from. This is good science and good management.

Safety

Part of the enjoyment of a practical investigation is that the topic may be unconventional or use an innovative method. Such situations, however, can present some risk, so special care needs to be taken to ensure yourself and others are safe.

Some simple rules to follow are:

- Do the investigation as outlined in your approved plan. Don't vary your plan without approval from your teacher.
- Don't do experimental work unsupervised unless you have prior approval from your teacher.
- Investigations can take up more space than usual experiments, so be sensitive to the needs of other students in the classroom.
- When first setting up electrical experiments, ask your teacher to check the circuit.
- Don't interfere with the equipment set-up of others.

Writing a report

The report should have an obvious and logical structure. There is no single prescriptive format, but your report should include the sections listed in table 13.2.

TABLE 13.2 Aspects of a written report

Section	Description
Title	A precise and complete description of what you investigated
Physics concepts and relationships	A short paragraph explaining the relevant concepts and relationships and how they apply to this investigation
Aim or purpose	Why are you doing this investigation? What do you hope to find?
Procedure	This is a major section. It describes what you measured, your selection of equipment and measuring instruments, and your step-by-step method. Include diagrams and photos. Refer to how you controlled variables; achieved the desired accuracy; and overcame, avoided or anticipated difficulties.
Observations and measurements	Include your data and graphs. If there is too much data, then refer to your logbook for the full set. Show how calculations were done using actual data. Also include illustrations of how uncertainties were calculated.
Analysis of results	How does your data support your initial intentions? How much is your analysis limited by uncertainties? Identify strengths and weaknesses in the investigation, indicating how you would do it differently if you repeated it, and what your next steps in the investigation would be if you had more time.
Conclusion	A short summary related to the initial purpose, summarising the meaning of your results

Presenting as a digital poster

A written report would be read in depth by your teacher, who will often spend more than 20 minutes going through it in detail. A poster has a different intent and a different audience. The structure of your investigation should be apparent and give the viewer a good sense of the investigation within several minutes' perusal. If presenting as a poster, your teacher would also need access to your logbook to get a fuller appreciation of your work.

A poster addresses the sections outlined in table 13.2 above, without going into too much detail. For example, you would display only a subset of the data to convey your findings and accuracy. Similarly, not all your graphs need appear.

PowerPoint templates can assist with designing posters and make it much easier than putting together a hard copy on a large sheet of card. Check out the websites on JacPlus for templates as well as examples of science posters.

Advice on assembling a poster

Layout

- Set up a clearly visible structure for your poster.
- Include a photo, diagram or graphs in each section, if possible.
- Have a short title.
- Start with an engaging statement about the topic you investigated.
- Give a quick overview of your approach, with images of experimental set-up and equipment used. A flow chart is an effective way of conveying your procedure.
- Present results in graphical form with commentary; this will be the largest section of the poster.
- Discuss your results with perceptive comments.
- Decide on font size and line spacing to achieve the best impact for your poster.

Language

- Restrict the text to 800–1000 words.
- Adopt a more personal tone in the writing; use the active voice.
- Avoid large blocks of text and long sentences.
- Don't plagiarise; if you must quote, then acknowledge your sources.
- Use sentence case; that is, no all upper case sentences and avoid italicised sentences.
- Use serif fonts, such as Times New Roman and Palatino.
- Use italics for emphasis, rather than underlining or bold.
- Check spelling and grammar as well as whether the correct word has been chosen, e.g. affect or effect, it's or its etc.

Graphs

- Avoid grid lines on graphs, they complicate the picture.
- Ensure scales are readable.
- Use informative titles to support the communication message of the poster.

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Investigation topics
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Topics

Here are some sample topics to get you thinking.

Motion

- The performance of a CD hovercraft
- The performance of a firework rocket or a water-driven rocket
- The impact force on and the energy loss by a bouncing ball
- Motion of a yoyo
- Flight of a table-tennis ball
- The energy delivered by a catapult
- Energy changes on a trampoline
- Dry sand is soft; wet sand is hard; wetter sand is soft again; investigate this phenomenon
- The energy stored in a spiral clock spring
- Maximising the adhesion of blu-tack
- Factors affecting the design of a good paddlewheel

Astronomy
- The resolution of close-spaced objects by the eye
- The field of view of a simple telescope
- The depth of focus of a simple telescope

Forces and the human body
- Effect of force on a bone (beam, cantilever)
- Effect of a twisting force on a bone
- The physics of a bicep curl
- The strength of girders of different construction (using balsa wood)
- The strength of human hair

AC to DC
- The design of an AC ammeter
- The value of fins for regulator heat sinks

Flight
- The thrust of a propeller (in air or in water)
- The drag on spheres in an airstream
- The resistance to water flow of various plumbers' fittings (pipe, bends, etc.)
- The effect of changing the size or shape of the wings of a glider
- The flight of a Magnus glider
- The supporting of a ball on a jet of air
- Paper plane design

Nuclear energy and Medical physics
- Variation in range of alpha particles with air pressure
- Variation in range of beta particles in different metals
- How many beta particles are scattered back from various substances?
- The natural radioactivity of potassium salts
- Can background radiation be reduced by screening?

Light and vision
- Do people vary in the range of wavelengths they can see?
- How quickly does the iris of the eye contract when the light is made brighter?
- Does the resolution of the eye depend on the illumination?
- The adaptation to dark of the human eye
- The depth of focus of a microscope
- The resolution of a microscope
- Moiré fringes

Sound and music
- How long does a sound last in a large hall?
- Frequency range of a microphone
- The behaviour of a loudspeaker cabinet at low frequencies
- The frequencies of a stretched wire
- Diffraction of sound waves

Ball games
- The sweet spot of a tennis racquet
- Effect of the mass of a cricket bat on ball speed after impact
- The changeover from sliding to rolling
- Compare static and kinetic friction of running shoes

Bioelectricity
- How does the resistance between two points on a conducting sheet vary with distance?
- How does the resistance between two flat plates in a tank of conducting liquid vary with their spacing?

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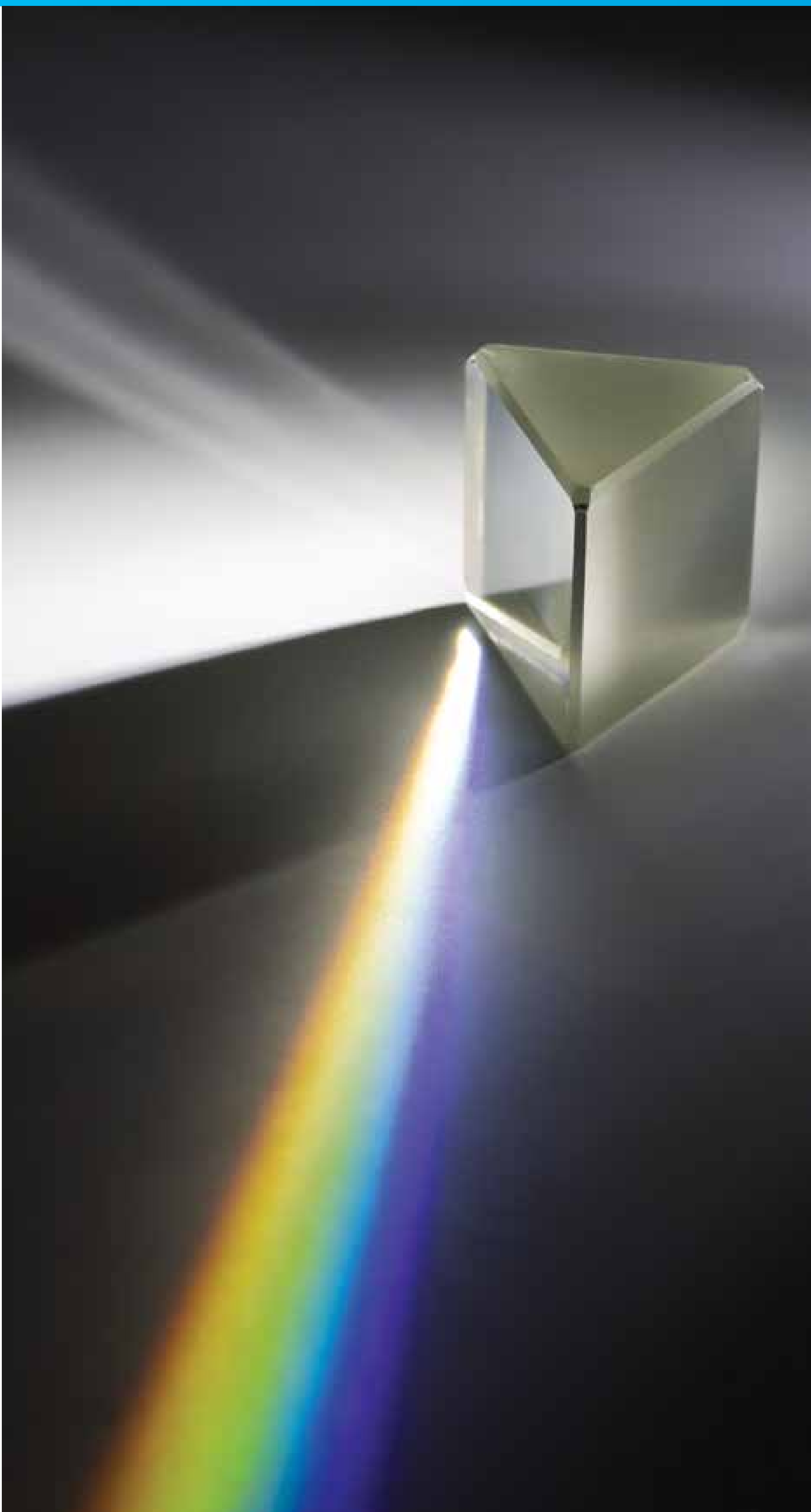
OPTIONS



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The Options chapters 14–25 can be found in your eBookPLUS. A copy of each chapter can be downloaded from the Resource panel. Students will study only one Option chapter.

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CHAPTER

14 What are stars?

REMEMBER

Before beginning this chapter, you should be able to:

- recognise that light from the Sun contains the spectrum of colours: red, orange, yellow, green, blue, indigo, violet
- recognise that the electromagnetic spectrum contains many other wavelengths that are not visible, such as radio waves and X-rays
- describe the structure of the atom in terms of protons, neutrons and electrons
- recall the nature of alpha and beta decay
- interpret nuclear equations
- recall Hubble's Law.

KEY IDEAS

After completing this chapter, you should be able to:

- explain that the electromagnetic spectrum is our key source of information about stars
- describe how standard candles, parallax and red shift are used to determine the distance to stars
- recall that the Sun is a typical star
- describe stars in terms of their luminosity, radius, mass, temperature and spectral type
- describe nuclear fusion as the energy source of a star and explain that the extent of fusion depends on the size and age of the star
- use the Hertzsprung–Russell diagram as a powerful technique for examining the life cycle of stars
- describe how stars end as either white dwarfs, neutron stars or black holes depending on their mass.

Chapter review

Summary

- The information we know about the universe is gathered from the electromagnetic radiation that has reached us.
- From electromagnetic radiation, astrophysicists are able to determine the temperature and elements that make up the stars.
- Standard candles, such as Cepheid variables whose period of varying luminosity is related to their average luminosity, enable us to measure distances to distant stars.
- Parallax is the only direct method that astrophysicists have to measure the distance to stars, and it only works for stars that are relatively nearby due to the small parallax of such distant objects.
- The spectra of more distant galaxies are all red shifted by an amount that increases with distance, so red shift is a very useful technique for measuring how far away distant galaxies are.
- The Sun is a typical star, enormous by Earth standards but dwarfed by many larger stars.
- The Sun is made mostly of ionised hydrogen and helium.
- The total energy output of a star is called its luminosity, which varies with the age and mass of the star.
- More massive stars shine more brightly and are hotter than low mass stars, and also pass through their life cycle more quickly.
- The Hertzsprung–Russell (H–R) diagram is a graph of the luminosity of stars against their temperature or colour.
- In an H–R diagram, most stars are found on a diagonal line called the main sequence, from hot and luminous down to cool and dim.
- Main sequence stars are fusing hydrogen into helium in their cores.
- Fusion is the source of energy in stars and involves a mass loss in accordance with $E = mc^2$.
- Stars above the main sequence in an H–R diagram have consumed all of the hydrogen in their cores and have expanded in size to form red giants due to fusion heating outer layers of the star.
- Stars below the main sequence in an H–R diagram are ending their life cycle; fusion has finished and most of their material has been shed, forming a planetary nebula. They are remnants of stars cooling down as white dwarfs.
- The event horizon is the name given to the radius around a black hole beyond which no matter or light can escape. The radius is called the Schwarzchild radius and can be calculated using $r = \frac{2GM}{c^2}$.
- To observers at a distance from a black hole, time is measured to pass more slowly for objects near the black hole.
- Black holes distort the shape of space around them to the point that it collapses on itself.
- The Milky Way, our galaxy, is a large spiral galaxy. Other galaxies vary vastly in size and shape.
- Spectroscopy can be used to analyse the chemical composition of stars, which provides the key to determining the age of the star.

Questions

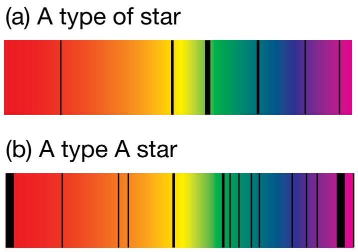
Characteristics of the Sun

1. What provides most of the Earth's energy?
2. Stars appear as pinpoints of light in the night sky. List evidence that the Sun is also a star.
3. The luminosity of the Sun is 3.86×10^{26} W, the radius of Earth's orbit is 1.50×10^{11} m and the Earth has a radius of 6.37×10^{6} m.
   (a) Find the surface area of a sphere whose surface lies at the Earth's orbit and is centred on the Sun.
   (b) Find the fraction of that surface that is taken up by the Earth.
   (c) Calculate the total energy that the Earth receives from the Sun each day.
   (d) Calculate the total energy received by one solar panel of area 1 m^2 per day (average of 6 hours sunshine per day).
4. The volume of the Sun is how many times that of the Earth?
5. Use the diagram in 'The temperature of stars' to estimate how many times greater the radius of Rigel is than the radius of the Sun.
6. Calculate how many times the mass of all the planets in the solar system would fit into the mass of the Sun.
7. Describe the process used to identify the elements that make up the Sun.

Properties of stars

8. List in order of size from smallest to largest: galaxy, universe, cluster of galaxies, supercluster of galaxies, Earth, solar system, Sun.
9. How is a star's spectral type determined?
10. Alpha Centauri and Beta Centauri are a pair of stars in the southern sky. Alpha Centauri appears slightly brighter than Beta Centauri. Alpha Centauri is a yellow star and Beta Centauri is a blue star. Using these two pieces of information, what else can you infer about these two stars?

11. Would you expect to find planets like Earth around Population II stars? Explain.
12. Compare and contrast the spectra of type O and type A stars.



Fusion as the energy source of stars

13. What is the source of energy in a star?
14. What two elements make up the vast majority of the universe?
15. The Sun radiates energy at 3.86×10^{26} J s^{-1}. Assume that this is all the result of the fusion of hydrogen to helium following the chain of reactions presented in this chapter. We can summarise the fusion of these reactions by the equation:

$$4{}_1^1\text{H} \rightarrow {}_2^4\text{He} + 2\beta^+ + \nu + \gamma + 26.76 \text{ MeV}$$

$(1 \text{ MeV} = 1.6 \times 10^{-13} \text{ J})$.

(a) How many of these fusion reactions would occur in the Sun per second?
(b) Given that the Sun has about 10^{57} hydrogen nuclei but only about 10% of those will fuse in the core, how long do you predict the Sun will continue to fuse hydrogen? (Give your answer to one significant figure.)

16. One of the reactions that occur in the Sun is the fusion of helium-3 and helium-4.
(a) Complete the equation:

$${}_2^3\text{He} + {}_2^4\text{He} \rightarrow \_\_\_ + \gamma + 1.59 \text{ MeV}.$$

(b) Use the energy released by the reaction to determine the mass difference between the nuclei on the left- and right-hand sides of the equation.
(c) Where could the helium isotopes for this reaction have come from?
(d) This is an intermediate reaction in a chain of reactions that occurs in the Sun. What is the final product of this chain of reactions, given that the Sun is a main sequence star?

17. (a) What are three arguments for the case that fusion is the source of the Sun's energy?
(b) Why is gravity not a good explanation of the source of the Sun's power?
18. Explain why, if hydrogen and helium make up the vast majority of the universe, they are relatively rare on Earth.
19. Research two nuclear reaction chains that occur in the Sun, other than the one that features in this chapter.

Evolution of stars

20. List three possible objects that can form in a star death.
21. What are the main chemical elements found in a planetary nebula? Explain why.
22. Anne argues that a massive star will last longer than a small star. Is she correct? Explain.
23. (a) Sketch an H–R diagram and circle and label the main sequence.
(b) Is it normal for stars to move along the main sequence during their life spans?
(c) Will the Sun ever become a supergiant?
(d) Circle and label the stars that have mainly fusion of helium and heavier elements in their cores.
(e) In what circumstances is it possible to have a very massive star positioned at the right-hand side of the diagram?
(f) What section of the diagram contains remnants of stars that no longer have fusion reactions as a source of energy?
(g) Andre measures the composition and temperature of two stars to be the same. He expects to place them in the same region of the H–R diagram. One of the stars is brighter than the other. What does this tell him about the two stars?
(h) A star lies on the main sequence. What does this tell you about the star?
(i) What colour are stars on the left-hand side of the diagram?
24. You are an astronomer with a research project to search for black holes. How will you look for them?
25. Use the internet to identify two black hole 'candidates' and explain why astrophysicists believe them to be black holes.
26. Write a description of the life cycle of a one solar mass star.
27. A massive star sheds a lot of material in a supernova explosion and the remaining mass, equal to four solar masses, collapses to form a black hole. What is the Schwarzchild radius of this black hole?
28. The black hole from question 27 consumes more mass over time, stripping it from a neighbouring star. What happens to the Schwarzchild radius?
29. You are in a spacecraft just outside the event horizon of a black hole.
(a) Do you notice anything different about the rate that time passes on the spacecraft?
(b) Later you return to Earth. What do you notice about how you have aged compared with those who remained on Earth?

Measurement of distances to stars and galaxies

30. What is a galaxy?

31. Describe the role of measuring distance in the discovery of galaxies.

32. A star's parallax is 0.155 arc seconds using a baseline of 1 AU. How far is this star from the Sun in:
(a) parsecs
(b) metres
(c) light-years?

33. The Hubble Space Telescope (HST) can measure parallax angles as small as 0.05 arc seconds. What is the furthest object for which the HST could be used to measure its distance using the method of parallax?

34. Describe a method that extends the baseline used in parallax measurements to greater than 1 AU in order to increase the distance that can be measured.

35. The moving cluster method is limited to measuring the distances to which stars?

36. What makes Cepheid variable stars so useful in measuring distances to galaxies?

37. A Cepheid variable star in one galaxy has the same period as a Cepheid variable star in a second galaxy. However, the first star has a brightness that is eight times that of the second. What can you say about the distance of the second galaxy compared to the first?

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CHAPTER

15 Is there life beyond our solar system?

REMEMBER

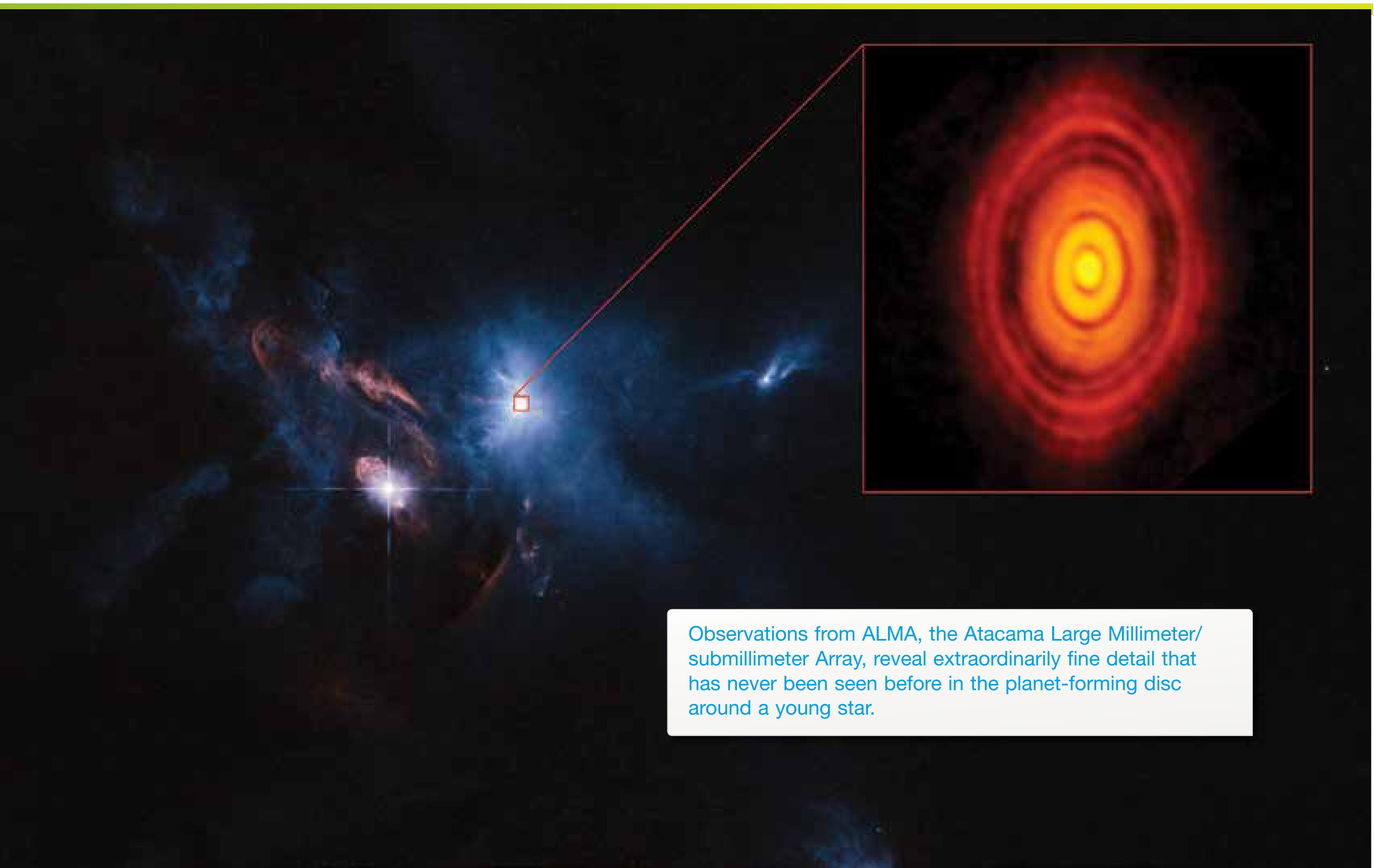
Before beginning this chapter, you should be able to:

- explain the arrangement and properties of the particles that make up an atom
- describe simple relationships between distance, velocity, acceleration and time
- recall that all objects with mass exert a gravitational force on other masses
- recognise that light is modelled as a wave as part of the electromagnetic spectrum
- recall that light is produced when electrons transition between energy levels in an atom.

KEY IDEAS

After completing this chapter, you should be able to:

- describe how light is modelled as a wave
- recognise the relationship between an object's temperature and the light it emits
- use atomic absorption and light emission spectra to describe how astronomers identify chemicals in the universe
- understand how an object's motion can cause a Doppler shift in its spectrum
- evaluate the methods used to search for extrasolar planets
- recognise the importance of liquid water in the search for life outside the solar system
- examine the use of the radio section of the spectrum in SETI.



Observations from ALMA, the Atacama Large Millimeter/submillimeter Array, reveal extraordinarily fine detail that has never been seen before in the planet-forming disc around a young star.

Chapter review

Summary

- Our understanding of the makeup of the universe is based on our ability to interpret the light from stars.
- The electromagnetic spectrum describes the range of energies light can have.
- White light can be separated into its constituent colours through the process of dispersion.
- Spectroscopy is the process of analysing the dispersion of light.
- Spectra can be continuous or discrete, absorption or emission.
- Spectra are used to determine the chemical makeup of stars by observing the distinct lines that signify particular elements.
- Electromagnetic radiation is produced when electrons accelerate.
- Incandescent sources of light make their light through heat and have a continuous spectrum.
- A blackbody curve can be used to determine the temperature of stars, which are then classified into spectral types.
- The wave model is used to explain many properties of light and is applied using the wave equation: $c = f\lambda$.
- The Doppler effect enables astronomers to determine how fast stellar objects are moving in relation to Earth.
- The search for exoplanets uses several methods including radial velocity, transit, direct imaging and microlensing.
- The exoplanets found so far challenge our understanding of planet formation; many are very large gas giants orbiting very close to their suns and with eccentric orbits.
- The way in which exoplanets are discovered can be biased toward particular types of planets.
- The search for life on other planets is based on a search for liquid water which can be found in the habitable zone around a star.
- The Fermi paradox and the Drake equation both express the probabilities associated with the search for intelligent life in the universe.
- The search for extraterrestrial intelligence (SETI) is based in radio astronomy due to the signature of the 21 cm neutral hydrogen line and the ground-based radio window.
- Multiple projects using targeted and untargeted methods have, to date, not revealed intelligent life outside of Earth.

Questions

The key is in the light

1. Define the following terms: refraction, reflection, dispersion, spectrum, spectroscopy.
2. (a) White light enters a crown glass rectangular prism. Sketch the path of red and deep blue light through the glass and back into air. How does the direction of the emerging coloured rays compare with that of the incoming white ray?
   (b) Suggest why a glass triangle is used to observe the visible spectrum, rather than a glass rectangle.
3. Explain the difference between absorption and emission spectra.
4. Explain how incandescent light is produced
5. What type of spectrum does an incandescent source have? Why?
6. Describe how the shape of the emission curve of a blackbody changes as the object gets hotter.
7. How can we use our understanding of blackbody emission curves to determine the temperature of stars?
8. Why does the spectral type only describe a star's surface temperature?
9. Betelgeuse appears red in images. What class of star is Betelgeuse and what does this indicate about its properties?
10. Explain how the spectra from a star can enable us to determine the chemicals present in the star.

The wave properties of light

11. How does the period of a wave relate to its frequency?
12. Calculate the frequency of the minute hand on a clock.
13. What type of wave is light modelled as?
14. Calculate the wavelength of orange light given its frequency is 4.8×10^{14} Hz.
15. Would yellow light have a longer or shorter wavelength than blue?
16. Which travels faster, green light or red light?
17. Which part of the spectrum is light with a wavelength of 4.5×10^{-11} m.
18. A spectral line is found at 385 nm. What is the frequency of this light? Is it visible?

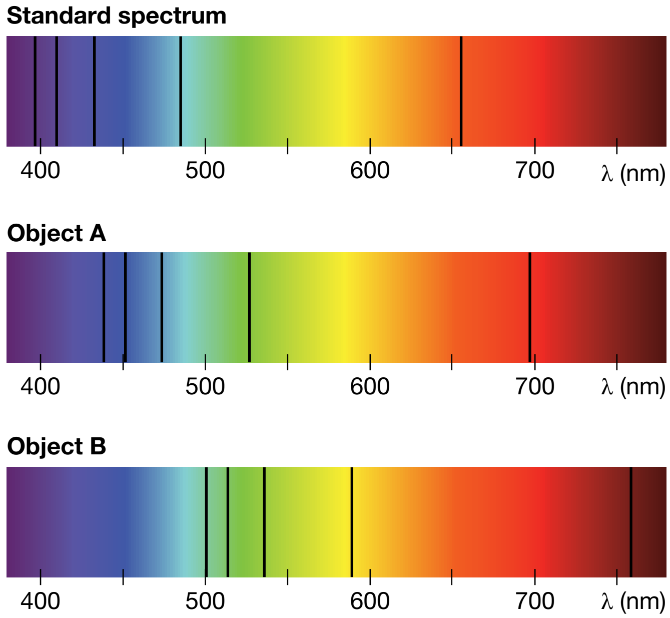
Using the Doppler shift

19. What causes the red shift in light from distant galaxies?

20. The light from the Andromeda galaxy is shifted toward blue. What does this mean?

21. What are the limitations of Doppler observations?

22. Consider the images below. What can you conclude about the relative motion of the objects and Earth?



The search for exoplanets

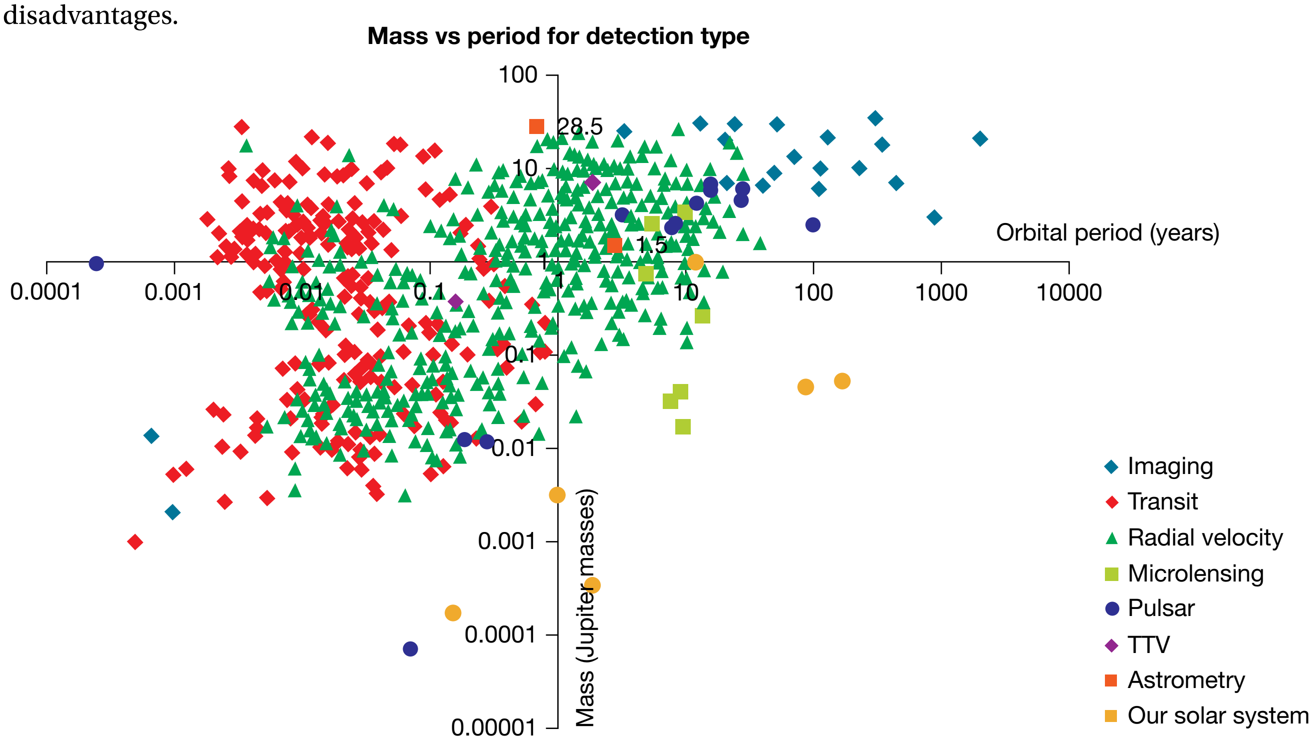
23. Why is finding exoplanets so difficult?

24. How does our understanding of gravity help us find exoplanets?

25. Create a table that summarises the different techniques used for finding exoplanets, identifying their success rate, their advantages and their disadvantages.

26. Using the above spectra, calculate the radial velocity of objects A and B.

27. Would you expect the velocities calculated in question 26 to be due to movement about a star or something else? Justify your answer.



Questions 28–31 relate to the scatterplot of mass versus period for detection type shown on page 266.

28. Why is the mass of the exoplanets measured in Jupiter masses?
29. What is the relationship between the period of a star's orbit and its radius?
30. Why would we conclude that certain methods of detection favour particular types of planets?
31. Does this data support the idea that our solar system is unique and we will never find another one like it? Justify your answer.

Life outside the solar system

32. What are the chemical constituents of life?
33. How do we know that these constituents are relatively abundant in the universe?
34. How do meteorites help us understand the origins of life?
35. Why is liquid water so important in the search for life?
36. What factors influence the habitable zone of a star?
37. What is an eccentric orbit, and why is this an issue for life on an exoplanet?
38. Other than the habitable zone, what factors affect the prospect for life on another planet?

Search for intelligent life

39. Explain the Fermi paradox.
40. If the Drake equation is impossible to calculate accurately, why is it valuable?
41. Sample problem 15.5 calculated the rate at which stars might form in our galaxy. Could this value be used for R^* in the Drake equation? Why or why not?
42. Search the internet to get values for f_p and n_e. Give reasoning as to why you believe them to be valid.

Listening out for a signal

43. Why is the radio part of the spectrum thought to be the best frequency to use in SETI?
44. What part of the spectrum is defined as radio?
45. Show why the 1420 MHz frequency of neutral hydrogen is called the 21 cm line.
46. What are the wavelengths for the hydroxyl radicals at 1665 MHz and 1720 MHz?
47. Describe two types of search methods employed in SETI.
48. Why is processing the data from sky surveys difficult and how is this problem solved?
49. Do you think it is a good idea to be 'shouting out' to the universe by sending messages into space?

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CHAPTER

16 How do forces act on the human body?

REMEMBER

Before beginning this chapter, you should be able to:

- describe mechanical levers
- recall the structure of the skeletal and musculature systems of the human body.

KEY IDEAS

After completing this chapter, you should be able to:

- identify different types of forces that act on the human body
- calculate the centre of mass of a system
- model translational forces and torque
- calculate stress and strain
- apply Young's modulus
- compare building materials with human tissues
- use stress and strain graphs to calculate the potential energy stored in a material
- investigate the materials used in prosthetics, both internal and external
- compare the functions and longevity of natural and artificial limbs.

Try to think of your body as a structure made of bone, tendons, muscles and skin. To find out what the body is capable of, we will look at the forces and loads on these structures.

Chapter review

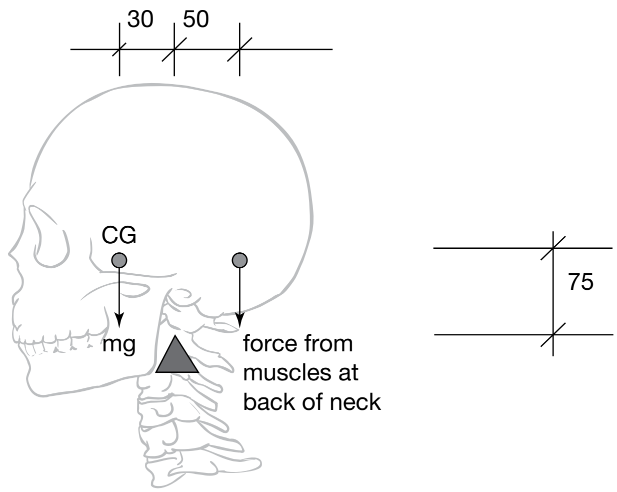
Summary

- A structure is in equilibrium if the net force acting on it is zero and the net torque acting on it is zero.
- Each part of a stationary structure must be in translational and rotational equilibrium.
- A force that pulls on something is called a tensile force.
- A force that pushes on something is called a compressive force.
- When a force is applied to a material, the material deforms. The amount of deformation depends on the size of the force and the stiffness of the material.
- When a material is bent, part of it is in compression and part is in tension.
- Deformation that is reversed when the load is removed is called elastic deformation.
- Deformation that is not completely reversed when the load is removed is called plastic deformation.
- Stress, σ, is the force per unit area of cross-section under load.
- Strain, ε, is the ratio of the change in length, Δl, to the original length of the material under load, L.
- When the stress–strain curve is a straight line, the gradient is called Young's modulus, E. The relationship between stress and strain is an expression of Hooke's Law and is written in the form $\sigma = E \times \varepsilon$. Young's modulus is a measure of the stiffness of a material.
- The strain energy of a material is equal to the work done to deform it. The area under the stress–strain curve measures the strain energy per unit volume of material.
- Toughness is a measure of the energy required to fracture a material and is determined from the total area under the stress–strain curve up to the fracture point.
- Brittle materials show little or no plastic deformation before breaking.
- Ductile materials show plastic deformation before breaking.
- Composite materials are made by combining two or more different materials to create a single material with enhanced characteristics.

Questions

Forces in the human body

1. The skull shown in the following figure acts as a lever with its fulcrum at the top of the spine.



(a) Calculate the magnitude of the force in the muscles at the back of the neck.

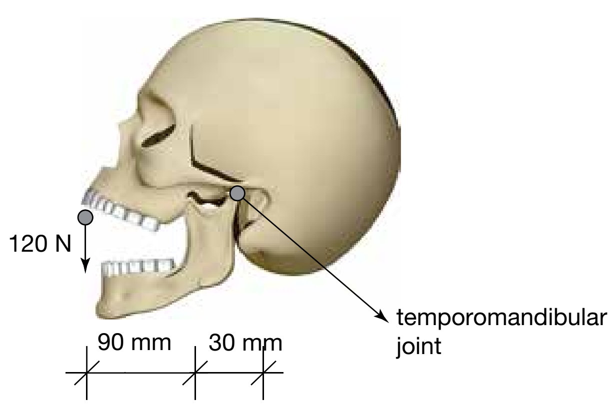
During a car crash, the shoulders of the person shown in the figure are restrained by a seatbelt. However, their head is initially accelerated forward, to be resisted only by the muscles in the back of the neck.

(b) On a diagram of a skull, show the forces that are now acting.

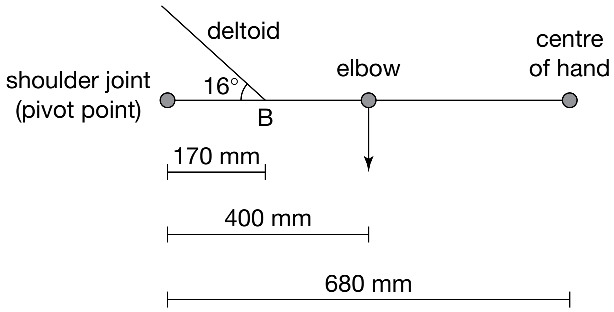
(c) Calculate the force in the muscles at the back of the neck when the acceleration is 4*g* forward.

(d) What is the force in the spine when the acceleration is 4*g* forward?

2. Your jaw acts as a lever when you eat, hinging at the temporomandibular joint. If the force needed to bite a carrot is 120 N, what force is required from the muscles shown in the figure below?



3. When holding an arm horizontally and to the side as shown in the figure below, Ben's arm acts as a lever that rotates at the shoulder joint.



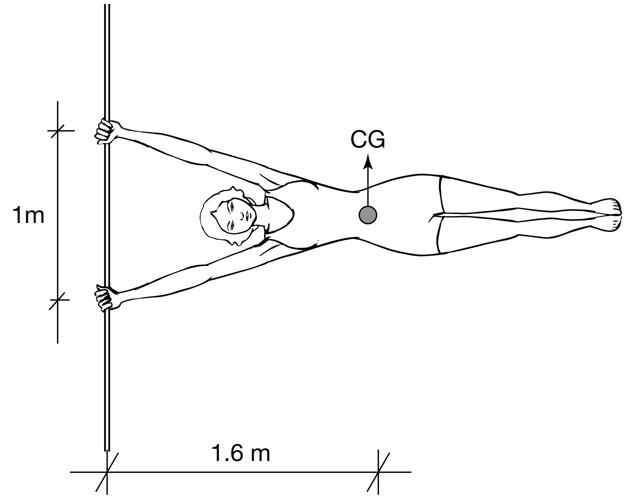
(a) If the mass of Ben's arm is 4 kg with its centre of mass at mid-length, what force is needed at B to keep his arm horizontal?

The deltoid muscle group, which is the primary muscle group acting, inserts at the bone at approximately 16° to the horizontal.

(b) What force must be provided by the deltoids?

(c) When Ben also holds a 3 kg mass in his hand, what force must be provided by his deltoids?

4. (a) For the circus routine shown in the figure below, draw a diagram that shows the forces acting on the performer.



(b) The performer's mass is 64 kg. Calculate the direction and magnitude of the force in each arm. (Assume the vertical forces are equally distributed between each arm.)

Materials in the human body

5. At its mid-length, Belinda's femur is approximately circular in cross-section with a diameter of 22 mm. If her mass is 56 kg, calculate the stress in her femur.

6. (a) What stress will cause a strain of 0.04 in a tendon with a Young's modulus of 0.25 GPa?
   (b) If the original length of the tendon was 200 mm, how much has it stretched under this load?

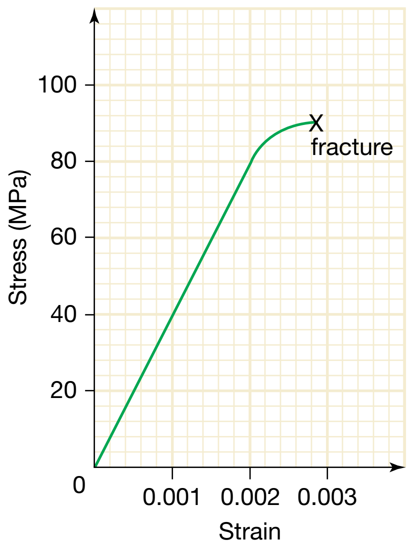
7. A 2 mm diameter steel cable 5 m long lifts a 15 kN load. Assuming Young's modulus for the steel is 200 GPa, how much will the cable stretch?

8. A 12.7 mm square bar 50.8 mm in length is loaded in tension. The data shown in table 16.3 were collected.
   (a) Convert the data to stress and strain.
   (b) Plot the data and calculate Young's modulus.
   (c) What stress would cause a strain of 0.5% in a 10 mm square bar?

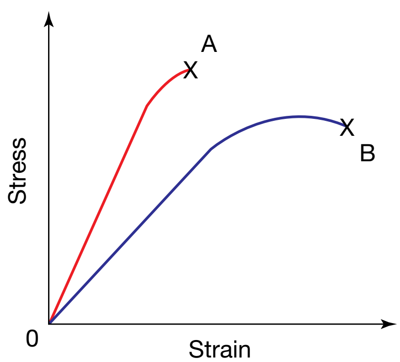
TABLE 16.3 Data for square bar

Force (kN)	Length (mm)
0	50.80
72.4	50.90
108.6	50.95
144.8	51
161.2	51.05
189.5	51.10

9. Estimate the stiffness of the material described in the graph shown below.



10. The stress–strain characteristics for two different materials, A and B, tested to fracture are shown.



(a) Which material has the greater Young's modulus?
(b) At the elastic limit, which material has the greater strain?
(c) Which material is tougher?
(d) Which material is more ductile?
(e) Which material is stronger?

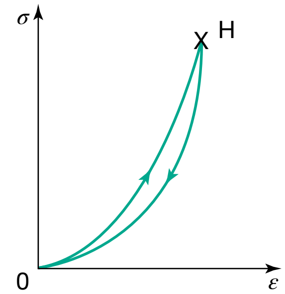
11. What stress would create a strain of 0.0005 in a bone with a Young's modulus of 18 GPa?

12. The results of a tensile test are given in table 16.4.
(a) Plot the stress–strain graph for this material.
(b) Is the material brittle or ductile? Explain.
(c) Calculate Young's modulus for the material.
(d) How much energy is stored in the material when it is stretched to twice its original length?

TABLE 16.4 Tensile test results

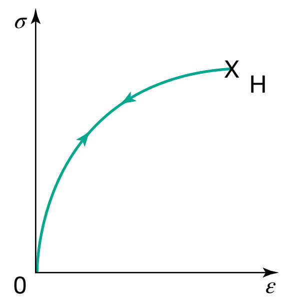
σ (MPa)	0	4	8	12	16	20	24
ε (%)	0	2	4	6	8	10	12
σ (MPa)	22	20	19	20	20	20	18
ε (%)	15	30	50	80	110	160	210

13. The stress–strain relationship for skin is shown in the graph below.



(a) Describe how the skin will behave when it is acted on by a force from zero to H.

The stress–strain relationship for another material, A, is shown at right.



(b) If material A was used to make synthetic skin, what would happen as it was loaded from zero to a stress H?
(c) Would you consider this an adequate substitute for skin?

14. A 5 m long cable made from a linear elastic material stretches by 2 mm when a stress of 54 MPa is applied. Determine the strain energy in the cable.

15. A 12.5 mm diameter aluminium bar was tested in tension. The bar fractured at a length of 55.13 mm. Table 16.5 shows the data collected up to the point of fracture.
(a) Convert the data to stress versus strain.
(b) Plot the stress–strain graph.
(c) On the graph, label:
(i) elastic limit (ii) ultimate tensile strength
(iii) breaking strength.
(d) Calculate:
(i) elastic limit (ii) ultimate tensile strength
(iii) breaking strength.

TABLE 16.5 Data up to point of fracture

Load (kN)	Length (mm)
0	50.00
4.5	50.02
13.4	50.07
22.3	50.13
31.2	50.18
33.4	50.75
35.2	52.00
35.7	53.00
35.7	54.00
33.8	55.13

16. A dental technician is stretching a 40 mm long piece of stainless steel wire 1.2 mm in diameter. Stainless steel has the following mechanical properties:

E = 195 GPa; yield strength = 215 MPa;
tensile strength = 505 MPa.

(a) What is the minimum force needed to deform the wire permanently?
(b) How much must the wire be stretched to create a permanent change in length?
(c) What is the maximum force that the wire can tolerate before it breaks?

17. The data sheet provided by a manufacturer for its fibre product stated that it had a Young's modulus of 75 GPa and an ultimate strength of 90 MPa. If the stress–strain curve for the fibre is linear, by how much would a 1 m long fibre elongate before fracture?

18. A 0.500 m long piece of wire stretched 0.4 mm when a 6.0 kN force was applied. The wire had a diameter of 3.0 mm. Assuming that it was behaving in a linear elastic manner, what was:

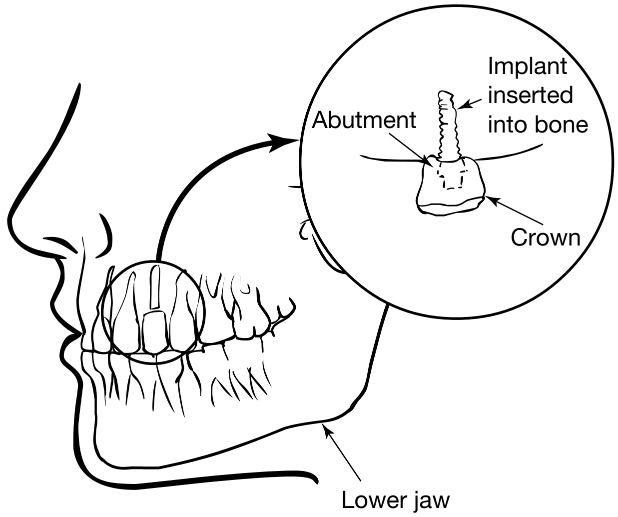
(a) the maximum stress
(b) the maximum strain
(c) the Young's modulus
(d) the strain energy
(e) the total energy absorbed by the wire?

19. (a) For each of the items listed below, which terms best describe the loads which they are most likely to experience: tension, compression, bending or shear?

(i) Strings of a tennis racquet
(ii) Human skin
(iii) Blade of a kitchen knife
(iv) Human bone
(v) A lift cable
(vi) Bicycle tube
(vii) Soft drink bottle
(viii) Human tendon
(ix) Sole of a running shoe
(x) Kitchen cling wrap
(xi) Silicon filler

(b) Identify the relevant material properties for each of the items listed, for example elastic, plastic, stiff, brittle, ductile or tough.

20. The dental implant shown in the figure below includes a titanium alloy replacement for the tooth root inserted into the jaw. An abutment is then added to which a ceramic crown is fitted.



(a) What are the properties of the titanium alloy and the ceramic tooth that make them suitable for this use in the human body?
(b) What factors might affect the success of this implant?

21. To manufacture a 30 mm diameter pylon for a below-the-knee limb prosthesis, three potential materials are being examined. The mechanical properties of each material are shown in table 16.6.

TABLE 16.6 Mechanical properties of material for prostheses

Material	Density (kg m^{-3})	Strength (MPa)	Young's modulus (GPa)
Bone	2000	200	20
Material A	4430	970	110
Material B	1400	190	30
Material C	2200	140	20

List and describe the advantages and disadvantages of each of the materials being considered relative to natural bone.

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CHAPTER 17

How can AC electricity charge a DC device?

REMEMBER

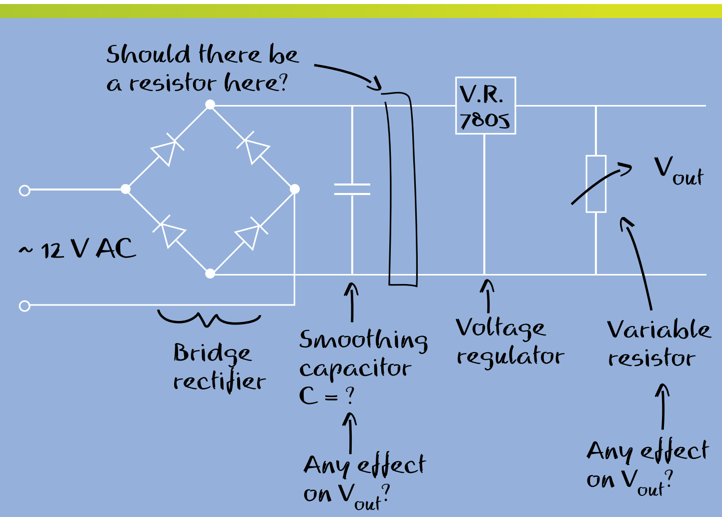
Before beginning this chapter, you should be able to:

- apply the concepts of charge (*Q*), current (*I*), voltage (*V*), energy (*U*) and power (*P*) to electric circuits
- analyse electric circuits using mathematical relationships and graphs
- model resistance in series and parallel circuits using voltage-versus-current graphs
- state and apply Ohm's Law, $V = IR$, for ohmic devices at a constant temperature
- find the resistance for resistors in series and in parallel
- recall and apply the principle of conservation of energy: *Energy cannot be created nor destroyed, but it can be transformed from one form to another*
- distinguish between ohmic and non-ohmic resistors
- calculate the effective resistance of devices connected in series and in parallel
- calculate the voltage drop across, and current through, devices connected in series or in parallel
- recall that a voltage divider consists of two or more resistors arranged in series to produce a smaller voltage at its output
- recall that a diode allows current to pass through it in only one direction
- recall that a capacitor is a device that stores charge.

KEY IDEAS

After completing this chapter, you should be able to:

- apply the concepts of current, potential difference (voltage drop) and power to the operation of circuits that use diodes and resistors
- calculate the effective resistance of series and parallel circuits and unloaded voltage dividers
- apply the rules $V = IR$ and $P = VI$ to electric circuits
- specify AC voltages by peak, root mean square and peak-to-peak values
- describe the role of a transformer
- describe how to use a cathode ray oscilloscope to measure voltage as a function of time
- explain how diodes are used to convert alternating currents into direct currents
- describe the differences between half-wave and full-wave rectifiers
- explain what happens to the voltage and current of capacitors when they are charged and discharged
- calculate the time constant for charging and discharging capacitors using the relationship $\tau = RC$
- describe how capacitors are used to smooth the outputs of DC power supplies
- apply the current–voltage characteristics of voltage regulators when designing a circuit
- explain the effects that a multimeter has on measurements of voltage, resistance and current
- design, construct and explain the operation of a low-voltage AC to DC regulated voltage power supply system
- explain the use of optical fibres for short- and long-distance telecommunications
- carry out calculations for circuits that respond to temperature using thermistors.



A circuit diagram of a voltage regulated power supply system

Chapter review

Summary

- A voltage divider consists of two or more resistors arranged in series to produce a smaller voltage at its output.
- The output of a basic voltage divider can be calculated using the equation:

$$V_{out} = \frac{R_2 V_{in}}{R_1 + R_2}$$

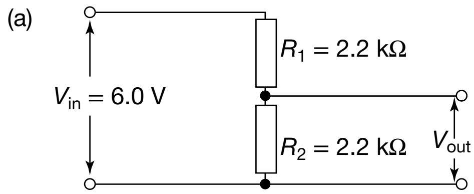
- A transducer is a device that can be affected by, or affect, the environment.
- An input transducer transforms non-electrical energy into electrical energy.
- A thermistor is a semiconductor device whose resistance varies with temperature.
- The resistance of a negative coefficient thermistor falls as the temperature increases.
- The resistance of a positive coefficient thermistor rises as the temperature increases.
- The relationship between resistance and temperature for a thermistor is usually shown graphically.
- A diode is a semiconductor device that allows current to pass through it in one direction only.
- Photonics involves the use of photons to manipulate, encode, transmit, decode and/or store information.
- A photonic transducer transforms light energy into electrical energy, or electrical energy into light energy.
- A light-emitting diode (LED) is a semiconductor diode that emits light when a current passes through it.
- A light-dependent resistor (LDR) is a semiconductor device that has a resistance that decreases as the amount of light falling on it increases.
- The relationship between resistance and light intensity for an LDR is shown graphically.
- Photodiodes produce a current when they are reverse biased and light falls on the junction. The current is proportional to the intensity of the light.
- Phototransistors generally have two terminals. A photosensitive collector–base junction provides the base current.
- Photodiodes are faster at responding to light than phototransistors, but phototransistors are more sensitive.
- An optical fibre can carry 30 000 telephone calls at a time.
- Attenuation is the loss of power of a signal along a communicating channel.
- The bandwidth of an information system is essentially the highest frequency or rate at which the data can be transmitted.
- Optical intensity modulation in photonic communications systems involves varying the output intensity of a carrier light source by using the electric signal from a transducer.

Questions

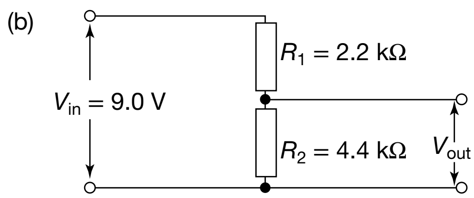
Note: Questions 1–29 can be found in your eBookPLUS.

Circuit analysis

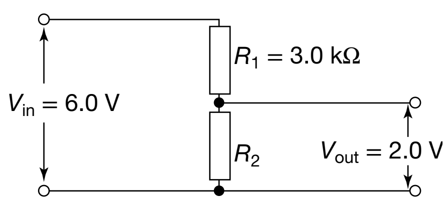
30. (a) Find the output voltage for the voltage divider shown in circuit (a) below.



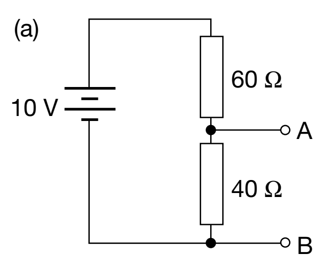
(b) What is the output voltage of circuit (b) if a load of resistance 4.4 kΩ is connected across the output terminals of the voltage divider?



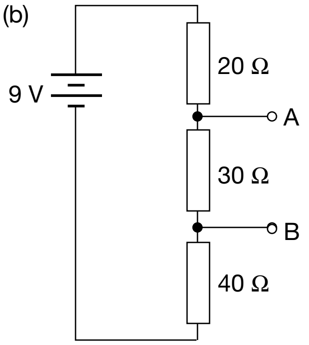
31. Find the value of R_2 in the voltage divider in the following figure which would give an output voltage of 2.0 V.



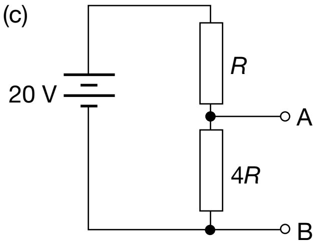
32. Find the voltage drop between A and B in each of the following voltage divider circuits.



(b)



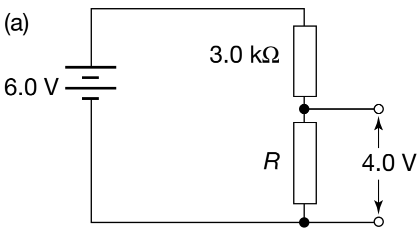
(c)



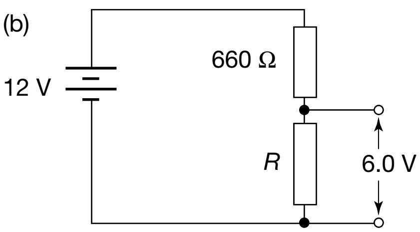
33. What happens to the voltage drop across a variable resistor in a two-element voltage divider when its resistance decreases and the other resistance is unchanged?

34. Find the value of the unknown resistor in the following voltage dividers.

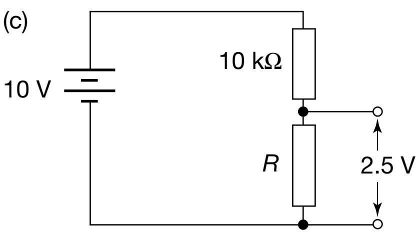
(a)



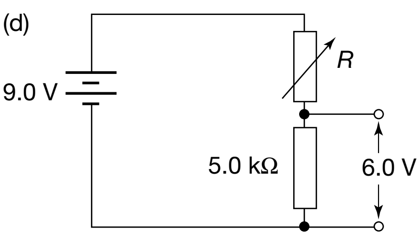
(b)



(c)



(d)



Transducers

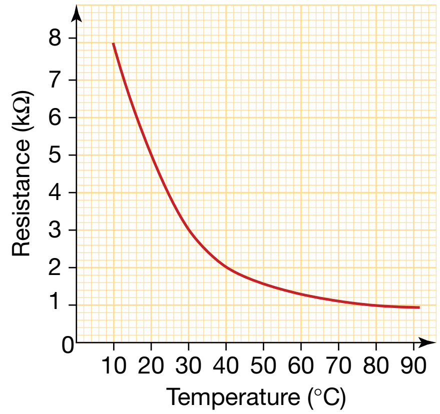
35. A thermistor has the characteristic curve shown below.

(a) What is the resistance of the thermistor at the following temperatures?

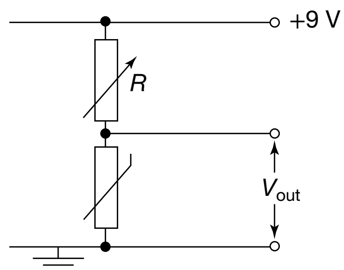
(i) 20 °C (ii) 80 °C

(b) What is the temperature when the thermistor has the following resistances?

(i) 4 kΩ (ii) 1.5 kΩ



36. The thermistor from question 35 is placed in a voltage divider as shown.



(a) If the variable resistor is set at 4 kΩ and the temperature is 40 °C, what is the output voltage?

(b) An output voltage of 6.0 V is required when the temperature is 80 °C. What must the value of the variable resistor be?

37. A voltage divider circuit is set up as shown in figure (a) below. The thermistor has the characteristic curve shown in figure (b).

(a) Is this a positive or negative coefficient thermistor? Explain your answer.

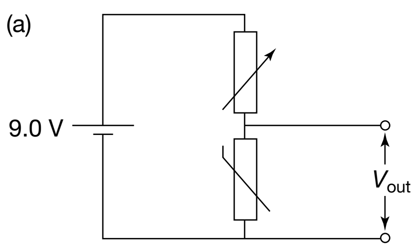
(b) What is the temperature when the resistance of the thermistor is 5 kΩ?

(c) What is the resistance of the thermistor when the temperature is 90 °C?

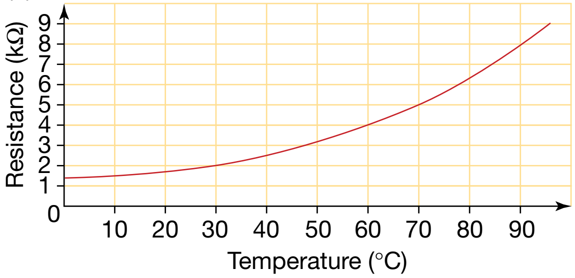
(d) What is the value of the variable resistor that gives an output voltage of 3.0 V when the temperature is 90 °C?

(e) What happens to the value of the output voltage as the temperature falls and the variable resistor remains at a fixed value? Explain your answer.

(a)



(b)



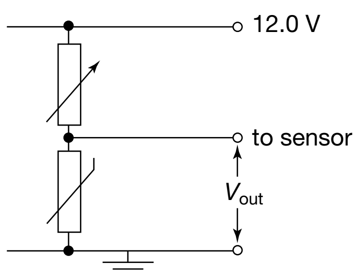
38. A temperature sensing system in an oven consists of a thermistor connected into a voltage divider as shown in figure (a) below. The thermistor has the characteristic curve shown in figure (b).

(a) What is the resistance of the thermistor when the temperature in the oven is 100 °C?

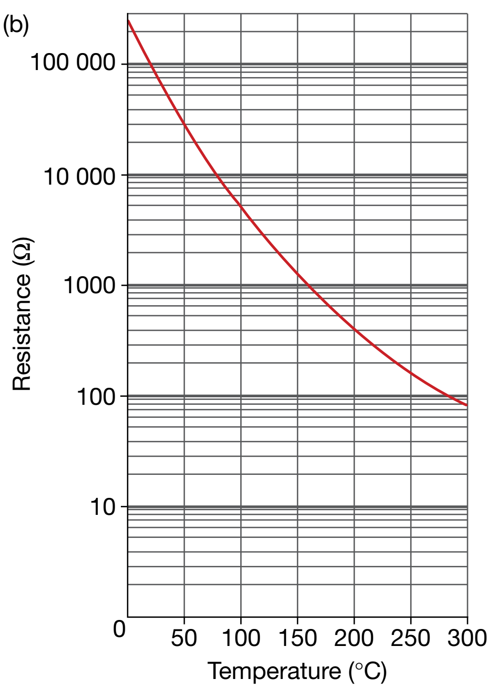
(b) What is the temperature in the oven when the resistance of the thermistor is 400 Ω?

(c) Calculate the resistance of the variable resistor when the temperature in the oven is 200 °C and the output voltage V_{out} is 8.0 V.

(a)

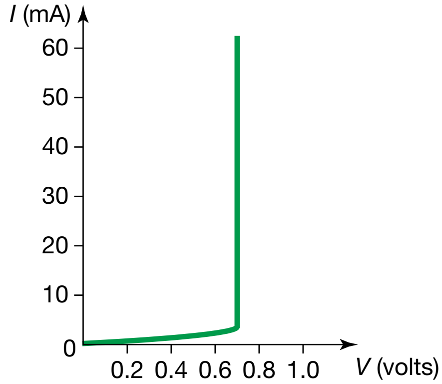


(b)

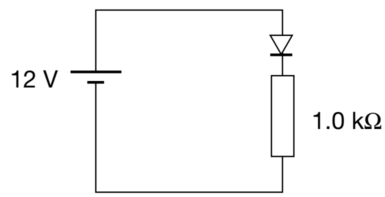


Diodes

39. The current–voltage characteristic curve of a diode is shown below.



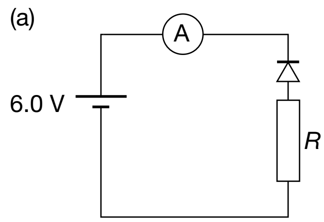
The diode is placed in the circuit shown below.



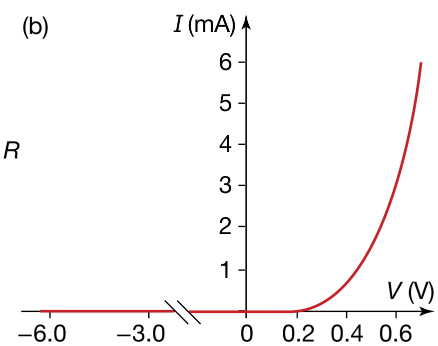
Calculate the current flowing in the circuit. Express your answer in mA.

40. Consider the circuit shown in the following figure (a). The characteristic curve of the diode is shown in figure (b).

(a)



(b)



If the current is measured to be 4.0 mA:

(a) What is the voltage drop across the diode?

(b) What is the voltage drop across the resistor?

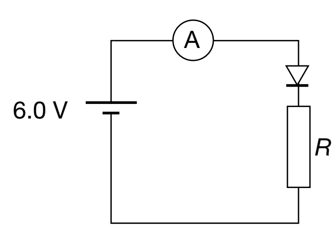
(c) What is the resistance of the resistor?

The diode is now reversed, as shown below.

(d) What is the voltage drop across the diode?

(e) What is the current flowing in the circuit?

(f) What is the voltage drop across the resistor?



Photonic transducers

41. What is a transducer?

42. Explain the relationship in a light-dependent resistor (LDR) between the resistance and the amount of light falling on the LDR.

43. What is the role of LDRs in cameras?

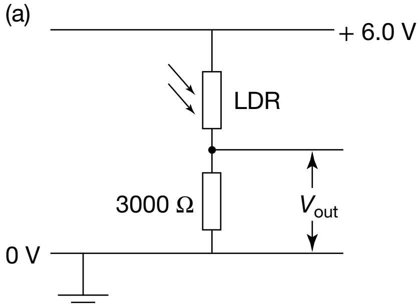
44. An LDR is used in a voltage divider circuit as shown in figure (a) below. The characteristic curve of the LDR is given in figure (b).

(a) What is the illumination when the LDR has a resistance of 2.0 kΩ?

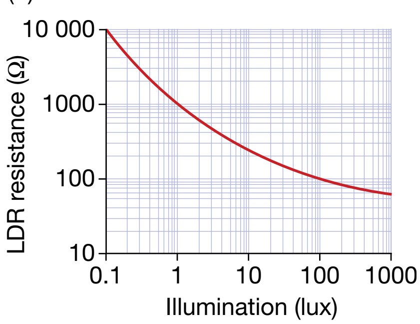
(b) Calculate V_{out} for this illumination.

(c) Describe what happens to V_{out} as the illumination increases.

(a)



(b)



45. A student carries out a practical activity to construct a characteristic curve of an LDR. She obtains the data in the table below.

(a) Copy and complete the table, calculating the resistance of LDR for each light intensity, the log of R_L and the log of I_L.

(b) Plot a graph of log R_L against log I_L.

(c) Determine the relationship between R_L and I_L from your graph.

(d) Is the LDR an ohmic or non-ohmic device? Explain your answer.

46. (a) Describe the structure of LEDs in terms of p-type and n-type semiconductors.

(b) What is the meaning of the terms 'forward biased' and 'reverse biased'?

(c) Draw circuit diagrams to show how to:

(i) forward bias an LED

(ii) reverse bias an LED.

47. Give three examples of a situation where an LED would be preferable to an ordinary light source. Analyse each case to justify your choices.

48. Why is it that not all diodes emit light?

49. Why are limiting resistors placed in series with LEDs?

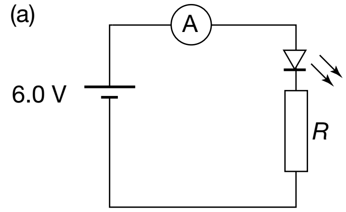
50. (a) Consider the circuit shown in figure (a) below. The characteristic curve of the light-emitting diode is shown in figure (b). If the current is measured to be 20 mA:

(i) What is the voltage drop across the LED?

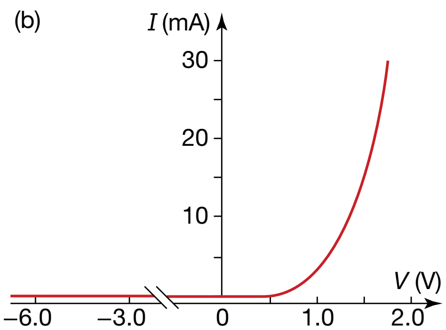
(ii) What is the voltage drop across the resistor?

(iii) What is the resistance of the resistor?

(a)



(b)



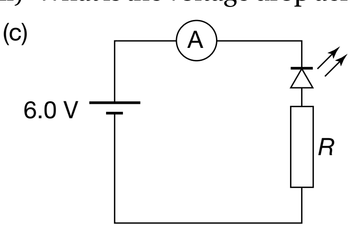
(b) The LED is now reversed, as shown in figure (c).

(i) What is the voltage drop across the LED?

(ii) What is the current flowing in the circuit?

(iii) What is the voltage drop across the resistor?

(c)

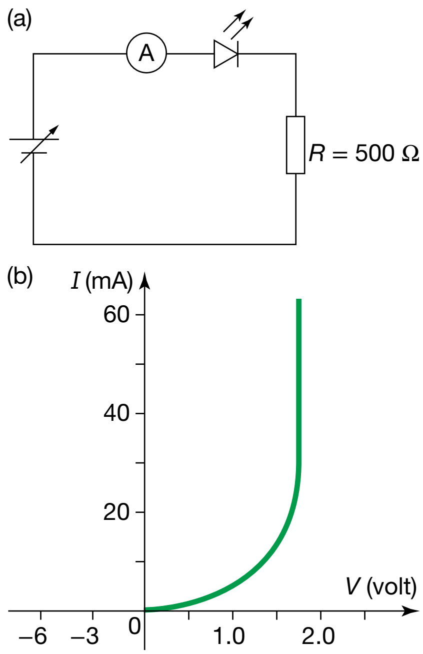


Relative light intensity I_L	Current through LDR (μA)	Voltage across LDR (V)	Resistance (kΩ)	Log R_L	Log I_L
0.60	350	38.7			
0.40	220	39.0			
0.20	90	39.1			
0.10	40	39.0			
0.05	20	39.0			

51. A student carries out a practical activity on an LED. She initially sets up the circuit shown in figure (a) below. She is able to measure the voltage drop across the diode and the resistor as well as the emf supplied by the variable DC supply. This enables her to construct the *I*–*V* characteristic curve for the diode, as shown in figure (b).

When the current in the circuit is 60 mA, calculate the following quantities:

(a) the voltage drop across the diode
(b) the voltage drop across the resistor
(c) the emf of the supply.

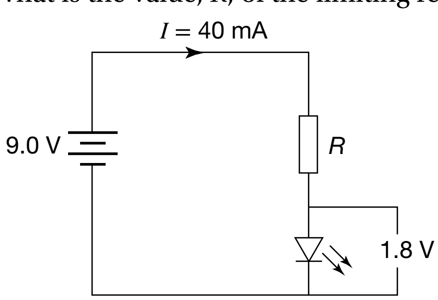


52. If the student from question 51 reverses the polarity of the supply, very little current flows through the circuit.

(a) Explain why this occurs.
(b) If the emf of the supply is –2.5 V, what is the voltage drop across the diode? Justify your answer.

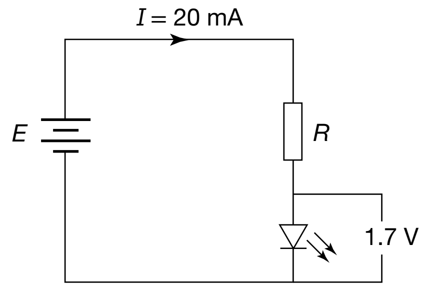
53. The LED shown below has a voltage drop across it of 1.8 V and carries a current of 40 mA.

(a) What is the voltage drop across the limiting resistor?
(b) What is the value, *R*, of the limiting resistor?



54. Refer to the circuit diagram shown below. If the LED has a voltage drop of 1.7 V across it and carries a current of 20 mA, calculate the value of the limiting resistor if the emf of the power supply is:

(a) 9.0 V
(b) 12 V
(c) 24 V
(d) 50 V.



55. A student connects a 100 Ω resistor in series with an LED and a 15 V power supply.

(a) Calculate the current through the LED if it has a voltage drop of 2.0 V across it.
(b) What might happen to the LED in this situation?

56. Describe the purpose of a photodetector.

57. (a) Describe the operation of a photodiode.
(b) Describe the operation of a phototransistor.
(c) Which device has the fastest response time?
(d) Which device is the most sensitive?
(e) Describe the effect of response time on bandwidth.

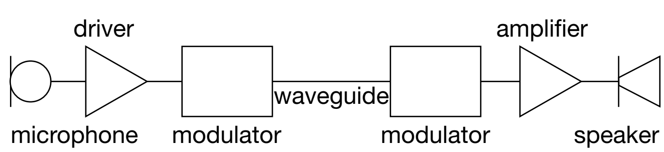
Modulation and demodulation

58. (a) What is the bandwidth of an information system?
(b) State the bandwidth of a communications system that can carry a maximum frequency of 15 000 Hz.
(c) Compare the bandwidths of metal wires and optical fibres.

59. (a) What is optical intensity modulation?
(b) Describe how an analog signal — for example, the electrical output signal from a microphone — can be used to alter the intensity of light produced by a light-emitting diode.

60. The diagram below shows part of an optical-fibre telephone system.

(a) Explain the terms *modulation* and *demodulation* as they apply to the transmission of sound by this system.
(b) State a device that could be used as a modulator in this system.
(c) State three devices that could be used to demodulate the light signal.



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CHAPTER

18 How do heavy things fly?

REMEMBER

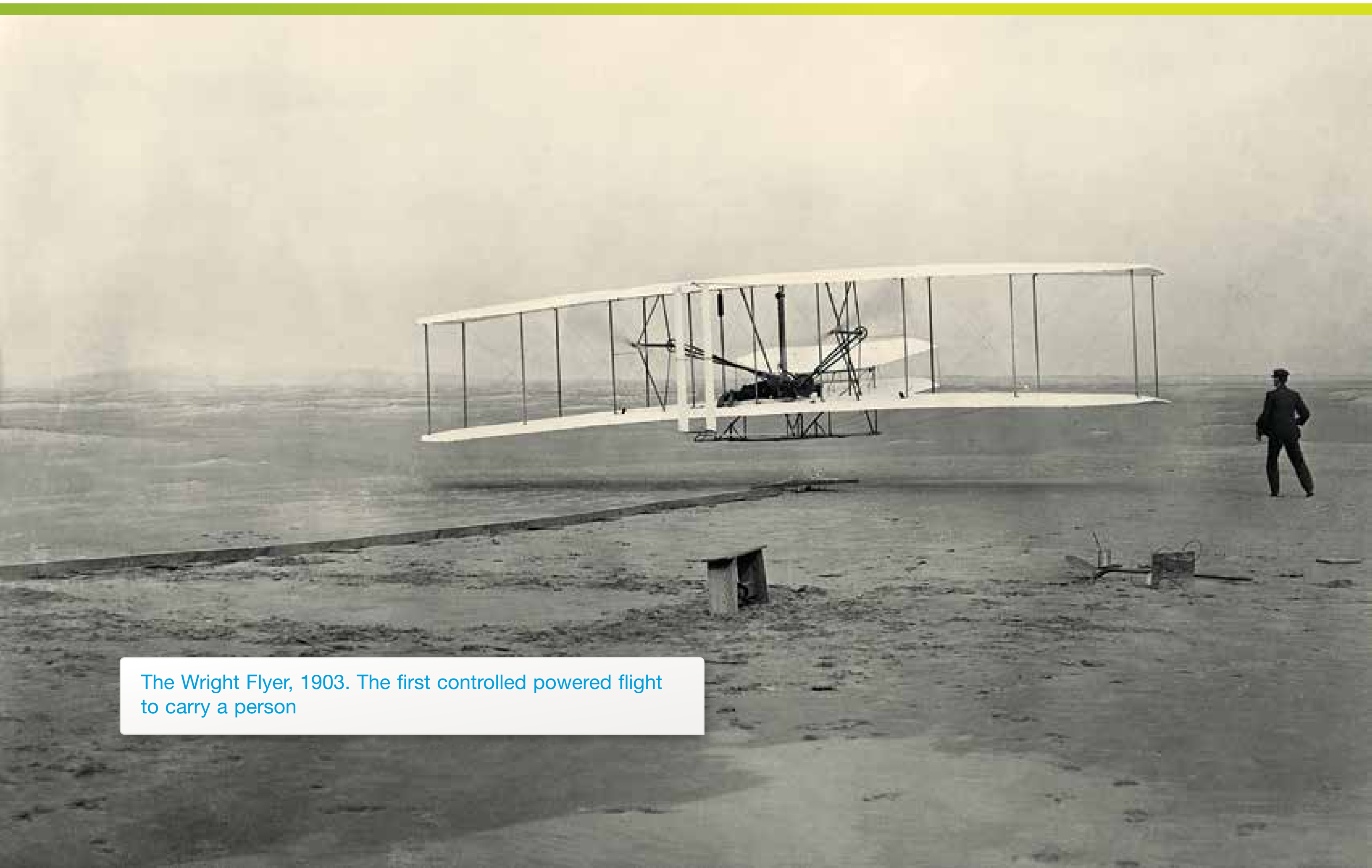
Before beginning this chapter, you should be able to:

- recall that pressure is a measure of force per unit area
- recall that density is a measure of mass per unit volume
- describe motion in terms of distance, displacement, speed, velocity and acceleration
- explain how the action of forces changes the way an object moves
- calculate the torque applied by a force
- explain movement in terms of Newton's three laws of motion.

KEY IDEAS

After completing this chapter, you should be able to:

- apply Newton's laws of motion to describe the action of forces on the motion of an aircraft
- identify factors that affect performance of an aircraft
- apply the concepts of torque and equilibrium to the motion of an aircraft
- relate the generation of lift to airspeed and pressure using Bernoulli's equation, and to the rate of change of momentum using Newton's laws of motion
- differentiate between induced drag and parasitic drag
- analyse the performance of an aircraft during take-off, climb, descent and cruise
- use a model to investigate aspects of the performance of an aircraft
- identify the effects of flying at very high speeds
- explain the operation of the elevator, rudder and ailerons in controlling a conventional aircraft
- apply aeronautical principles to the design of efficient cars and wind turbines.



The Wright Flyer, 1903. The first controlled powered flight to carry a person

Chapter review

Summary

- Lift and the force due to gravity are a force pair that acts on an aircraft in flight.
- Thrust and drag are a force pair that acts on an aircraft in flight.
- The force due to gravity acting on an aircraft is thought of as acting at one position, the centre of gravity.
- When a force acting on an aircraft in flight is drawn as an arrow, the arrow represents the resultant of all the component forces that contribute from various parts of the aircraft.
- The Equation of Continuity can be expressed as:

$$Q = v_1 A_1 = v_2 A_2.$$

- The Bernoulli principle was expressed as an equation and states:

$$\tfrac{1}{2}pv^2 + pgh + P = \text{constant}.$$

- Another way to express the Bernoulli principle in the context of flight is that 'faster moving fluids have lower pressure.'
- The generation of lift by a wing can also be explained using Newton's Third Law of Motion. The wing pushes the air downwards and the air pushes the wing upwards.
- There are several types of drag that are created when an aircraft moves through the air. The two main types are induced drag and parasite drag.
- Parasite drag is the combined effect of skin friction drag and form drag.
- The total drag acting on an aircraft in flight determines the necessary thrust required for the aircraft to maintain a given airspeed.
- The behaviour of airflow changes when travelling at or beyond the speed of sound. This can lead to the formation of shockwaves and significant increases in drag.
- Torque is the turning effect of a force about a pivot or reference point.
- An aircraft in flight can move around three different axes: the lateral (known as pitch), the longitudinal (known as roll) and the vertical (known as yaw).
- The primary control surfaces on an aircraft are the elevator, rudder and ailerons.
- There are six main stages of flight: take-off, climb, cruise, turn, glide and landing. The balance of forces on the aircraft is different in each stage.
- Wind tunnels are used extensively to test the aerodynamics of aircraft designs.
- An aircraft's performance can be judged from its lift-to-drag ratio, also known as the glide ratio.

Questions

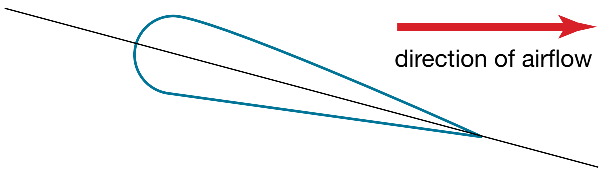
Applying Newton's laws to aircraft

1. Explain the difference between the centre of pressure and the centre of gravity.
2. Describe the resulting motion if an aircraft has the following forces acting on it in flight:
   (a) lift = 6000 N, drag = 500 N, weight = 5900 N, thrust = 500 N
   (b) lift = 4000 N, drag = 600 N, weight = 4000 N, thrust = 500 N
   (c) lift = 7000 N, drag = 300 N, weight = 6800 N, thrust = 310 N
   (d) lift = 6600 N, drag = 450 N, weight = 6800 N, thrust = 460 N.
3. A business jet is travelling at a constant speed of 200 m s^{-1} while its engines provide a total thrust of 25 kN.
   (a) If it is in level flight, what is the magnitude of the total drag on the jet?
   (b) Assuming that all of the energy delivered by the engines is used to provide thrust, what is the power output of the engines?

Moving through fluids and Bernoulli's equation

4. What basic difference between fluids and solids causes them to behave differently in terms of their motion?
5. If a fluid flows through a pipe of cross-sectional area 61 cm^2 at a speed of 9.3 cm s^{-1}, what must the cross-sectional area be to make it speed up to 13 cm s^{-1}?
6. If a fluid flows at a speed of 2.1 m s^{-1} through a pipe of diameter 0.15 m, what speed will it flow at when the pipe widens to a diameter of 0.45 m?
7. Air flows through a wind tunnel with a circular cross-section.
   (a) How would you change the cross-sectional area of the wind tunnel in order to double the speed of the air passing through it?
   (b) By what factor would the radius of the wind tunnel change to achieve the doubling of airspeed?
8. Assuming that everything else remains constant, what change in diameter of a wind tunnel would produce a 10-fold increase in the speed of the air moving through it?
9. Describe what happens to the pressure in a fluid as its speed increases.
10. Explain in terms of Bernoulli's principle how an aerofoil develops lift.

11. On the aerofoil below:

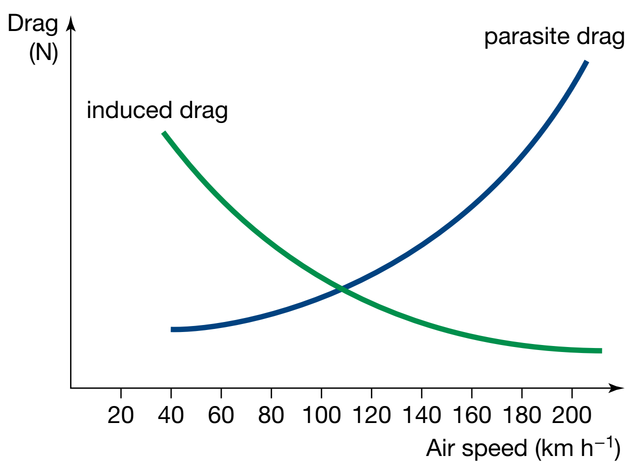


(a) draw and label an arrow to represent the lift force acting on the aerofoil
(b) draw and label the angle of attack
(c) label the trailing edge of the aerofoil.

12. The Airbus A380 has four jet engines, each capable of producing a maximum thrust of 370 kN. If the aircraft is travelling at 270 km h^{-1} and each engine is running at maximum thrust, what is the total mechanical power output of the aircraft?

Lift and drag

13. What is the cause of wing-tip vortices?
14. The graph below shows how the parasite drag and induced drag acting on a particular aircraft change as the airspeed changes.



(a) On the graph, draw and label the curve representing the total drag (that is, the sum of the parasite and induced drags).
(b) At what airspeed does the maximum lift-to-drag ratio occur?
(c) Explain the importance of a high lift-to-drag ratio.
(d) Which region of the graph represents the conditions under which a stall is likely to occur?
(e) Explain what happens to the air around an aircraft wing when a stall occurs.

15. An aircraft has a glide ratio of 9:1 and is at an altitude of 1200 m when its engine cuts out.
(a) How far could it travel before landing, assuming minimal thermal activity?
(b) What is the lift-to-drag ratio for this aircraft while it is gliding?

16. A glider loses 800 m in altitude while it covers a ground distance of 12 km. Calculate its:
(a) glide ratio (b) lift-to-drag ratio.

17. A glider with a glide ratio of 40:1 glides in a straight path over a ground distance of 3.6 km to make a perfect landing. What was its initial altitude?

18. The lift equation is given as:

$$F_L = C_L \tfrac{1}{2}\rho v^2 A$$

What would be the overall effect of the lift produced by an aircraft in each of the following scenarios?
(a) Decreasing the wing area by a factor of 1.5 by retracting the flaps
(b) Increasing the aircraft speed by a factor of 2
(c) Increasing the lift coefficient by a factor of 2 by deploying the flaps
(d) Halving the aircraft speed

Torque and equilibrium

19. An aircraft in level flight has a wing lift force of 15 000 N. The centre of pressure is 1.1 m behind the centre of gravity. The tail lift acts at a distance of 9.3 m from the centre of gravity.
(a) What is the size and direction of the tail lift?
(b) Why is it not necessary to know the mass of the plane to answer part (a) of this question?

20. If the tail lift in question 19 was reduced while the wing lift remained the same, the centre of gravity of the aircraft would need to be shifted. How can this be achieved?

21. A cargo plane is loaded with two large containers. The first container, which has a mass of 10 000 kg, is loaded into a hold located 12 m behind the plane's centre of gravity. The second container, which has a mass of 15 000 kg, is loaded so that it compensates for the torque applied by the first container. Where should the second container be located?

22. A passenger plane's rear fuel tank has been filled to allow for the usual amount of baggage in the rear hold, which is located 3.6 m behind the plane's centre of mass. The rear fuel tank is 4.0 m behind the centre of mass. However, an extra 200 kg of cargo has been placed in the hold. What mass of fuel must the pilot release from the rear tank before taking off to compensate for the turning effect of the extra baggage?

Performance and control of an aircraft

23. Describe, without the aid of a diagram, the longitudinal, vertical and lateral axes of an aircraft.
24. Complete the following table.

Type of motion	Axis about which motion occurs	Aircraft control surface responsible for motion
	Vertical	
		Elevators
Roll		

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CHAPTER

19 Are fission and fusion viable nuclear energy power sources?

REMEMBER

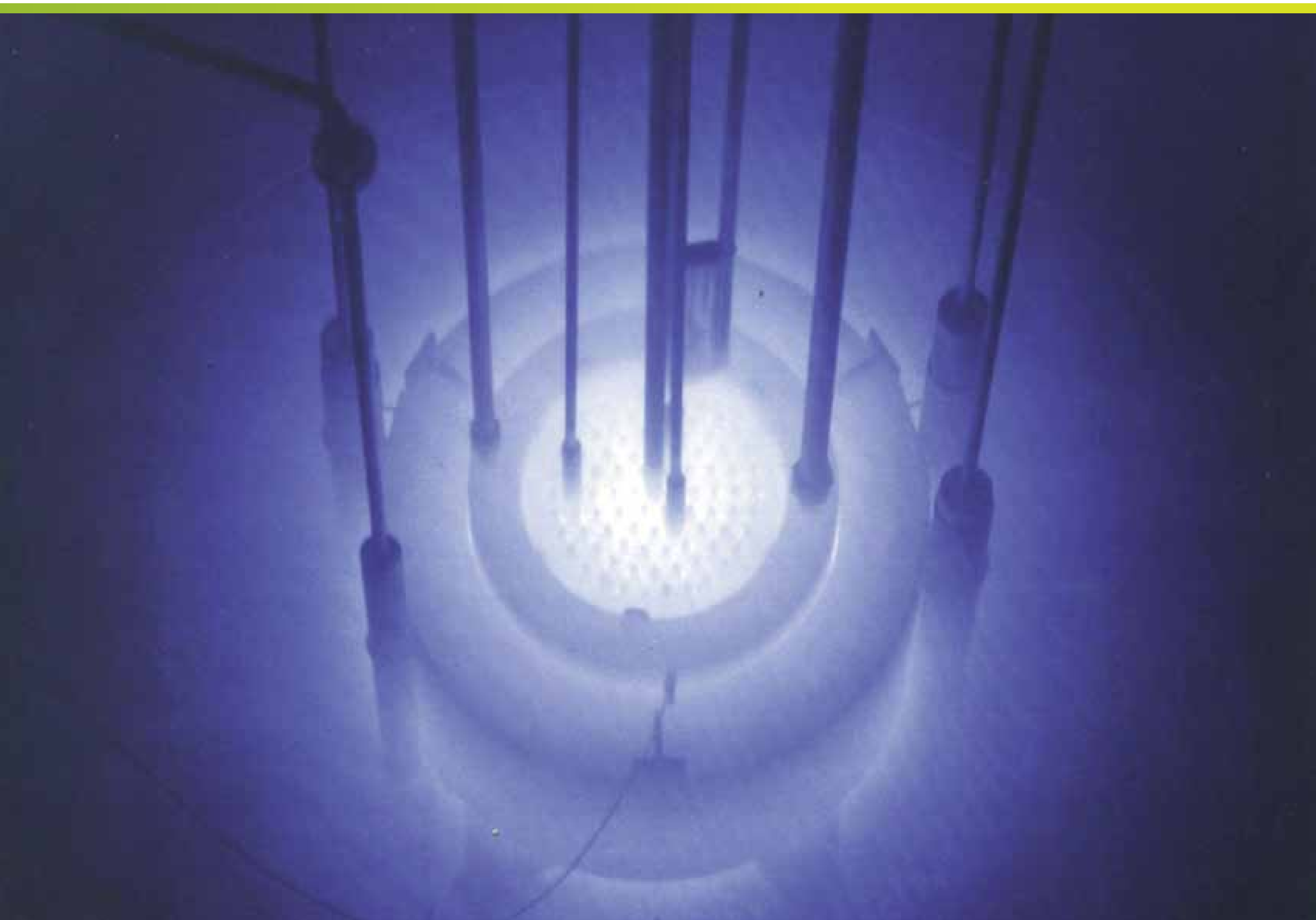
Before beginning this chapter, you should be able to:

- explain nuclear energy as energy resulting from the conversion of mass into energy using $E = mc^2$
- describe the processes of nuclear fusion and nuclear fission
- explain, using a binding energy curve, why both fusion and fission are reactions that produce energy.

KEY IDEAS

After completing this chapter, you should be able to:

- explain nuclear fission reactions of ^{235}U and ^{239}Pu
- explain nuclear fusion reactions of proton–proton and deuterium–tritium
- explain the formation of ^{239}Pu from neutron absorption in ^{238}U and other effects of this reaction
- explain fission chain reactions including the role of moderators and control rods, and the importance of critical mass
- examine how power generation from nuclear energy involves the transformation of energy
- compare nuclear fission and fusion as energy sources.



Chapter review

Summary

- Fission reactions occur when a nucleus is split into smaller, more stable fission fragments. If every neutron released in fission is free to initiate more fission reactions, an uncontrolled chain reaction occurs. Controlled chain reactions occur when some of the free neutrons are absorbed by non-fissionable substances.
- Nuclear reactors use the energy generated by controlled chain reactions to heat water. The steam produced turns the turbines that produce electricity.
- The fuel in some nuclear reactors is more likely to undergo fission when it absorbs slow-moving neutrons. Moderators are used in these reactors to slow down neutrons. Control rods start and stop the nuclear reaction by absorbing neutrons.
- The amount of uranium-235 in natural uranium is not enough to sustain a chain reaction. In order for it to be used in some types of nuclear reactors and nuclear weapons, the percentage of uranium-235 needs to be increased to 1–4% for nuclear reactors and 97% for weapons.
- The fuel in fast breeder reactors undergoes fission when it absorbs fast-moving neutrons. This fuel does not need to be enriched because it uses plutonium-239 derived from uranium-238 as the fuel source. The reaction is:

$$^{238}_{92}\text{U} + ^{1}_{0}\text{n} \rightarrow ^{239}_{92}\text{U} \rightarrow ^{239}_{93}\text{Np} + \beta^- \rightarrow ^{239}_{94}\text{Pu} + \beta^-$$

- A critical mass is needed for a sustainable chain reaction.
- The nuclear fusion reaction between deuterium and tritium is a possible energy source.
- The processes of nuclear fission and fusion can be compared by a variety of measures including energy released per nucleon and percentage of mass lost.

Questions

The nucleus

1. (a) Define the terms fusion and fission.
   (b) Which of these reactions occurs in our sun?
2. Why does the *splitting* of uranium-235 nuclei release energy, but the *joining* of hydrogen atoms also releases energy?
3. Why is energy released in the process of fusing two small nuclei together?

Nuclear fission

4. Explain why a large spherical mass of uranium may be able to sustain a chain reaction while the same mass spread into a flat sheet could not.
5. In what form does the released energy from a nuclear fission reaction appear?
6. Why are neutrons good at initiating nuclear reactions?
7. Describe a chain reaction.

Nuclear reactors

8. Make a list of the similarities and differences between the way electricity is produced in a nuclear power plant and the way it is produced in a coal-burning plant.
9. How do control rods allow the fission chain reaction to be controlled?
10. Explain why fast breeder reactors are likely to be the main producers of nuclear power in the future.
11. Enriching uranium is difficult. Why?
12. After the explosion at the Chernobyl reactor, tonnes of lead, sand and boron were dropped into the reactor. Why was boron used?
13. Why are 'thermal' reactors so called?
14. What do control rods control?

Nuclear waste

15. What does the phrase 'reprocessing of spent fuel rods' mean?

Nuclear weapons

16. How can a nuclear bomb contain sufficient fissionable material to explode, but be transported without exploding? (Use the term *critical mass* in your answer.)

Nuclear fusion

17. In what form does the energy released from a nuclear fusion reaction appear?
18. What are the advantages and disadvantages of fusion power as compared to fission power?
19. Using data from the table below, calculate the following for the two reactions:

$$^{2}_{1}\text{H} + ^{2}_{1}\text{H} \rightarrow ^{3}_{1}\text{H} + ^{1}_{1}\text{H}$$

$$^{2}_{1}\text{H} + ^{6}_{3}\text{Li} \rightarrow ^{4}_{2}\text{He} + ^{4}_{2}\text{He}$$

   (a) The difference between the sum of the binding energies of the products and the binding energies of the reactants

(b) The difference between the sum of the masses of the products and the masses of the reactants
(c) The energy equivalent of this mass difference in joules and in MeV
(d) The energy released per nucleon of reactants in MeV
(e) The percentage of mass transformed into energy. Confirm your answers by using the mass values for the reactants and the products.

Particle	Symbol	Mass (kg)	Total binding energy (MeV)
Helium-4	$^{4}_{2}He$	$6.665\,892 \times 10^{-27}$	28.295 673
Proton	$^{1}_{1}p$ or $^{1}_{1}H$	$1.678\,256 \times 10^{-27}$	
Hydrogen-2	$^{2}_{1}H$ or $^{2}_{1}D$	$3.344\,494 \times 10^{-27}$	2.224 573
Hydrogen-3	$^{3}_{1}H$ or $^{3}_{1}T$	$5.008\,267 \times 10^{-27}$	8.481 821
Lithium-6	$^{6}_{3}Li$	$9.988\,344 \times 10^{-27}$	31.994 564

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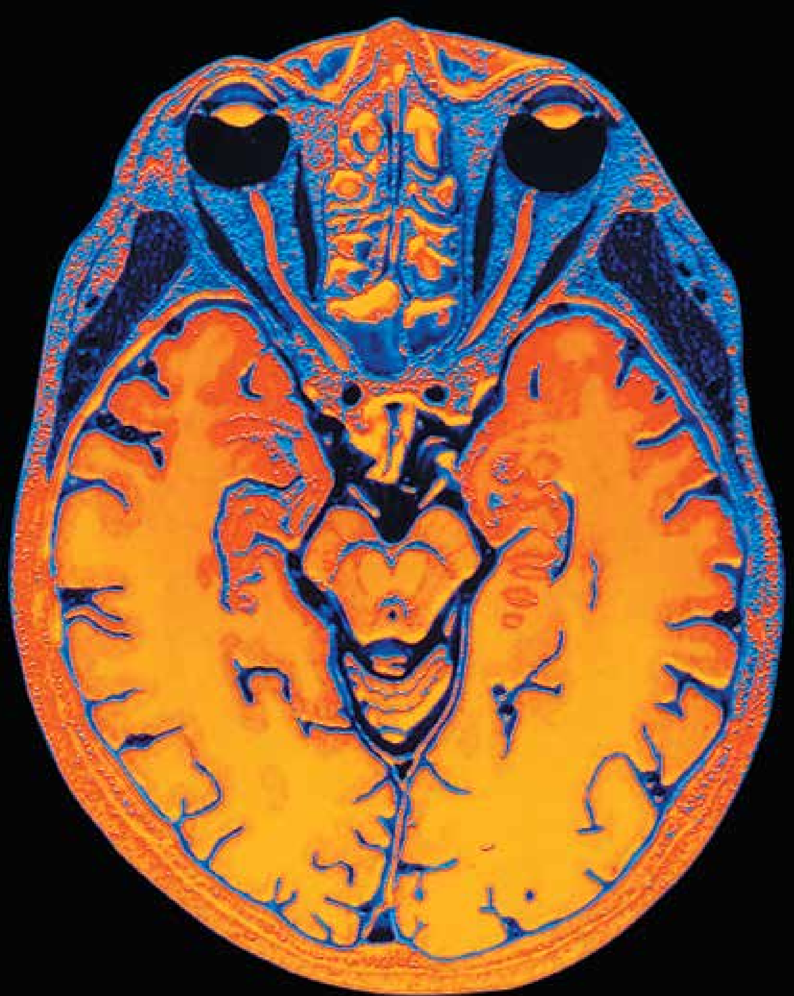
CHAPTER

20 How is radiation used to maintain human health?



Using computer analysis, the data from images of 'slices' through the body can be combined to produce a three-dimensional image of the area under investigation.

REMEMBER

Before beginning this chapter, you should be able to:

- recall that all matter is made up of atoms
- explain the arrangement of particles in an atom, in particular that atoms have a central nucleus containing protons and neutrons
- recall that energy cannot be created, just transformed from one type to another or transferred from one object to another
- recall the features of a wave, including speed, frequency and wavelength
- distinguish between transverse and longitudinal waves
- outline the properties of waves, including reflection, refraction and scattering
- describe what is meant by critical angle and outline the conditions needed for total internal reflection
- recall the nature of alpha, beta and gamma radiation
- describe what is meant by half-life.

KEY IDEAS

After completing this chapter, you should be able to:

- describe how X-rays are produced
- describe the use of X-rays and CAT scans in medical imaging and diagnosis
- recognise and name radioisotopes that are used to obtain scans of organs
- describe the use of PET scans in medical diagnosis
- explain how MRI works and how it is used in medical diagnosis
- compare the information obtained from images produced by X-rays, CAT, PET and MRI scans
- make simple interpretations of images produced by ultrasound, X-rays, CAT, PET and MRI scans
- discuss the advantages and disadvantages of imaging techniques in medical diagnosis.

Chapter review

Summary

- The effect of radiation exposure can range from nausea to death. The amount of radiation energy received by each kilogram of living tissue is measured in grays (Gy), but this value does not take into account the type of radiation that has been absorbed. Each type of radiation has a different effect because of its ionising power.
- Dose equivalent measures the radiation energy absorbed by each kilogram of biological tissue *and* its effect by taking into account the form of radiation energy absorbed. Dose equivalent is measured in sieverts (Sv). The Australian average annual radiation dose is 2 mSv, most of which is from background radiation.
- Gamma radiation from radioisotopes is detected and used to make an image of an organ. This process is known as SPECT (single photon emission computed tomography). Radiopharmaceuticals to which radioisotopes have been attached are taken up by particular organs in the body. The rate at which the radioisotope accumulates in the target organ indicates the health of the organ.
- The half-life of the radioisotope and length of time needed for the procedure must be considered when choosing an appropriate radioisotope.
- PET uses radioisotopes that are positron emitters. Positrons and electrons annihilate each other in the body, producing two gamma rays. Detecting the position from which the gamma rays originate enables the position of the positron emitter to be mapped.
- X-rays are produced by the collision of electrons with a target material. Soft X-rays are less penetrating and have lower frequency than hard X-rays.
- A CAT scan is produced by the computer analysis of the attenuation of X-rays moving around a slice of the body. CAT scans can distinguish soft tissue with small differences in density and can produce an image of tissue behind bone.
- PET scans indicate the biochemistry, metabolism and function of a particular area. PET scans are used for studying the brain and heart, detecting cancers at an early stage and monitoring cancers during treatment.
- MRI scans make use of the magnetic effects of a strong external magnetic field on certain nuclei, particularly hydrogen, together with pulses of radio waves to produce images of internal body tissue.
- MRI scans show soft tissue clearly, making them suitable for imaging the brain and spinal cord.

Questions

Effects of radiation

1. Why can the formation of free radicals and ions be damaging to living cells?
2. A 30 kg child receives 3 mGy of radiation. How much energy did the child absorb?
3. An adult (60 kg) absorbs the same amount of energy as the child in question 2. What is the adult's absorbed dose?
4. What is the dose equivalent of the child in question 2, assuming the energy was delivered by γ radiation?
5. What is the dose equivalent of the adult in question 3, assuming the energy was delivered by α radiation? Assume a quality factor of 20.
6. Why is α radiation given a higher quality factor than γ radiation?
7. How much energy, absorbed via γ rays, would cause the death of an 80 kg person within 48 hours due to vascular system damage?
8. Why is dose equivalent often a more useful measure than absorbed dose?
9. It is more dangerous for pregnant women to be exposed to high radiation levels than for other people. Why?
10. A particularly concerned man is keen to minimise his exposure to background radiation. What advice could you give him on the lifestyle changes he should make?
11. Australians receive on average 2.0 mSv of radiation each year. Assuming this radiation is all beta particles with energy of 1.0 MeV, how many beta particles pass in or out of your body every second? (*Hint:* Estimate your body mass and find out how many joules of radiation you receive each year. Find out how many joules of energy there are in a 1.0 MeV beta particle, then find out how many beta particles pass through your body every year, then every second.)
12. Ionising radiation can cause cancer, yet it also can cure cancer. Explain this contradictory statement.

Radioactivity as a diagnostic tool

13. Carbon-11 has a half-life of 20 min and bromine-75 has a half-life of 100 min. If samples of these isotopes initially have the same activity, show on the same graph how their activities vary with time.
14. A small amount of iodine-131, which has a half-life of 8 days, is used to treat a patient with a

thyroid condition. Sixteen days later, an amount of 6.0 mg remains.
(a) How much iodine-131 was used in the treatment?
(b) How much of the radioisotope will remain after another 16 days?
(c) When is iodine-123 preferred to iodine-131 even though it is more expensive?

15. A sample of a radioisotope has a half-life of 2.0 minutes.
(a) Calculate the time it will take the activity to drop from 4.0 MBq (megabecquerels) to 1.0 MBq.
(b) Calculate the time it will take for its activity to be 0.25 MBq.

16. A particular isotope has a half-life of 100 days. Discuss the suitability of this isotope for use in medical diagnosis.

17. Describe the problems associated with using a radioisotope of very short half-life for medical diagnosis.

18. (a) Choose two specific radioactive isotopes used in medical diagnosis and outline where they would be used in the body. Justify your answer.
(b) Explain why α-emitting radioisotopes are not used for medical imaging.

19. Identify a radioactive tracer study in which the tracer:
(a) mixes with the substance under investigation
(b) is accumulated in the organ of interest.

20. Explain why technetium-99m is such an ideal radioisotope for medical imaging.

21. The lower figures in 'Bones, lungs and brain' show two different types of studies of lungs.
(a) Contrast the studies.
(b) Relate the type of study to the disease diagnosed.

22. The upper figures in 'Bones, lungs and brain' show an X-ray of a leg and a bone scan of the body.
(a) Compare the X-ray image with the bone scan.
(b) Explain why there are differences in the images obtained.

23. The function of the lungs can be studied using a radioactive gas. The choices are xenon-133 or krypton-81m and their properties are listed in the table following. Evaluate the claim that 'Xenon should be used in preference to krypton for investigations of lung function.'

Isotope	Emission products	Half-life
Xenon-133	β, γ	5.3 days
Krypton-81m	γ	13 seconds

X-rays and CAT scans

24. (a) With the aid of a labelled diagram, give a description of the way in which X-rays are produced.
(b) Explain why the X-rays usually pass through a thin filter before they are used to image the patient.

25. (a) Outline how the attenuation of X-rays changes for different materials in the body.
(b) Describe and account for the appearance of an X-ray image of part of the body containing bone, muscle and air spaces.

26. X-rays can be classified as hard or soft.
(a) How are hard X-rays different from soft X-rays?
(b) Why are hard X-rays preferred for imaging the human body?

27. Describe the differences between the ways in which CAT scans and conventional X-ray images are produced.

28. Use a table to summarise situations in which CAT scans are a superior diagnostic tool to X-rays and ultrasound.

PET, MRI and comparisons

29. How are the radioisotopes used in PET scans different from those that are not used in PET scans?

30. (a) What is a positron?
(b) How are positrons obtained?
(c) Identify issues associated with positron–electron interaction and describe how this interaction is used in medical diagnosis.

31. Describe how a radioisotope of your choice is used in a PET investigation. In your answer you should name the isotope, state what radiation is emitted and how it is monitored. You should describe what measurements are made and how they are used to obtain a result. You should also mention any precautions or safety procedures.

32. Describe how an external magnetic field influences a hydrogen proton.

33. Why are hydrogen nuclei imaged more than any other nuclei in MRI?

34. Describe two different pieces of information that can be analysed during an MRI scan when the low-energy radio frequency pulse is turned off.

35. Why is MRI useful for imaging cancerous tumours in the brain?

36. Compare the advantages and disadvantages of X-ray scans, CAT scans, ultrasound and MRI scans for each of the following purposes:
(a) imaging the brain
(b) imaging bone
(c) imaging the heart and circulation.

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CHAPTER

21 How do particle accelerators and colliders work?

REMEMBER

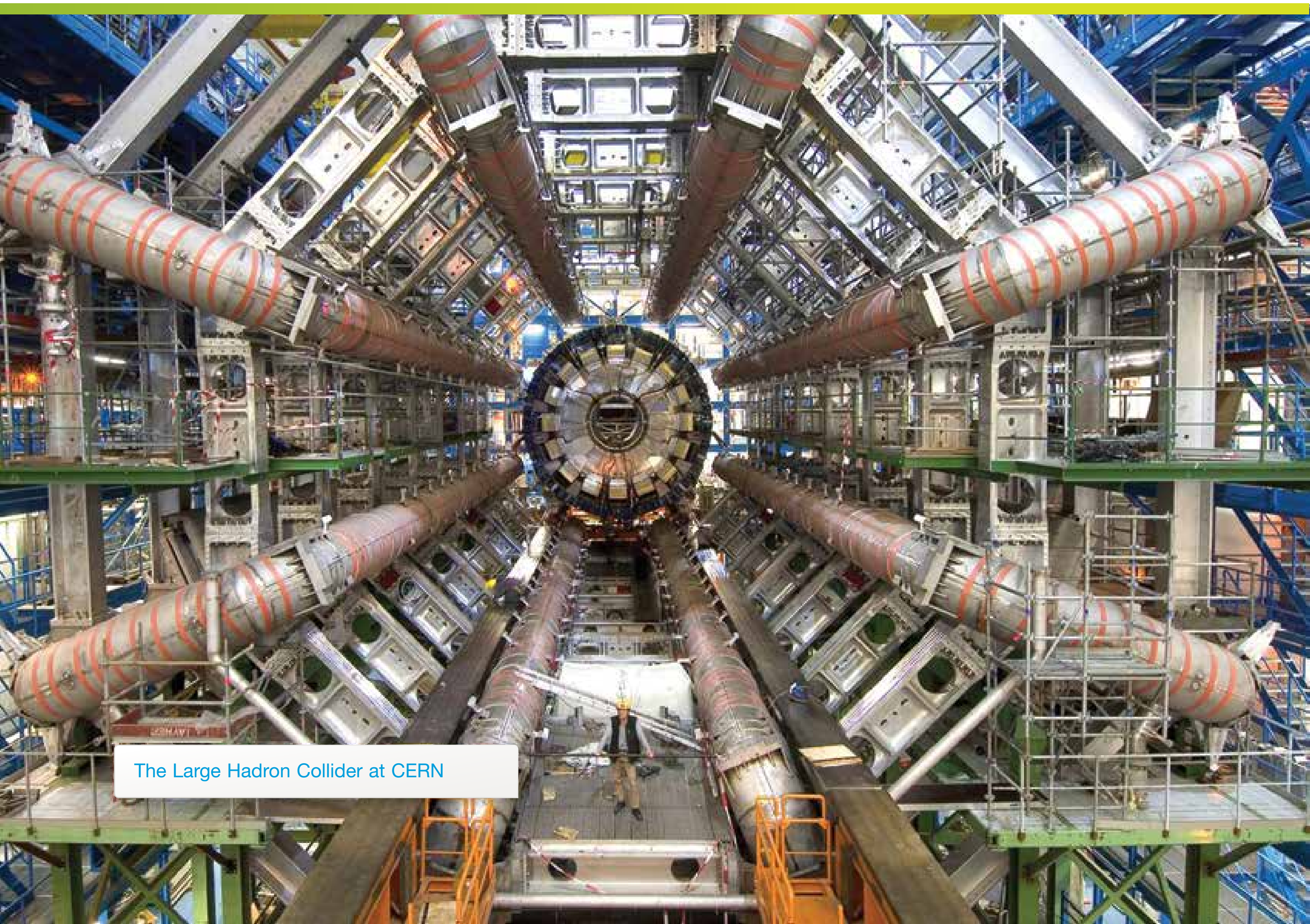
Before beginning this chapter, you should be able to:

- describe the production of synchrotron radiation by an electron travelling on a curved path
- give examples of leptons and hadrons, as well as baryons and mesons and the part quarks play in their composition.

KEY IDEAS

After completing this chapter, you should be able to:

- compare and contrast particle colliders with particle accelerators that produce synchrotron light
- describe the general structure of the Australian Synchrotron
- explain how synchrotron radiation compares to laser light and X-rays
- recall the different particles involved in accelerators
- describe how the maximum energies of particle accelerators and colliders have increased over the years
- appreciate the role of colliders in the development of our understanding of particle physics
- describe the diverse products from colliders
- compare the particle detectors at the Large Hadron Collider.



The Large Hadron Collider at CERN

Chapter review

Summary

- Synchrotrons accelerate electrons to produce light, called synchrotron radiation.
- Colliders accelerate electrons, protons and heavy ions to produce particle collisions. The maximum energies have grown exponentially since the 1950s.
- In the Australian Synchrotron the linac (linear accelerator) is where the electrons receive most of their energy gain. The circular booster ring raises the energy even further before the electrons are passed to storage ring. At each bending magnet in the storage ring, synchrotron radiation is produced along the tangent into beamlines.
- Synchrotron radiation is characterised by its extreme brightness, wide spectrum and narrow spread. Laser light has a narrower spread.
- Colliders have played a central role in detecting and measuring subatomic particles that support the Standard Model of particle physics.
- The LHC has several ways of detecting the particles produced in collisions. These include ATLAS, CMS, ALICE and LHCb, which have different purposes.
- The need to store massive amounts of data produced by the LHC, the software to analyse it and the networks to share it have had an impact on the development of information processing technologies.

Questions

Comparisons between the LHC and the Australian Synchrotron

1. What is the fundamental difference of purpose between the LHC and the Australian Synchrotron?
2. Describe the purpose of each of the following components of the Australian Synchrotron: linac, circular booster, storage ring and beamlines.
3. Describe the structure of the LHC in a similar sequence to that of the Australian Synchrotron, as listed in the previous question.
4. What components do the LHC and the Australian Synchrotron have in common?
5. Which charged particles has the LHC detected and how?
6. What components do each of the LHC and the Australian Synchrotron have that the other does not?
7. What can the LHC do that the Australian Synchrotron can't?
8. What can the Australian Synchrotron do that the LHC can't?
9. What is the significance of the word 'hadron' in the title of the LHC?
10. Explain the meaning of the words brightness, spectrum and divergence as applied to a beam of light.
11. How does synchrotron light compare to laser light and X-rays in terms of brightness, spectrum and divergence?
12. What features does the LHC have that the early particle colliders did not?
13. In what way is the LHC crucial for our increased understanding of the universe?
14. Just over a hundred years ago, when Becquerel discovered radioactivity, our understanding of matter and the universe could be described as quite primitive compared to what seems a complete understanding of the universe today. Are there questions remaining and if so, is the cost of the machines to investigate them worth the effort?

CHAPTER

22 How can human vision be enhanced?

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Sight is one of the senses we heavily rely on for collecting data and making observations. How can vision be extended to gather even more information?

REMEMBER

Before beginning this chapter, you should be able to:

- describe light as the part of the electromagnetic spectrum detected by the human eye.

KEY IDEAS

After completing this chapter, you should be able to:

- describe the use of ray tracing as a technique to investigate the behaviour of light in optical devices
- explain that reflected rays obey the law of reflection
- explain that, when passing from one medium to another, light refracts in accordance with Snell's Law, $n_1 \sin \theta_1 = n_2 \sin \theta_2$
- describe how optical devices such as eyes, cameras, telescopes and microscopes form images by manipulating light
- describe how the size of an image compares with the size of an object in magnification
- apply ray tracing to explain common problems with sight.

Chapter review

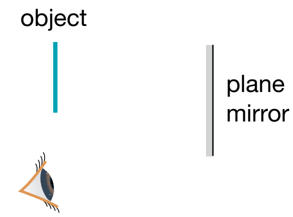
Summary

- The ray model depicts light as straight lines in a uniform medium.
- Rays of light reflect from a plane surface so that the angle of incidence equals the angle of reflection.
- The incident ray, reflected ray and the normal to the surface all lie in the same plane.
- When passing from one medium to another, light refracts in accordance with Snell's Law, $n_1 \sin\theta_1 = n_2 \sin\theta_2$.
- Pinhole cameras are powerful tools for understanding the behaviour of light and image formation.
- Convex lenses cause parallel rays of light to diverge. Concave lenses cause parallel rays to converge.
- Convex lenses result in image formation that depends on where the object is placed. Concave lenses produce upright, virtual, diminished images.
- the position of image formed by thin lenses can be determined by accurate ray tracing and by using the thin lens equation, $\frac{1}{u} + \frac{1}{u} = \frac{1}{f}$.
- For pinhole cameras and simple cameras, the magni fication is given by $M = \frac{v}{u}$.
- Light from distant objects can be gathered by telescopes to form clearer and larger images. Telescopes use either concave mirrors or convex lenses to collect light.
- Small objects can be enlarged by using a compound microscope with the object placed inside the focal length of the objective lens.
- The operation of the eye can be explained with an understanding of refraction and lenses.
- Two of the major conditions that are corrected using glasses and contact lenses are short-sightedness (myopia) and long-sightedness (hypermetropia).
- The power of a lens is calculated using $P = \frac{1}{\text{focal length}}$.
- The lens of the human eye can focus on near and distant objects by changing the curvature of its lens. This ability tends to decrease with age, causing hypermetropia.
- The lens in the eye can go cloudy (cataracts), causing blindness. This can be treated by removing the lens and replacing it with an plastic lens.
- Using technology to replace damaged retinas and optic nerves with a 'bionic eye' is an area of intensive research and development.

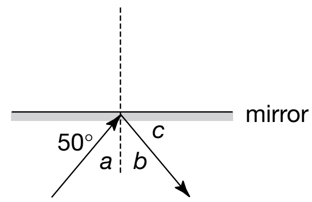
Questions

Reflection

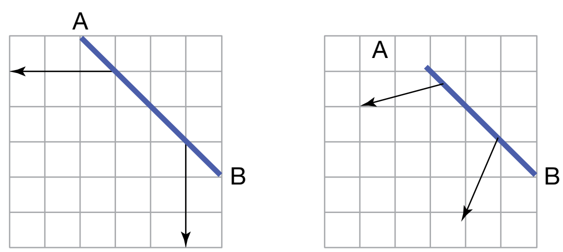
1. Describe the light path from a light source to your eye in seeing an object.
2. Use the ray model and the sources of light to rephrase the statements (a) 'I looked at a flower through the window' and (b) 'I watched the TV.'
3. Explain how early astronomers knew the Moon must have a rough surface.
4. Copy the following figure and draw the incident and reflected rays from the two ends of the object to the eye. Locate the image.



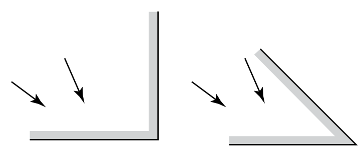
5. Calculate the angles, *a*, *b* and *c* in the following figure.



6. The two arrowed lines in the figures below represent reflected rays. The line AB represents the plane mirror. Locate the image and the light source in each of the two figures.



7. A student argues that you cannot photograph a virtual image because light rays do not pass through the space where the image is formed. How would you argue against this statement?
8. Sketch the path of each of the rays entering each of the pair of joined mirrors in the following figure.

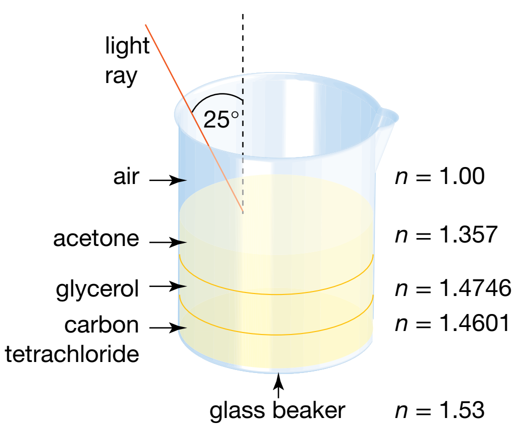


9. You are walking towards a plane mirror at a speed of 1.0 m s^{-1}. How fast is your image walking? How quickly are you and your image approaching each other?

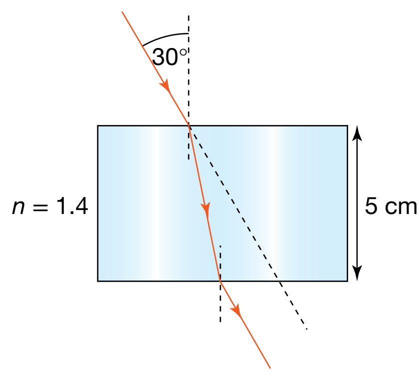
10. (a) You are standing 2.0 m in front of a plane mirror and you wish to take a sharp photograph of yourself in the mirror. At what distance do you set the camera lens?
(b) Your friend is standing beside you, 1.0 m away. At what distance do you set the camera lens for a sharp photograph of your friend?
11. How can you see raindrops if water is transparent?

Refraction

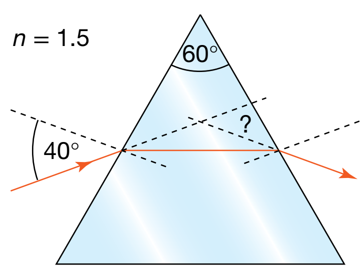
12. What is the angle of refraction in water ($n = 1.33$) for an angle of incidence of 40°? If the angle of incidence is increased by 10°, by how much does the angle of refraction increase?
13. A ray of light enters a plastic block at an angle of incidence of 55° with an angle of refraction of 33°. What is the refractive index of the plastic?
14. A ray of light passes through a rectangular glass block with a refractive index of 1.55. The angle of incidence as the ray enters the block is 65°. Calculate the angle of refraction at the first face of the block, then calculate the angle of refraction as the ray emerges on the other side of the block. Comment on your answers.
15. Immiscible liquids are liquids that do not mix. Immiscible liquids will settle on top of each other, in the order of their density, with the densest liquid at the bottom. Some immiscible liquids are also transparent.
(a) Calculate the angles of refraction as a ray passes down through immiscible layers as shown in the figure below.



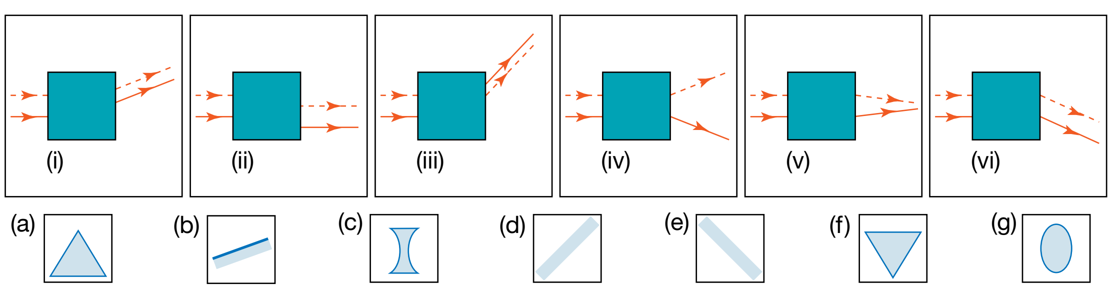
(b) If a plane mirror was placed at the bottom of the beaker, calculate the angles of refraction as the ray reflects back to the surface. Comment on your answers.
16. Light rays are shown passing through boxes in the figure at the base of the page. Identify the contents of each box from the options (a)–(g) given at the bottom of page*. Option (b) is a mirror. All others are solid glass. *Note:* There are more options than boxes.
17. (a) To appear invisible you need to become transparent. What must your refractive index be if your movement is not to be detected?
(b) The retina of your eye is a light-absorbing screen. What does that imply about your own vision if you are to remain invisible? (*Hint:* If you are invisible all light passes through you.)
18. Calculate the angle of deviation at a glass–air interface for an angle of incidence of 65° and refractive index of glass of 1.55.
19. Calculate the sideways deflection as a ray of light goes through a parallel-sided plastic block ($n = 1.4$) with sides 5.0 cm apart, as in the figure below.



20. Calculate the angle of deviation as the light ray goes through the triangular prism shown in the figure below.



16*.



Convex lenses

21. Use ray tracing to determine the full description of the following objects:
(a) a 4.0 cm high object, 20 cm in front of a convex lens with a focal length of 15 cm
(b) a 3.0 mm high object, 10 cm in front of a convex lens with a focal length of 12 cm
(c) a 5.0 cm high object, 200 cm in front of a convex lens with a focal length of 10 cm.

22. What does 'accommodation mechanism' mean? Give an example.

23. (a) You are carrying out a convex lens investigation at a bench near the classroom window and you obtain a sharp image of the window on your screen. A teacher walks past outside the window. What do you see on the screen?
(b) The trees outside the classroom are unclear on the screen. What can you do to bring the trees into focus?

24. Use ray tracing to determine the magnification of an object placed under the following two-lens microscope. The object is placed 5.2 mm from an objective lens of focal length 5.0 mm. The eyepiece lens has a focal length of 40 mm. The poles of the lenses are 150 mm apart.

25. A convex lens with a focal length of 5.0 cm is used as a magnifying glass. Determine the size and location of the image of text on this page if the centre of the lens was placed:
(a) 4.0 cm above the page
(b) 3.0 cm above the page.

26. A 35 mm slide is placed in a slide projector. A sharp image is produced on a screen 4.0 m away. The focal length of the lens system is 5.0 cm.
(a) How far is the slide from the centre of the lens?
(b) What is the size of the image?
(c) Looking from the back of the slide projector, the slide contains a letter 'L'. What shape will appear on the screen?
(d) The slide projector is moved closer to the screen. The image becomes unclear. Should the lens system be moved closer to or further away from the slide?

27. A teacher is using a slide projector but the image on the screen is smaller than the screen. What needs to be done to produce a clear image on the full screen?

Correcting eye defects

28. A person suffers from myopia. Describe what this means to them.

29. Sketch a diagram of a myopic eye, using rays to show what is happening to cause this problem.

30. Sketch the profile of a lens that might be used to correct myopia.

31. Identify one cause of hypermetropia.

32. Sketch a profile of a hypermetropic eye, using rays to show what is happening to cause this problem.

33. Cataracts are the leading cause of blindness. What treatment is required to restore the sight to those with cataracts?

34. Investigate three different research programs on bionic eyes. What is the difference between each of their approaches, and what conditions do they aim to alleviate?

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CHAPTER

23 How do instruments make music?

Musical instruments produce sound in various ways, but they all rely on the same physical principals.

REMEMBER

Before beginning this chapter, you should be able to:

- describe waves as a method of the transfer of energy from one place to another without any net transfer of matter
- describe periodic waves in terms of their wavelength (λ), amplitude (*A*), period (*T*) and frequency (*f*)
- distinguish between transverse waves and longitudinal waves
- understand how waves can interfere constructively and destructively.

KEY IDEAS

After completing this chapter, you should be able to:

- examine models relating to sound such as the wave model
- explore ideas about sound in the making of music and how the human ear responds to it
- explore how the wave model is applied in the design and development of musical instruments
- examine particular combinations of sounds including chord progressions and cadences
- explore the idea that certain combinations of sounds affect the human ear differently
- describe and analyse the production of sound in musical instruments and by the human voice.

Chapter review

Summary

- Sound waves are longitudinal.
- As longitudinal waves move through a medium, the particles of the medium vibrate parallel to the direction of propagation.
- The intensity (I) of a sound is the power per unit area at a point and it is measured in W m^{-2}.
- The intensity of a sound is inversely proportional to the distance from the source.
- The intensity level (L) of a sound is measured in decibels (dB).
- $L = 10\log_{10}\frac{I}{I_0}$
- Resonance is the condition where a medium responds to a periodic external force by vibrating with the same frequency as the force.
- Standing waves are caused by the superposition of two wave trains of the same frequency travelling in opposite directions.
- The fundamental frequency of a string or pipe is the lowest frequency at which a standing wave occurs.
- Harmonics are whole number multiples of the fundamental frequency.

Questions

Wave speed or velocity

1. What is the speed of sound in air if it travels a distance of 996 m in 3.0 s?
2. How far does a wave travel in one period?
3. Do loud sounds travel faster than soft sounds? Justify your answer.
4. A marching band on the other side of a sports oval appears to be 'out of step' with the music. Explain why this might happen.
5. You arrive late to an outdoor concert and have to sit 500 m from the stage. Will you hear high-frequency sounds at the same time as low-frequency sounds if they are played simultaneously? Explain your answer.
6. A loudspeaker is producing a note of 256 Hz. How long does it take for 200 wavelengths to interact with your ear?
7. During an electrical storm the thunder and lightning occur at the same time and place. Unless the centre of the storm is directly above, you see the lightning flash before you hear the thunder. How far away is lightning if it takes 5.0 s for the sound of thunder to reach you after the flash is seen? Assume the speed of sound in air is 335 m s^{-1}.

The wave equation

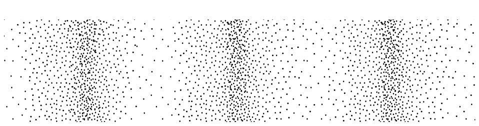
8. What is the wavelength of a sound that has a speed of 340 m s^{-1} and a period of 3.0 ms?
9. What is the speed of a sound if the wavelength is 1.32 m and the period is 4.0×10^{-3} s?
10. The speed of sound in air is 340 m s^{-1} and a note is produced that has a frequency of 256 Hz.
    (a) What is its wavelength?
    (b) This same note is now produced in water where the speed of sound is 1.50×10^3 m s^{-1}. What is the new wavelength of the note?
11. Copy and complete table 23.1 by applying the universal wave formula.

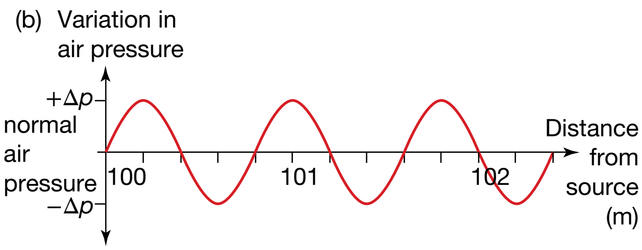
TABLE 23.1

v (m s^{-1})	f (Hz)	λ (m)
	500	0.67
	12	25
1500		0.30
60		2.5
340	1000	
260	440	

Producing sound

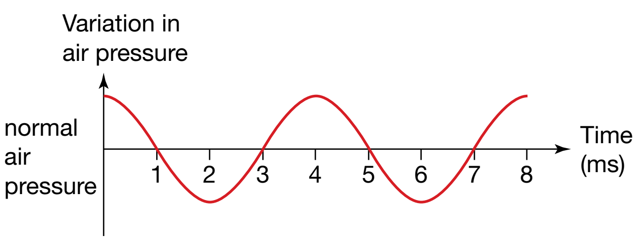
12. Sketch a graph showing the variation of air pressure as a function of distance for a sound wave of wavelength 1.0 m.
13. Sketch a pressure–time graph to illustrate the following situations:
    (a) a 100 Hz sound of a certain loudness
    (b) a sound with the same frequency, but louder
    (c) a sound with the same loudness as in (a) but twice the frequency
    (d) a sound that is an octave lower than in (a) and quieter.
14. Figure (a) below shows the pressure variation as a function of distance from a sound source at an instant in time. The graph shown in figure (b) shows the pressure variation as a function of distance from the sound source. The speed of sound in air is 340 m s^{-1}.

(a)




(a) What is the wavelength of this sound?
(b) What is the period of this sound?
(c) Using the same scale as shown in figure (b), sketch the distribution of particles one-sketch the pressure variation one-quarter of a period later.
(d) Using the same axes as shown in figure (b), sketch a graph of pressure variation versus distance one quarter of a period later than shown in the graph.

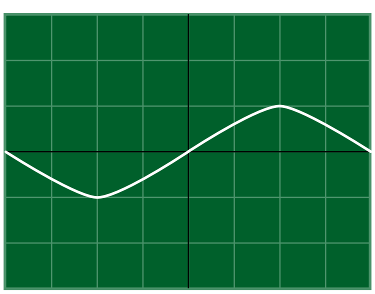
15. The figure below shows the variation of air pressure as a function of time near a sound source.



(a) What is the period of this sound?
(b) What is the frequency of this sound?
(c) What is the wavelength of this sound if the speed of sound is 330 m s^{-1}?

Observing sound

16. The figure below shows the trace on a CRO screen for a sound detected by a microphone. The time scale is 2 ms cm^{-1}.
(a) What is the period of this sound?
(b) What is the frequency of this sound?



(c) If the wavelength is 5.28 m, what is the speed of sound in this case?

(d) Using the same scale shown in the figure, sketch the trace you would get under the following circumstances:
 (i) if the frequency is doubled, but the loudness stays the same
 (ii) if the frequency stays the same, but the loudness is increased.

The power of sound

17. What is the acoustical power of a source if it produces 2.0 J in 100 s?

18. What is the sound intensity if 4.0×10^{-8} W pass through an area of 0.080 m^2?

19. Calculate the power passing through an area of 2.0 m^2 if the sound intensity is 4.5×10^{-5} W m^{-2}?

20. One siren produces a sound intensity of 3.0×10^{-3} W m^{-2} at a point which is 10 m away. What would be the sound intensity produced at that point if five identical sirens sounded simultaneously at the same place as the original?

21. If the sound intensity 4.0 m from a point sound source is 1.0×10^{-6} W m^{-2}, what will be the sound intensity at each of the following distances from the source?
(a) 1.0 m
(b) 2.0 m
(c) 8.0 m
(d) 40 m

22. What are the sound intensity levels associated with the following sound intensities?
(a) 5.0×10^{-10} W m^{-2}
(b) 3.2×10^{-7} W m^{-2}
(c) 4.9×10^{-3} W m^{-2}
(d) 1.8×10^{-9} W m^{-2}

23. Calculate the sound intensities associated with the following sound intensity levels:
(a) 7.0 dB
(b) 25 dB
(c) 54 dB
(d) 115 dB.

24. Show that the rule of thumb stated in the text — halving the sound intensity reduces the intensity level by 3 dB — is true.

25. The area of a human eardrum is approximately 5.0×10^{-5} m^2. Sabiha is listening to music through a button earphone. How much energy arrives at her eardrum during a song that lasts for 3 min if the average sound intensity produced at the eardrum by the button earphone is 1.0×10^{-2} W m^{-2}?

The human ear's response to sound

26. What is meant by the expression 'threshold of hearing'?

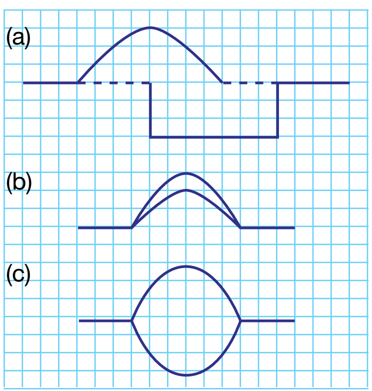
For questions 27 and 28, refer to the graph showing the sensitivity of the average human ear in 'The human ear's response to sound'.

27. (a) What is the sound intensity level at the threshold of hearing at the following frequencies?
(i) 100 Hz
(ii) 500 Hz
(iii) 2000 Hz
(iv) 10 000 Hz
(b) At what frequency is the average human ear the most sensitive?
(c) What is the sound intensity level at the threshold of hearing at that frequency?

28. (a) Estimate the range of frequencies that an average human being can hear for sounds with a sound intensity level of 10 dB.
(b) Estimate the highest frequency used in the speech region.
(c) What is the approximate range of frequencies that can be above 100 dB in performing music?

Transverse standing waves in strings or springs

29. The figure below shows the positions of three sets of two pulses as they pass through each other. Copy the diagram and sketch the shape of the resultant disturbances.



30. What is the wavelength of a standing wave if the nodes are separated by a distance of 0.75 m?

31. The figure below shows a standing wave in a string. At that instant ($t = 0$) all points of the string are at their maximum displacement from their rest positions.

If the period of the standing wave is 0.40 s, sketch diagrams to show the shape of the string at the following times:
(a) $t = 0.05$ s
(b) $t = 0.1$ s
(c) $t = 0.2$ s
(d) $t = 0.4$ s.

Sound and standing waves

32. Kim and Jasmine set up two loudspeakers in accordance with the following arrangements:
- They faced each other.
- They were 10 m apart.
- The speakers are in phase and produce a sound of 330 Hz.

Jasmine uses a microphone connected to a CRO and detects a series of points between the speakers where the sound intensity is a maximum. These points are at distances of 3.5 m, 4.0 m and 4.5 m from one of the speakers.
(a) What causes the maximum sound intensities at these points?
(b) What is the wavelength of the sound being used?
(c) What is the speed of sound on this occasion?

Stringed instruments

33. A standing wave is set up by sending continuous waves from opposite ends of a string. The frequency of the waves is 4.0 Hz, the wavelength is 1.2 m and the amplitude is 10 cm.
(a) What is the speed of the waves in the string?
(b) What is the distance between the nodes of the standing wave?
(c) What is the maximum displacement of the string from its rest position?
(d) What is the wavelength of the standing wave?
(e) How many times per second is the string straight?

34. The speed of waves in a string is 250 m s^{-1}. It has a length of 1.0 m.
(a) What is the wavelength of the longest standing wave that can be produced in this string?
(b) What is the fundamental frequency for this string?
(c) What is the frequency of the first resonant frequency above the fundamental?
(d) What harmonic corresponds to the second resonant frequency above the fundamental and what is its frequency?

35. If the fundamental frequency of a string is 240 Hz, find the frequencies of the following quantities:
(a) the first resonant frequency above the fundamental
(b) the third resonant frequency above the fundamental
(c) the third harmonic
(d) the 22nd harmonic.

36. The following figure represents four standing waves for a string of length L that is fixed at both ends. Use this figure to complete table 23.2.

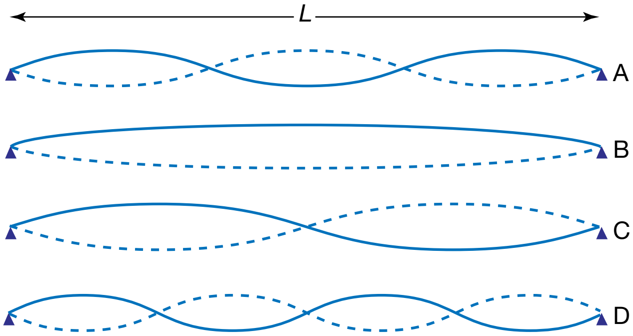


TABLE 23.2

String	Nodes	Antinodes	λ	Tone	Harmonic
	2			f_0	
			$\frac{L}{2}$		
		2			
A					

37. (a) The first resonant frequency above the fundamental of a string is 500 Hz. What is the fundamental frequency of this string?
(b) The second harmonic of a string is 516 Hz. What is the fundamental frequency of the string?

38. The third harmonic of a string is 810 Hz. What is the fundamental frequency?

39. The fourth resonant frequency above the fundamental of a string is 1400 Hz. Find the following frequencies:
(a) the fundamental frequency
(b) the second harmonic
(c) the second resonant frequency above the fundamental.

Wind and brass instruments

40. If the speed of sound in air is 340 m s^{-1}, find (i) the longest wavelength tone and (ii) the fundamental frequencies of the following pipes:
(a) open at both ends, length 40 cm
(b) open at both ends, length 60 cm
(c) open at both ends, length 1.21 m
(d) open at both ends, length 1.00 m
(e) closed at one end, length 0.50 m
(f) closed at one end, length 0.25 m
(g) closed at one end, length 12.5 cm
(h) closed at one end, length 17 cm.

41. The figure above right represents four standing waves in a pipe of length L. The pipe is open at both ends. Use this figure to complete table 23.3.

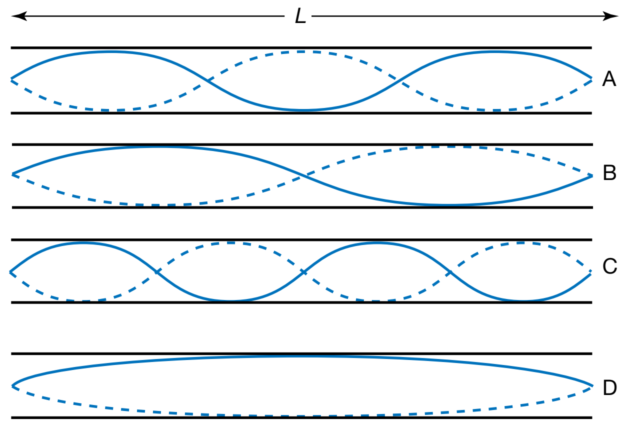


TABLE 23.3

Pipe	Nodes	Antinodes	λ	Resonant Frequency	Harmonic
B					
					First
			$\frac{2L}{3}$		
	5				

42. The figure below represents four standing waves in a pipe of length *L*. The pipe is closed at one end. Use this figure to complete table 23.4.

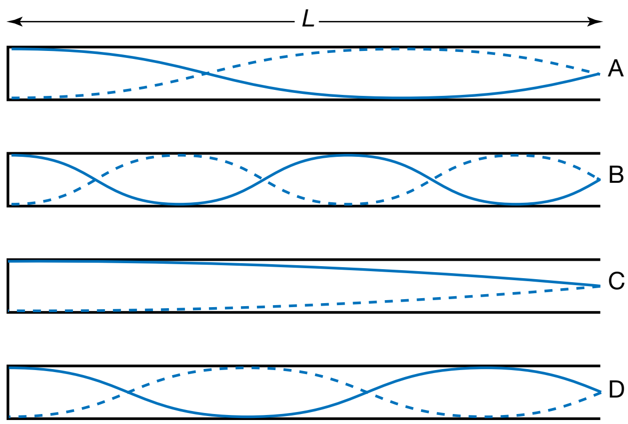
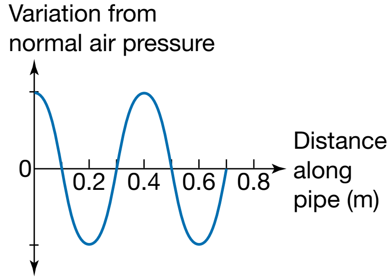


TABLE 23.4

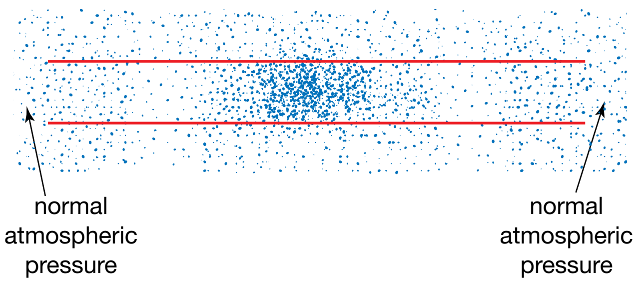
Pipe	Nodes	Antinodes	λ	Resonant Frequency	Harmonic
			$\frac{4L}{5}$		
C					
		2			
					Seventh

43. A graph of how air pressure varies with distance along a pipe at a particular instant is shown below. A standing wave has been set up in the pipe and the graph represents the maximum variation from normal air pressure. Assume that the speed of sound in air is 340 m s^{-1}.



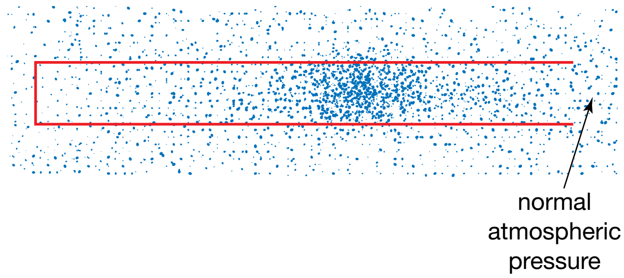
(a) Is the pipe open at both ends or closed at one end? Explain.
(b) What is the length of the pipe?
(c) What is the wavelength of the sound being produced?
(d) What is the frequency of the sound being produced?
(e) Which harmonic and resonant frequency above the fundamental is being produced?
(f) What is the fundamental frequency for this pipe?
(g) Sketch a graph showing the variation of air pressure from normal along the pipe at a time half a period later than the instant shown in the diagram.

44. The figure below shows pressure variation in and around a pipe open at both ends as it is resonating at one of its harmonics. Assume that the speed of sound in air is 340 m s^{-1}.



(a) What harmonic is represented in the diagram?
(b) If the pipe is 0.85 m, what is the wavelength of the tone that the pipe is producing?
(c) What is the frequency of the tone being produced?
(d) Make a sketch to show the pressure variation in and around the pipe half a period later than the instant shown.
(e) Sketch the pressure variation in and around the pipe one quarter of a period later than the instant shown.
(f) What is the period of the sound being produced by the pipe?
(g) What is the frequency of the second resonant frequency above the fundamental for this pipe?

45. The following figure shows the pressure variation in and around a pipe closed at one end as it is resonating at one of its harmonics. Assume that the speed of sound in air is 340 m s^{-1}.



(a) What harmonic is represented in the diagram?
(b) If the pipe has a length of 50 cm, what is the wavelength of the tone that the pipe is producing?
(c) What is the frequency of the tone being produced?
(d) What is the fundamental frequency for this pipe?
(e) What is the frequency of the third resonant frequency above the fundamental of this pipe? What harmonic does this frequency correspond to?
(f) Make a sketch to show the pressure variation in and around the pipe half a period later than the instant shown.

46. A student is tuning a guitar using a tuning fork with a frequency of 440 Hz. When the A string is struck at the same time as the tuning fork, the string sounds higher in pitch and a beat frequency of 2 Hz is heard. What is the frequency of the string?

47. The tone A has a frequency of 440 Hz. What is the frequency of the tone:
(a) one octave above A
(b) one octave below A?

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CHAPTER

24 How can performance in ball games be improved?

Small changes to the equipment or technique a sportsperson uses can have a large effect on the outcome of a game. How can performance be improved?

REMEMBER

Before beginning this chapter, you should be able to:

- analyse motion along a straight line numerically and algebraically
- explain how the action of a force changes the way an object moves
- explain changes in motion in terms of Newton's three laws of motion
- describe and analyse simple interactions between objects in terms of change in momentum
- describe the turning effect of a force
- analyse work done in terms of force and distance travelled in the direction of the force
- apply the energy conservation model to energy transfers and transformations.

KEY IDEAS

After completing this chapter, you should be able to

- analyse the transfer of momentum in collisions using the coefficient of restitution, *e*
- describe and compare the different forms of friction: static, kinetic and rolling
- explain the retarding effect of kinetic friction in sliding
- explain the turning effect of kinetic friction in causing a sliding ball to begin rolling
- analyse rotational motion numerically and algebraically
- describe the energy transfer in the action of a double pendulum
- explain how air resistance limits a falling object's velocity
- analyse the flight of an object through the air
- explain the effect of spin on the flight of a ball.

Chapter review

Summary

- The coefficient of restitution, e, of an impact between two objects is the ratio of their speed or separation to their speed of approach.
- The coefficient of restitution, e, equals 1 for an elastic collision and 0 for a sticky collision.
- When the definition for the coefficient of restitution, e, is combined with the principle of the conservation of momentum, an expression for the final speed of the target ball can be obtained.
- The expression for the final speed of the target ball can be examined to determine the effect of increased mass and speed of the incident object as well as the mass of the target ball.
- A collision between two billiard balls can be considered elastic. The stationary target ball moves in a direction along a line connecting the centres of the two balls at the moment of impact. The incident ball moves off in a direction at right angles to the target ball motion.
- Static friction is the frictional force between two surfaces when one is being pushed across the other but there is no movement. The maximum value of static friction is given by $\mu_s N$, where μ_s is the coefficient of static friction and can take a value between 0 and 1 and N is the reaction force.
- Kinetic friction is the frictional force between two surfaces when there is movement. The value of kinetic friction is given by $\mu_k N$, where μ_k is the coefficient of kinetic friction and can take a value between 0 and 1, and N is the reaction force. For any two surfaces, μ_k is less than μ_s.
- Kinetic friction is a retarding force on a sliding object.
- Rolling friction is considerably less than kinetic friction, because there are no sideways forces between the surfaces. Rolling friction is due to the contact surface not fully rebounding from being squashed by the rolling object.
- The motion of rotating object can be described using the physical quantities angular speed, ω, and angular acceleration, α, which are defined as follows:

$$\omega = \frac{\Delta\theta}{\Delta t} \text{ and } \alpha = \frac{\Delta\omega}{\Delta t}$$

- The relation between angular speed, ω, and linear speed, v, is $v = r\omega$.
- The rotational equivalent of mass is called the moment of inertia, I. Its value depends of how the mass is distributed around the axis of rotation. The moment of inertia for a sphere and a cylinder are different.
- The rotational equivalent of force is torque, τ.
- The rotational equivalent of Newton's Second Law is $\tau = I\alpha$.
- Kinetic friction acts on a sliding ball in two ways. The friction reduces the linear speed of the sliding ball. The friction also applies a torque to the ball, increasing its angular speed. When the linear speed, v, and the angular speed, ω, satisfy the relationship $v = r\omega$, the ball stops sliding and begins to roll.
- Many sporting actions can be modelled as a double pendulum, in which two straight, jointed sections can move independently. In most actions the energy begins in the inner arm and during the action is transferred to the outer arm.
- Air resistance is a retarding force that acts on objects moving through the air. For most objects and most speeds, the air resistance is proportional to the square of the speed. The drag coefficient, C_D, is a measure of the air resistance due to the surface of an object. The air resistance or drag force can be given by $F_{drag} = \frac{1}{2} C_D \rho v^2 A$, where ρ is the air density and A is the cross sectional area of the object.
- For falling objects, the air resistance acts against the gravitational force. Initially, at low speeds, the air resistance is small, but as the downward speed increases, the air resistance increases to the point where it balances the gravitational force and acceleration becomes zero. The speed at this point is called the terminal velocity.
- For the flight of an object, air resistance will reduce the maximum height and the range.
- The air flow on opposite sides of a ball can be affected by spinning the ball or by making one side rougher than the other. These can affect the speed on one side of the ball compared to the other. On the side where the speed of the air flow is increased, the air pressure is less. On the side where the air speed is less, the air pressure is greater. The difference in pressure produces a sideways force on the ball. This effect is called the Magnus effect.

Questions

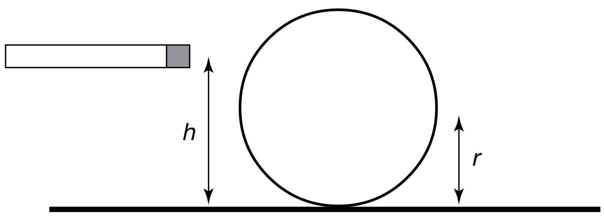
Coefficient of restitution

1. A golf ball bouncing on a concrete surface has a restitution coefficient of 0.8. If it is dropped from a height of 1.0 m, to what height does it rebound?
2. A ball is dropped from rest at a height h_1 above the ground. It rebounds to a height h_2. If the force of gravity is the only force acting, show that $e = \sqrt{\frac{h_2}{h_1}}$.

3. A ball travelling at 5.0 m s^{-1} approaches another ball of equal mass. The second ball is travelling in the same direction at 2.0 m s^{-1}. If the coefficient of restitution is 0.6, calculate the final velocities of the two balls.
4. A squash ball hits the front wall of the court head on at 10 m s^{-1} at a height of 1.0 m. If the coefficient of restitution is 0.8, how far back does the ball land?
5. Explain why the maximum theoretical speed a golf ball could achieve is twice the club head speed.

Sliding and rolling

6. A billiard ball of radius 2.5 cm is rolling on a billiard table. If the centre of the ball is moving at 1.0 m s^{-1}, what is the rate at which the ball is rotating?
7. Explain what a snooker player must consider and do in order to play the perfect stun shot and discuss why it works. (A stun shot is one in which the cue ball stops immediately at impact.)
8. A billiard cue strikes a billiard ball with a force F above the centre of the ball at a distance h up from the table surface. The ball has mass m and radius r. The force gives the ball a rotation. The value of h can be chosen so that the ball does not slide and only rolls straight from the impact.



The force produces a linear acceleration of the ball so that after time t, its speed is $v = \frac{F}{m}t$.

The force also applies a torque so that the angular velocity, ω, of the ball after time t is:

$$\omega = \frac{\text{torque}}{\text{moment of inertia}} \times t = \frac{F(h-r)}{I}t$$

For rolling, $v = r\omega$.

(a) Equate the expressions to show that for perfect rolling, $h = r + \frac{I}{Mr}$.

(b) Substitute the formula for the moment of inertia of a sphere to show that $h = \frac{7}{5}r$.

Note: This is the design height of the cushion on a billiard table so that balls don't slide when they rebound.

9. A player strikes a billiard ball with a level cue at a height h, causing it to move forward with spin. Immediately after the impact between the cue and the ball, the centre of the ball is moving at 1.2 m/s, while the ball itself is rotating at 2.0 revolutions per second. The ball has a radius of 2.0 cm.

(a) In which direction does the frictional force due to sliding act?

(b) In which region must the cue have struck the ball?

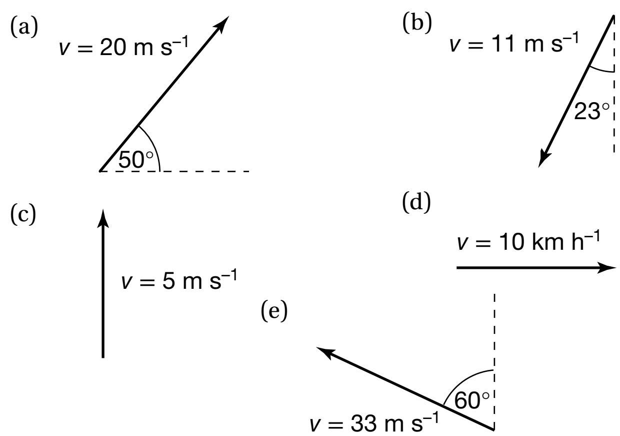
A $h < 2.0$ cm
B $2.0 < h < 2.8$ cm
C $h = 2.8$ cm
D 2.8 cm $< h <$ 4.0 cm

Double pendulum

10. Describe the energy changes that occur during a back hand return in tennis.
11. Describe the energy changes that occur when a foot ball is kicked.

Projectile motion

12. For a sphere moving through air, the drag force has the expression $F_{drag} = \frac{1}{2} C_D \rho v^2 A$. Explain each of the terms in the expression.
13. In each of the cases shown below, calculate the magnitude of the vertical and horizontal components of the velocity.

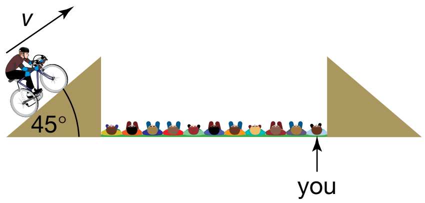


14. Explain why the horizontal component of velocity remains the same when a projectile's motion is modelled.
15. A cube-shaped parcel of flour with a volume about the size of a refrigerator is dropped from a height of 500 m from a helicopter travelling horizontally at a speed of 20 m s^{-1}.

(a) Describe the effects of air resistance on:
 (i) the horizontal component of the motion of the parcel
 (ii) the vertical component of motion of the parcel.

(b) Which of the horizontal or vertical components of the motion of the parcel is likely to experience the greater air resistance during:
 (i) the first 2 s of its fall
 (ii) the final 2 s of its fall?
Give reasons for each answer.

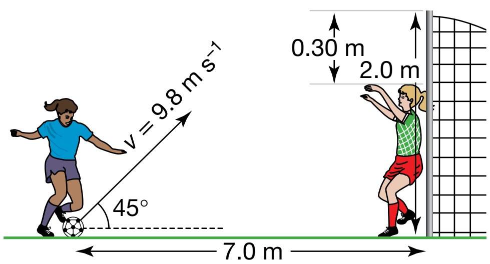
16. A friend wants to get into the *Guinness Book of Records* by jumping over 11 people on his push bike. He has set up two ramps, as shown below and has allowed a space of 0.5 m for each person to lay down in. In practice attempts, he has averaged a speed of 7.0 m s^{-1} at the end of the ramp. Will you lay down as the eleventh person between the ramps?



17. You have entered the javelin event in your school athletics competition. Not being a naturally talented thrower, you decide to use your brain to maximise your performance. Using your understanding of the principles of projectile motion, decide on the best angle to release your javelin. Back up your answer with calculations.

18. A skateboarder jumps a horizontal distance of 2 m, taking off at a speed of 5 m s^{-1}. The jump takes 0.42 s to complete.
(a) What was the skateboarder's initial horizontal velocity?
(b) What was the angle of take-off?
(c) What was the maximum height above the ground reached during the jump?

19. During practice, a young soccer player shoots for goal. The short goalkeeper is able to stop the ball only if it is more than 30 cm beneath the cross-bar. The ball is kicked at an angle of 45° and a speed of 9.8 m s^{-1}. The arrangement of the players is shown below.



(a) How long does it take the ball to reach the top of its flight?
(b) How far vertically and horizontally has the ball travelled at this time?
(c) How long does it take the ball to reach the soccer net from the top of its flight?
(d) Will the ball go into the soccer net, over it, or will the goalkeeper stop it?

Magnus effect

20. Explain, by using a labelled diagram showing flow lines, that a ball moving through the air with back spin will experience an upward force.

21. A ball is hit in such a way as to give it a rotation about an axis. The ball swings away to the left as it goes away from the hitter.
(a) Using a clear diagram, explain the air flow around the ball and the origin of the force.
(b) If the force is reasonably constant during the motion, describe how the path would appear from above.

22. Shots played with top spin are very popular in tennis. Discuss the advantages and disadvantages of hitting the ball with top spin. Suggest modifications the player may need to make apart from applying top spin in order that the shot may be more effective.

23. It is observed that a cricket ball swings more when the atmosphere is humid due to a change in the air pressure. However, as water molecules (H_2O) are lighter than the other gases in air (N_2 and O_2), humid air is less dense and therefore exerts less pressure. Suggest other factors that might explain why cricket balls swing more in humid weather.

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CHAPTER

25 How does the human body use electricity?

REMEMBER

Before beginning this chapter, you should be able to:

- recall that like charges repel and unlike charges attract
- explain the concept of current and electrical potential difference
- recall Ohm's Law, namely $V = IR$
- recall that electrical power can be expressed as $P = IV$
- recall that the electrical energy, E, transferred during a time interval, t, is related to the power consumed by $E = Pt = IVt$.

KEY IDEAS

After completing this chapter, you should be able to:

- compare mobile charge carriers in the human body with those in metals
- describe how an electrical potential difference arises across the cell membrane
- understand capacitance and its relationship to the separation of charge carriers and electrical potential difference
- model polarising and depolarising of a cell in terms of a simple circuit containing a resistor and capacitor in parallel
- explain how electrical signals are transmitted by nerve cells
- describe the chemical transfer of signals between nerve cells via the synapses
- describe the nature and role of electrical pulses in the function of the heart
- explain the effect of applying an external potential difference to the human body, including the nature of electric shock, the action of a defibrillator, the cauterisation of wounds, the activation of neural responses and the stimulation of neuroplasticity
- describe the varying electrical resistance of different organs and tissue types in the body and explain how they contribute to the total effective resistance of the body.
- explain the difference in the effect of direct and alternating sources of potential difference on the effective resistance of the body
- describe the detection and interpretation of electrical signals from the body by ECG and EEG machines
- describe modern developments in artificial transmission of stimuli by a device such as a pacemaker, the cochlear implant or the bionic eye
- describe modern developments in the reception and amplification of electrical signals at points of damage in the nervous system, enabling remote stimulation of real and artificial body parts.

Neurons in the brain carry electrical impulses.

Chapter review

Summary

- Our bodies contain many electrically charged ions that are able to respond to electrical forces
- Cells have a resting electrical potential difference due to a charge imbalance across the cell membrane. This arises from the difference in concentration of ionic species inside and outside the cell combined with the difference in mobility of the Na^+ and K^+ ions and the action of the ATP molecule transferring Na^+ ions out of the cell and K^+ ions into the cell.
- Neurons respond to electrical stimulus at a point in the cell by allowing sodium ions to enter the cell at that point, altering the local potential difference across the cell membrane. If the influx of sodium ions exceeds a threshold number, a process of depolarisation and repolarisation of the cell occurs, known as the action potential.
- The occurrence of the action potential at one point along the cell membrane triggers the onset of an action potential at the neighbouring section of the membrane, allowing the transmission in a domino-like fashion of the action potential along the length of the cell.
- The sheathing of axons in myelin for short sections increases the velocity of the transfer of the action potential.
- Neurons communicate with other neurons through synapses, where a chemical transfer takes place via a neurotransmitter. The transfer of electrical signals along axons is much faster than the transfer of chemical signals.
- The behaviour of a cell can be modelled by a simple circuit consisting of a capacitor in parallel with a resistor. The time taken to charge and discharge the cell as the action potential depolarises and repolarises the cell can be modelled as the characteristic time associated with charging and discharging the capacitor.
- Our bodies are able to conduct electricity. However, excessive currents damage cell tissue and disrupt electrical processes in the heart and nervous system.
- Alternating current sources pose greater risk to the human body than direct current sources due to the capacitative properties of body tissue.
- The nervous system can be stimulated artificially as seen in pacemakers, bionic eyes and cochlear devices.
- Heart and muscle cells also respond to electrical stimulus.
- Electrocardiograms detect the potential differences between various parts of the heart and are used to diagnose the quality of heart function.
- Stimulation of the heart generates a regular electrical signal with characteristic features that can be seen in an electrocardiogram.
- The defibrillator is a device that deliberately disrupts the function of the heart in order to effect a restart of the heart action.
- Electroencephalographs detect the potential difference between various parts of the brain and are used to monitor brain function.
- Neural signals are able to be detected and amplified, allowing bionic control of existing of artificial body parts.

Questions

Charge carriers and electrical potential difference in cells

1. List two ions essential to the function of nerve cells and describe their role.
2. When electrical forces are applied to a conducting material, the charge carriers move. What is the term used to describe how easily the charge carriers can move?
3. Electrons in Ag have a mobility of 56 $cm^2\,V^{-1}\,s^{-1}$ at 27 °C. Na^+ ions have a mobility of $5.2 \times 10^{-4} cm^2\,V^{-1}\,s^{-1}$ in extracellular fluid.
   (a) Which charge carriers move faster in response to an applied potential difference?
   (b) The resistivity of Ag is $1.59 \times 10^{-8}\,\Omega$ m, whereas the resistivity of extracellular fluid is approximately 20 Ω m, or 1000 million times larger. List two factors that result in the significantly smaller resistivity of Ag compared to extracellular fluid.
4. Describe the basic structural elements of a human cell.
5. Give two reasons why the Na^+ ions in the extracellular fluid try to enter the unstimulated cell.
6. How do proteins located in the cell membrane affect cell function?
7. Describe the role of the ATP pump in maintaining the resting cell potential difference.
8. The resting potential difference across cells varies for different types of cells, from –60 mV for smooth muscle cells to 95 mV for skeletal muscle cells. Explain how the resting potential difference across a cell can be made more negative.

The nervous system and electrical processes

9. List the principal components of a nerve cell.

10. What is the role of the synapses in the nervous system?

11. (a) Explain the difference between a nerve cell and a nerve.
(b) What happens when a neuron is stimulated by 5 mV or less?

12. Describe the phenomenon of hyperpolarisation.

13. When hyperpolarisation occurs, an action potential cannot be established. True or False?

14. The magnitude of the action potential depends upon the strength of the stimulus. True or False?

15. Which is the main direction of current flow as an action potential moves along an axon — across the membrane or along the membrane?

16. Towards the end of the refractory period, the neuron is able to be stimulated again. How does the threshold stimulus compare with the initial stimulus applied to the neuron?

17. List three differences between saltatory conduction and conduction by an unmyelinated axon.

18. Sensory receptors stimulate the sensory neurons. Which sensory receptors are connected to the thickest axons?

19. What is the advantage of a larger diameter axon?

20. If you perceive a tingling sensation in your arm, what is a likely explanation for this?

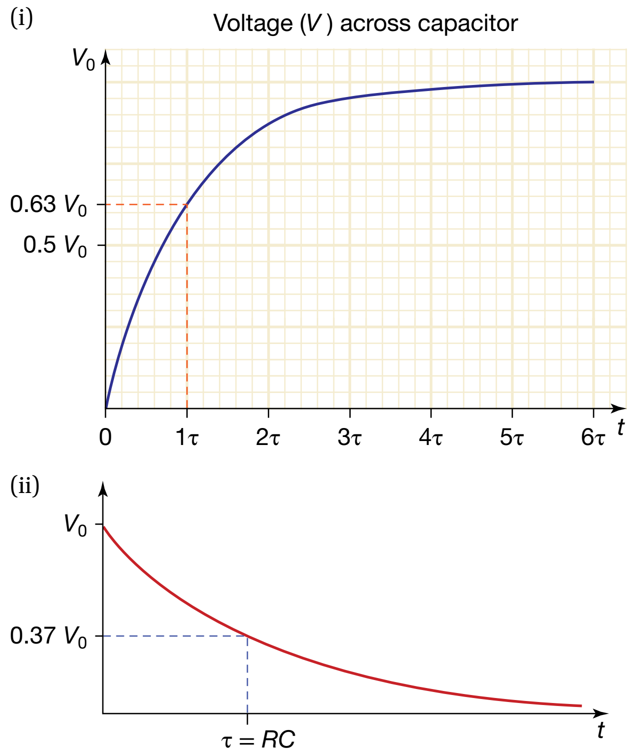
A simple electrical model of cells and the action potential

21. A circuit contains a 10 μF capacitor. If the voltage across the capacitor is 10 V, how much charge is stored by the capacitor?

22. A 0.50 μF capacitor is in series with a 500 Ω resistor.
(a) When attached to a 9.0 V battery, how long does it take for the potential difference across the capacitor to reach 5.7 V?
(b) Is the current in this circuit increasing or decreasing with time? Explain.

23. A 10 F capacitor is charged to 5000 V. It is then connected in series with a 500 Ω resistor.
(a) How long until the capacitor is regarded as fully discharged?
(b) What is the average current that passes through the resistor?

24. Compare the figures illustrating charging and discharging of a capacitor with the action potential measured for the giant squid axon, –70 mV.



How voltage varies with time when (i) charging and (ii) discharging a capacitor

(a) Which figure best describes the depolarising of the membrane?
(b) Which figure best describes the repolarising of the membrane?
(c) Do you think that the effective resistance of the membrane is the same during depolarising and repolarising?

The heart: an electrically powered pump

25. Describe the electrical activity of the heart as it progress from P through to U on an ECG.

26. What are two important diagnostic criteria for doctors when they look at an ECG?

27. What is the advantage of a dual-chamber pacemaker?

28. Explain how a supply of constant voltage such as a battery can be used in a circuit containing a resistor, a capacitor and a variable conductor such as a neon gas tube to produce a periodic voltage pulse.

29. Fibrillation can be induced by exposure to AC electrical currents as small as 100 mA. Why is the household 50 Hz AC supply particularly dangerous?

Electrical resistance of the human body

30. Compare the resistivity of fat and muscle cells.

31. Why is an alternating source of potential difference more dangerous than a constant voltage source?

32. When using a defibrillator, special skin contact pads are used. If the patient has hair on their chest, it must be shaved off before the pads are applied. Why is this essential?

33. What is the word used to describe a resistance that depends upon the frequency of the current in the circuit?

34. The output power of a Bovie being used in an electrosurgery cutting procedure is 200 W. How much energy is deposited in the cells in 1 minute?

35. A person is wearing a Galvactivator glove powered by a 6 V battery with a light that flashes red when the skin conductivity of the wearer changes by 50%.

(a) If the baseline resistance of the person's skin is 100 000 Ω, what is the current that passes through the person's hand?

(b) When the person is excited, the current rises to 100 μA. What is their skin resistance now?

Neuroscience: frontiers of human bioelectricity

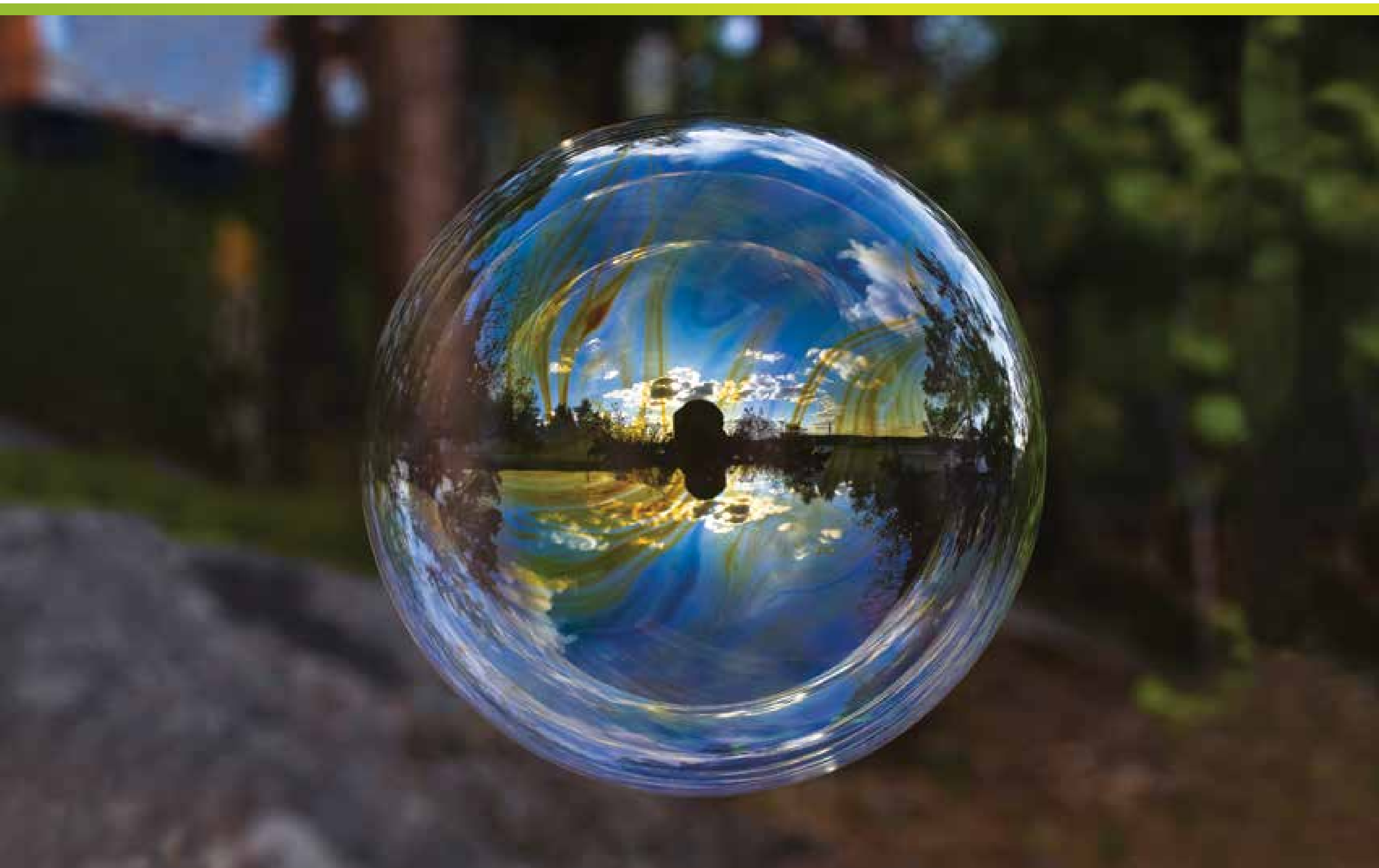
36. How is the signal monitored by an EEG related to the action potentials generated by individual neurons?

37. Compare the cochlear and bionic eye devices.

38. Describe the role of neuroplasticity in activity based training therapy.

39. Many current advances in biophysics and neuroscience could enhance experience for ordinary humans with normal neural function. Emergency workers such as firefighters could benefit from bionic aids to reduce fatigue. It is also speculated that localised electrical stimulation of the brain can improve both mood and memory. Identify ethical issues that might arise when such devices and techniques are employed on ordinary individuals.

INVESTIGATIONS



INVESTIGATION 1.1

The good oil on heating

Switch on a hotplate to about half its maximum setting. While waiting for the temperature of the hotplate to stabilise, pour 50 mL of water at room temperature into a 100 mL beaker and measure its mass. Add cooking oil to an identical beaker so that the beaker and oil have the same total mass as the beaker of water. Record the temperature of each liquid.

Place the beaker of water on the hotplate and, while gently stirring, use a stopwatch to record the time taken for the temperature of the water to increase by 10 °C.

Place the beaker of cooking oil on the hot plate and, while gently stirring, record the time taken for the temperature of the cooking oil to increase by 10 °C.

1. Which liquid required more energy to increase its temperature by 10 °C?
2. Which liquid has the greater resistance to change in temperature?

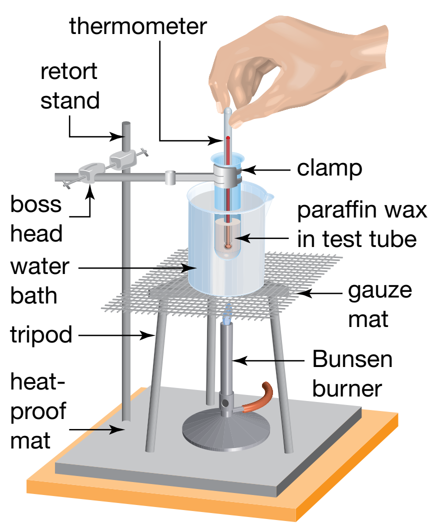
Repeat the procedure above using 100 mL of water at room temperature. Before commencing, however, predict how long it will take the water to increase its temperature by 10 °C.

3. By what factor did the amount of energy required to increase the temperature by 10 °C change when the amount of water was doubled?
4. Was the result consistent with your prediction? If not, suggest some reasons for the inconsistency.
5. If the cooking oil and water were supplied with the same amount of energy by heating for the same amount of time on the same flame, which would experience the greater increase in temperature?

INVESTIGATION 1.2

Cooling

Place some solid paraffin wax into a large test tube. Heat the test tube in a water bath until the temperature of the paraffin wax is about 80 °C.



A water bath is used to heat the paraffin wax.

Remove the test tube from the water bath and record the temperature of the paraffin every minute until the temperature has fallen to about 30 °C. Gently and carefully stir with the thermometer while the liquid paraffin is cooling.

1. Construct a graph of temperature versus time to display your data.
2. What causes the decrease in temperature of the liquid paraffin?
3. How does the rate of cooling change as the liquid paraffin solidifies?
4. During the process of solidification, what form of internal energy is being lost from the paraffin? Where is it going?
5. What is the meaning of the term latent heat of fusion and how does it relate to this investigation?

INVESTIGATION 4.1

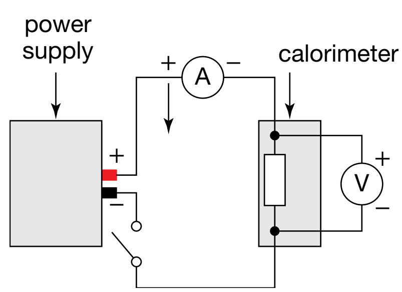
Energy transferred by an electric current

This investigation involves calculating how much energy is transformed from electrical potential energy into the internal energy of a load.

You will need the following equipment:

- DC power supply
- voltmeter
- ammeter
- calorimeter
- thermometer
- stopwatch.

Connect the circuit shown in the figure.



Find the mass of the copper vessel in the calorimeter.

Add 100 mL of water to the vessel.

Note the initial temperature of the water.

Set the power supply on 6 V and close the switch. Start the stopwatch.

Record the current passing through and the voltage drop across the calorimeter.

Agitate the water with the stirrer until the temperature of the water reaches a value 10 °C above its initial value.

Open the switch and stop the stopwatch.

1. Calculate the amount of energy transferred to the water and copper vessel using the formula:
   $Q = mC\Delta T$
   where Q = quantity of energy, *not* quantity of charge in this case
   m = mass of water
   C = specific heat capacity
   $C_{water} = 4.2 \times 10^3$ J kg^{-1} K^{-1}
   $C_{copper} = 3.8 \times 10^2$ J kg^{-1} K^{-1}
   ΔT = change in temperature

2. Use the data obtained from the voltmeter, ammeter and stopwatch to calculate the amount of energy transferred from the power supply to the calorimeter.
3. Compare your answer to question 2 with the reading on the voltmeter.
4. Account for any difference between the amount of energy transferred from the power supply to the calorimeter and the amount of energy transferred to the water and copper vessel.
5. Why was it necessary to agitate the water throughout the investigation?

INVESTIGATION 4.2

The current-versus-voltage characteristics of a light globe

You will need the following equipment:

- variable power supply
- 6 V light globe
- ammeter
- voltmeter
- switch
- connecting wires.

Design and construct a circuit that will enable you to find the current through the globe for a suitable range of voltages. Have your teacher check your circuit before taking any measurements. Gather the data and draw a graph of current versus voltage for the globe.

1. What happens to the resistance of the globe as the voltage increases?
2. What happens to the temperature of the globe as the voltage increases?
3. Why would the globe stop working if you kept increasing the voltage?

INVESTIGATION 4.3

Ohm's Law

Design and construct circuits to establish voltage drop (V) versus current (I) graphs for (a) a length of resistance wire, for example nichrome wire, and (b) a 6 V light globe. Vary the voltage across each from 0 V to 6.0 V and record your results. Draw V versus I graphs for each device.

1. Analyse the plots produced, commenting on the resistance of each device.
2. Account for the graph of the light globe, given that the filament is simply a long thin piece of tungsten wire.

INVESTIGATION 5.1

Series circuits

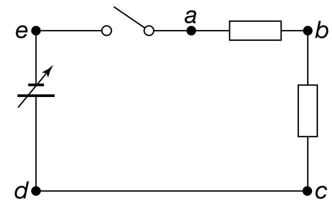
In this investigation, it is important that you understand the meaning of subscripts. For example, I_a means the current passing through a conductor at point *a*. An ammeter must be placed in the circuit at point *a*. V_{ab} means the voltage drop across points *a* and *b*. Therefore, a voltmeter should be connected from point *a* to point *b*.

You will need the following equipment:

- variable power supply
- two fixed resistors of different sizes
- ammeter
- voltmeter
- switch
- connecting wires.

Set up the circuit shown in the figure below.

Insert the ammeter at point *a*. Connect the voltmeter across points *d* and *e*. Adjust the power supply to give a value between 4.0 V and 6.0 V, as advised by your teacher. Measure and record the values of I_a and V_{de} with the switch closed.



Predict the value of I_b and I_c. Record and verify your predictions, noting down the measured results.

Measure V_{ab} and V_{bc}. Compare these results with V_{de}.

1. Are your measurements of current and voltage consistent with the expected values for a series circuit? Explain any discrepancies.
2. Use your data to estimate the effective resistance of the circuit. How does your estimation compare with the stated values of R_1 and R_2? If the resistors used were unmarked, calculate the resistance of each.
3. Account for any discrepancies between theoretical and actual values of resistance. Have parallax errors occurred in this investigation?
4. Write a conclusion in which you summarise the relationships between voltage, current and resistance in a series circuit.

INVESTIGATION 5.2

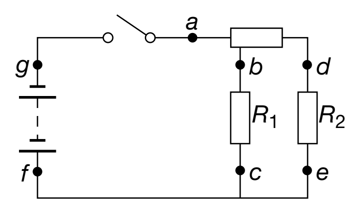
Parallel circuits

For this investigation, you will need the following equipment:

- variable power supply
- two fixed resistors of different sizes
- ammeter
- voltmeter
- switch
- connecting wires.

Set up the circuit shown in the figure below.

Insert the ammeter at point *a*. Connect the voltmeter across points *f* and *g*. Adjust the power supply to give a value between 4.0 V and 6.0 V, as advised by your teacher. Close the switch and measure and record the values of I_a and V_{fg}.



Measure and record the values of I_b and I_d. Compare these values with I_a.

Measure and record V_{bc} and V_{de}. Compare these results with V_{fg}.

1. Are your measurements of current and voltage consistent with the expected values for a parallel circuit? Explain any discrepancies.
2. Use the results obtained to predict the effective resistance of the circuit. Use the rule $\frac{1}{R_{\text{eff}}} = \frac{1}{R_1} + \frac{1}{R_2}$ and the stated values for R_1 and R_2 to calculate the theoretical resistance of the circuit. If the resistors are unmarked, calculate the resistance of each using Ohm's Law.
3. Account for any discrepancies between theoretical and actual values of resistance. Have parallax errors occurred in this investigation?
4. Write a conclusion in which you summarise the relationships between current, voltage and resistance in a parallel circuit.

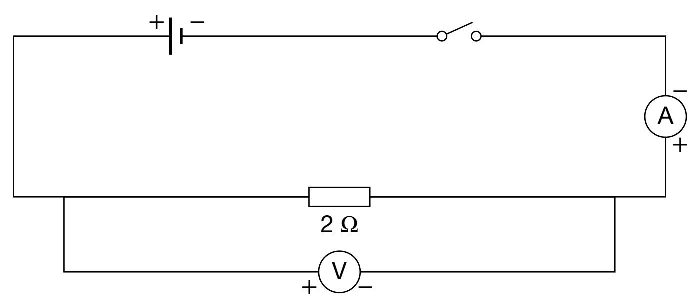
INVESTIGATION 5.3

Determining emf and internal resistance

For this investigation, you will need the following equipment:

- two dry cells, one old and one new
- high-resistance voltmeter
- ammeter
- resistors with values 2 Ω, 5 Ω, 10 Ω and one with a much larger value — at least 100 Ω (any carbon or metal film resistor could be used)
- connecting wires
- switch.

Set up the circuit as shown in the figure with the 2 Ω resistor and the old dry cell.



Construct a table with the headings 'External resistance', '*V* external' and 'Current' in which to record your results.

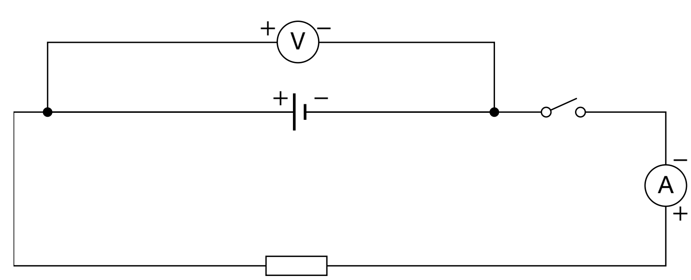
Close the switch and record the readings on the voltmeter and ammeter. Open the switch.

Repeat the procedure using the 5 Ω resistor, the 10 Ω resistor and the other resistor. Record your results and the value of the resistor.

With the switch open, measure the terminal voltage of the cell.

Repeat the previous steps using the new dry cell.

1. What was the highest voltage you recorded in each case?
2. For what value of the external resistance was this reading obtained?
3. What is the value of the external voltage when the switch is open?
4. What is the highest recorded voltage an indication of?
5. Estimate the internal resistance of each cell. Show your calculations.
6. Should it have made any difference to your results if the voltmeter had been connected as shown in the figure below?



7. What happens to the emf and internal resistance of a dry cell as it gets older?
8. Account for any discrepancies in your results.

INVESTIGATION 6.1

Examination of an electrical device

The aim of this investigation is to examine an electrical device and report on how it functions. You should identify any safety design features present.

You will need the following equipment:

- an electrical device, the simpler the better (e.g. toaster, electric iron, torch, electric jug, bar radiator, light globe)
- tools to take the device apart.

WARNING: The device should not be used again after this investigation. It is advised that the plug be cut off before the device is examined.

Take the device apart to such an extent that its circuitry can clearly be seen.

Draw a diagram of the structure of the device, identifying any safety features and the main components.

Draw a circuit diagram of the electrical components of the device.

Determine the average electrical power used by the device. This is usually printed on the device.

1. Calculate the current drawn by the device.
2. Write a report on how the device operates. Your report should include:
   - a drawing of the device
   - the circuit diagram of the device
   - what the useful function of the device is
   - how the device operates
   - the power used and the current drawn
   - how an electrical malfunction might occur
   - safety design features which are used to prevent electric shocks (e.g. double insulation, earthing, low voltage)
   - a summary of the examination and conclusions about the device.

Dispose of the device (in accordance with your teacher's instructions) after you have completed your report.

INVESTIGATION 6.2

Model circuits

The aim of this investigation is to apply the principles of series and/or parallel circuits to your chosen context.

Design series and/or parallel circuits which model household electrical or car electrical systems. For example, you could design a circuit to model a parallel lighting circuit used in cars or houses. A series circuit might be one in which a light or LED goes on whenever a heating element has a current flowing through it, as occurs in electric stoves or rear-window demisters.

Include instruments to measure voltage, current and time. Compile a list of equipment you require, and then consult your teacher. Construct your circuits and take the relevant readings.

Your report should include a diagram of each circuit; measurements taken in each circuit; calculations, graphs and explanations of each of the relationships studied; and an explanation of what the circuits model.

INVESTIGATION 7.1

Radioactive decay

In this investigation, the radioactive decay of a source will be analysed. The number of undecayed nuclei will be measured as time elapses. The 'source' is the Saunders 'Magic' Source box which simulates the decay of a radioactive substance over time. When it is switched on and source B is selected the display shows 1×10^{20} atoms. When the start button is pressed the source begins to decay and the display shows the *number of nuclei remaining in their original form*.

You will need the following equipment:

- Saunders 'Magic' Source
- 12 V power supply
- 2 × electrical leads.

Begin the experiment by starting the source. Read out the display every 15 seconds. The display represents the number of nuclei remaining in their original form, that is, the number of nuclei that have NOT yet decayed. The HOLD button on the box enables the reading to be frozen while the box continues on. Continue with the experiment for a total time of 300 seconds. Record your results in a suitable table.

Graph your results with *time* on the *x*-axis and *number of nuclei remaining* on the *y*-axis.

Draw a smooth line of best fit through your data points. (It does not have to pass through all points.) Determine four values from your graph of the half-life of the source.

It is legal in Victoria for schools to hold commercially available radioactive sources.

Half-life experiments with short-lived radioisotopes can be done in the classroom with a number of radioactive sources:

- protactinium-234, which is a decay product of uranium. The production of the 'cow' uses uranyl nitrate and a common organic solvent.
- barium-137 from a caesium-137 generator
- thallium-208 from thorium-232 'cow'
- radon-220 from a thorium hydroxide generator.

INVESTIGATION 7.2

Background radiation

This investigation involves measuring the background radiation in the classroom at school. You will need the following equipment:

- Geiger counter.

Set up the Geiger counter on a bench or table and turn it on.

Measure the background count for successive time intervals of one minute for about 10 minutes and obtain an average.

Compare your results to those obtained on different days or in different locations in the same classroom or in other locations around the school.

INVESTIGATION 7.3

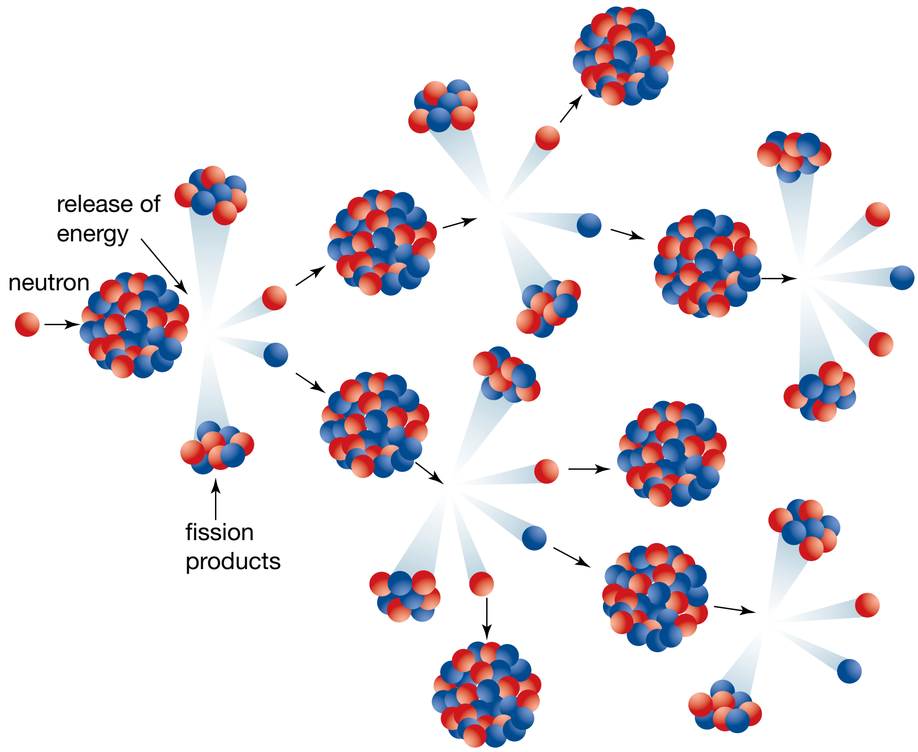
Chain reaction with dominoes

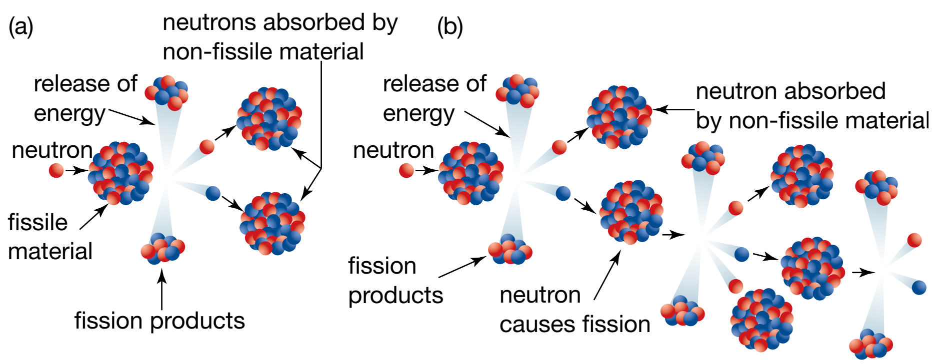
Try to model the figures using dominoes.

You will need the following equipment:

- dominoes
- stopwatch.

If a sufficient number of dominoes is available, try to measure the amount of time it takes to knock over all the dominoes in a controlled chain reaction and in an uncontrolled chain reaction. What does a longer time indicate, in terms of energy and power, for a real fission chain reaction?





INVESTIGATION 10.1

Going home

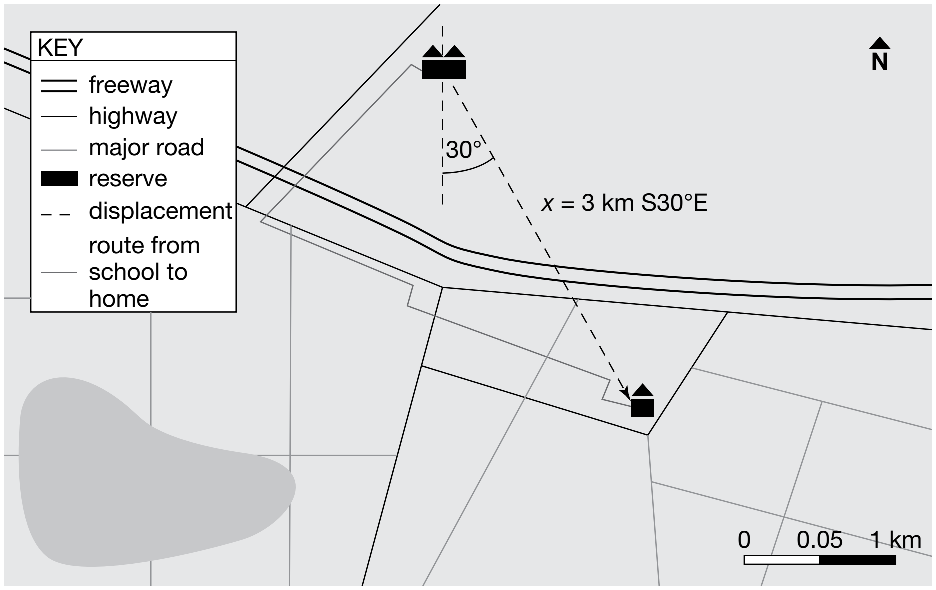
Study the sample map. Then draw a similar map to show your journey from home to school. It should occupy about half of an A4 page and be drawn to scale.

Record the time taken to travel home on a typical school day.

Draw and label your displacement on the map.

Determine and specify fully:

(a) your displacement
(b) your average velocity during the journey home
(c) the total distance travelled
(d) your average speed during the journey home.



Time to travel home: 10 min
Displacement: 3 km S30°E
Average velocity: $\frac{3000\text{ m}}{600\text{ s}} = 5\text{ m s}^{-1}$ S30°E
Total distance travelled: 4.2 km
Average speed: $\frac{4200\text{ m}}{600\text{ s}} = 7\text{ m s}^{-1}$

INVESTIGATION 10.2

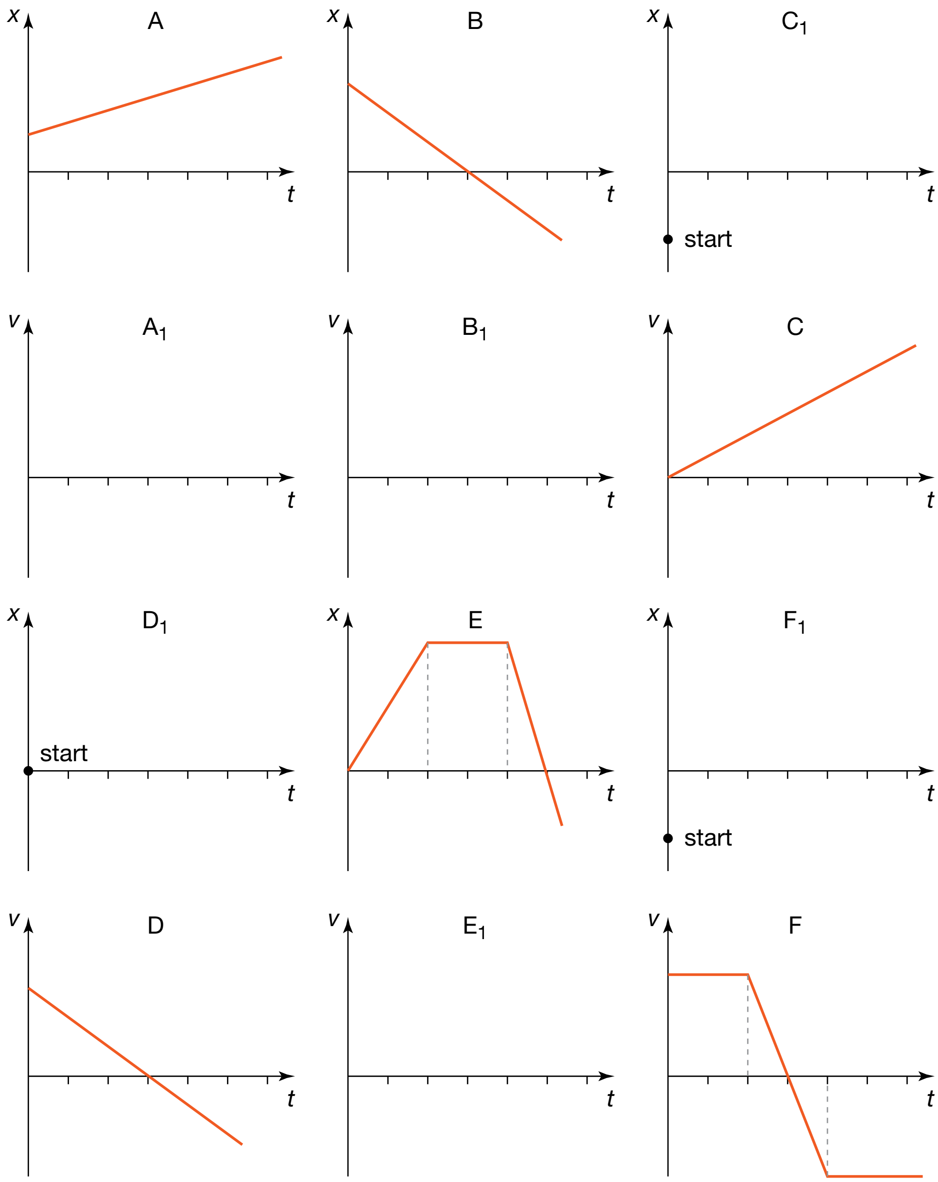
Let's play around with some graphs

Use a toy car (not battery-operated), a dynamics trolley, or just yourself to demonstrate the motion represented by each of the following graphs (labelled A to F). In some cases, you are given a position-versus-time graph ($\boldsymbol{x}$ versus t) and in others a velocity-versus-time graph ($\boldsymbol{v}$ versus t). The graphs are presented in order of increasing difficulty.

Follow the procedure below for each graph.

1. Look at each graph for a short time and imagine the motion that it is depicting.
2. Act out the motion represented by the graph while your partner watches. Your partner's role is to judge whether or not you have interpreted the graph correctly. If you and your partner disagree, complete step 3 and then try a second time to act out the motion before proceeding to step 4. If after a second attempt at acting out the motion, you and your partner do not agree, consult your teacher.
3. Copy the blank axes (labelled A_1 to F_1) into your workbook. Use these to sketch another graph representing the motion.
4. Swap roles with your partner and start on the next graph.
5. Once you have completed all six pairs of graphs, you can start drawing your own position-versus-time and velocity-versus-time graphs. Challenge your

partner to act out each one. Alternatively, you could act out the motion and challenge your partner to draw the graph.



INVESTIGATION 10.3

On your bike or on your own two feet

Record the motion of a bicycle or runner over a distance of 100 m on a straight track. Place timekeepers at 10 m intervals along the track. The role of each timekeeper is to record the time interval between the start and the instant that the cyclist or runner passes.

Construct a table like this one in which to record your results.

Motion over 100 m

Time (s)	Position (m)
	0
	10
	20

1. What was the average speed (in m s^{-1}) of the cyclist or runner?

Use your table to construct a graph of position versus time. Then use your graph to answer the following questions.

2. What information does the gradient of the position-versus-time graph provide?
3. At what instant did the maximum speed occur?
4. What was the maximum speed in m s^{-1}?
5. Express the maximum speed in km h^{-1}.

Now use your position-versus-time graph to construct a velocity-versus-time graph of the motion. Use your velocity-versus-time graph to answer the following questions.

6. How can the acceleration be determined from your velocity-versus-time graph?
7. During which time interval was the acceleration greatest?
8. Was the acceleration zero at any time during the ride or run? If so, at what instant or during which time interval was this the case?
9. During which time interval (if any) was the acceleration negative?
10. Calculate the area under the graph. Did you get the result that you expected? What does your result indicate about your graph?

INVESTIGATION 11.1

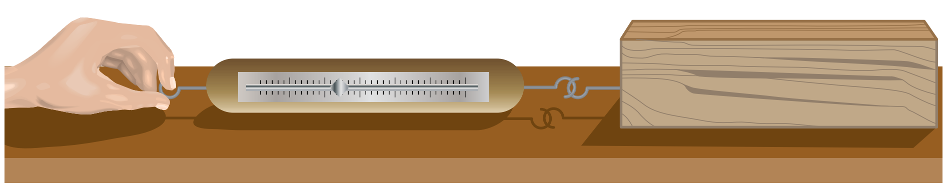
Friction

When a wooden block is pulled across a surface, two different types of friction are involved.

- Static friction is the force that prevents a stationary object from sliding across a surface. As you increase your pull on the stationary wooden block, the static friction increases so that it is equal in magnitude to the pull. This happens until the pull reaches the maximum value of limiting friction for the wooden block. This value is called the limiting static friction. Once the pull exceeds the limiting static friction, the block begins to slide.
- Once the block starts to slide, a different type of friction is applied — sliding friction. Sliding friction is a force that resists the motion of moving objects.

Use a wooden block with a hook attached, several identical blocks of wood (no hooks necessary) and a spring balance to investigate one or more of the following questions.

1. How does the magnitude of limiting static friction depend on the mass of the block?
2. How does the magnitude of sliding friction depend on the mass of the block?
3. How does the magnitude of limiting static friction compare with that of sliding friction?
4. Does the magnitude of the sliding friction depend on the speed of the block? (Ensure that the block is pulled along steadily at each speed investigated.)
5. Does the area of surface contact affect the size of:
   (a) limiting static friction
   (b) sliding friction?



INVESTIGATION 11.2

A flick of a coin

Flick a coin across a tabletop with your index finger so that it moves about 10 cm across the surface before it stops. Observe its motion until it stops.

Draw a diagram showing all of the forces acting on the coin while it is moving across the tabletop.

1. In which direction is the net force on the coin?
2. Describe the horizontal motion of the coin.

Now push the coin at a constant speed through a distance of 20 cm in a straight line across the same tabletop.

Draw a diagram showing all of the forces acting on the coin while it is being pushed across the tabletop.

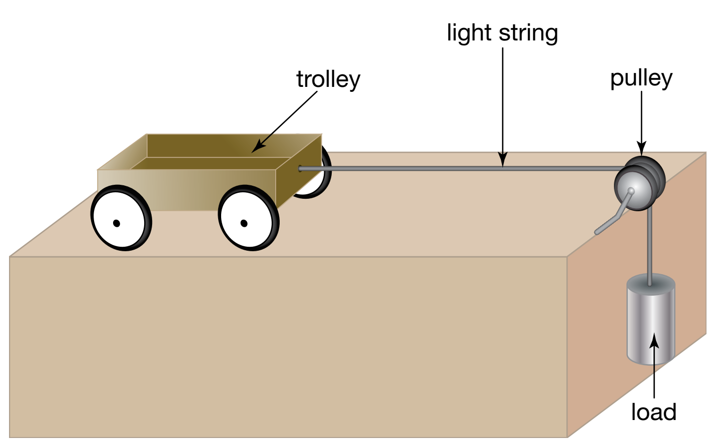
3. Describe the horizontal motion of the coin as it moves across the tabletop.
4. What is the magnitude and direction of the net force on the coin while it is travelling at a constant speed across the tabletop? (Think carefully about this one!)

INVESTIGATION 11.3

Impulse, momentum and Newton's Second Law of Motion

Connect a load of known weight to a dynamics trolley (or to a linear air track glider) with a light string over a pulley as shown in the figure. Measure and record the velocity of the trolley (or glider) at two separate instants as the load is falling. Do not measure the mass of the trolley (or glider).

1. Use your data to determine the magnitude of the acceleration of the system. If the data of other students are available or you can repeat your measurements, determine an average acceleration and estimate its uncertainty.
2. Use Newton's second law to estimate the mass of the system, and deduce the estimated mass of the trolley or glider.
3. Now measure the mass of the glider or trolley and compare it with your estimate. State the accuracy of your estimate as a percentage of the measured mass.
4. Use the measured masses and velocities to calculate the change in momentum of the system.
5. Use the net force on the system and the appropriate time interval to calculate the impulse on the system.
6. Compare the impulse and change in momentum of the system and discuss any difference between your expected results and your calculations.
7. Which of the measured quantities was least accurate? Why?



INVESTIGATION 12.1

Climbing to the top

Measure and record your mass in kilograms. Run up a flight of stairs and record the height climbed and the time taken.

1. Calculate the work done against gravity and the power developed as you ran up the stairs.
2. If your muscles were 25 per cent efficient, at what rate is chemical energy transformed by your body to get you up the stairs?

After you have had time to recover, repeat your run carrying a load of known mass (a school bag containing some books, for example).

3. Calculate the work done against gravity and the power developed as you ran up the stairs with the added load.
4. Compare and comment on the difference that the extra load makes to the work done against gravity and the power developed.

Appendix 1 SKILL CHECKS

To help in developing our basic understanding of our physical world, it is perhaps reassuring to know that scientific conventions and mathematical principles help us to express the concepts of physics precisely.

This skill checks appendix provides information on some of the conventions used in physics and some of the mathematical skills used in solving problems. Areas covered are SI units, scientific notation, significant figures, finding the area under a graph, direct variation, using trigonometry, and using spreadsheets.

SI units

So that scientists all over the world can communicate with each other effectively, it is important that they all use the same units to measure physical quantities. In 1960, the international authority on units agreed on a standardised system called the International System of Units. They are called SI units from the French '*Système International*'.

Base units

SI units consist of seven defined base units and other derived units that are obtained by combining the base units.

TABLE A1.1 The SI base units

Quantity	Unit	Symbol*
Length	metre	m
Mass	kilogram	kg
Time	second	s
Electric current	ampere	A
Temperature	kelvin	K
Luminous intensity	candela	cd
Amount of substance	mole	mol

*Symbols that are named after people begin with a capital letter; note, however, that the full name of such a unit begins with a small letter.

Each base unit is defined by a standard that can be reproduced in laboratories throughout the world. The standards have changed over time to make them more accurate and reproducible. For example, in 1800, the standard metre was defined as one-ten-millionth of the distance from the Earth's equator to either pole. By 1900, it had changed to the distance between two notches on a bar of platinum–iridium alloy kept in Paris. In 1960, it was redefined as 1 650 763.73 wavelengths of the light emitted by the atoms of the gas krypton-86. In 1983, the definition was changed to what it is today — the distance travelled by light in a vacuum in $\frac{1}{299\,792\,458}$ of a second.

The kilogram is defined by a standard mass of a platinum–iridium cylinder kept at the International Bureau of Weights and Measures in Paris since 1889.

The second is defined as the time taken for 9 192 631 770 vibrations of a caesium-133 atom.

Derived units

Speed is an example of a quantity that is measured in derived SI units. The SI unit of speed is the metre per second, written as m/s or m s^{-1}. Table A1.2 shows some other commonly used derived SI units.

TABLE A1.2 Some SI derived units commonly used in physics

Quantity	Unit	Symbol	Unit in terms of other units
Force	newton	N	kg m s^{-2}
Energy and work	joule	J	N m
Pressure	pascal	Pa	N m^{-2}
Power	watt	W	J s^{-1}
Electric charge	coulomb	C	A s
Voltage	volt	V	J C^{-1}
Resistance	ohm	Ω	V A^{-1}
Radiation dose equivalent	sievert	Sv	J kg^{-1}

Units and negative indices

Derived units are often expressed with negative indices. For example, the unit of speed is usually expressed as m s^{-1} rather than m/s. This is because:

$$\begin{aligned} 1\text{ m/s} &= 1\text{ m} \times \frac{1}{\text{s}} \\ &= 1\text{ m} \times 1\text{ s}^{-1} \\ &= 1\text{ m s}^{-1}. \end{aligned}$$

Similarly, the unit of power, joule per second or J/s, is written as J s^{-1}.

The unit of pressure, newtons per square metre, or N/m^2, is written as N m^{-2} because $\frac{1}{\text{m}^2} = \text{m}^{-2}$.

Metric prefixes

Some SI units are too large or small for measuring some quantities. For example, it is not practical to measure the thickness of a human hair in metres. It is also inappropriate to measure the distance from Melbourne to Perth in metres. The prefixes used in front of SI units allow you to use more appropriate units such as millimetres or kilometres.

Revision question A1.1

(a) Write down the full name of each of the units listed in the example column of table A1.3.

(b) Express each of the following quantities in SI base units:

(i) 1500 mA	**(ii) 750 g**	**(iii) 250 GW**
(iv) 0.52 km	**(v) 600 nm**	**(vi) 150 μs**
(vii) 5 cm	**(viii) 50 MV**	**(ix) 12 dm**

(c) **Acceleration is defined as the rate of change of velocity. Velocity has the same SI unit as speed. What is the SI unit of acceleration?**

(d) **The size of the gravitational force *F* on an object of mass *m* is given by the formula:**

$F = mg$ where *g* is the size of the gravitational field strength.

(i) What is the SI unit of *g*?

(ii) Express the SI unit of *g* in terms of base SI units only.

TABLE A1.3 Commonly used metric prefixes

Prefix	Symbol	Factor by which unit is multiplied	Example
giga-	G	10^9	GW
mega-	M	10^6	MV
kilo-	k	10^3	kJ
deci-	d	10^{-1}	dm
centi-	c	10^{-2}	cm
milli-	m	10^{-3}	mA
micro-	μ	10^{-6}	μg
nano-	n	10^{-9}	nm

Scientific notation

Very large and very small quantities can be more conveniently expressed in scientific notation. In scientific notation, a quantity is expressed as a number between 1 and 10 multiplied by a power of 10. For example, the average distance between the Earth and the moon is 380 000 000 m. This is more conveniently expressed as 3.8×10^8 m.

Using the power of 10 in scientific notation involves counting the number of places the decimal point in a number between 1 and 10 needs to be shifted to the right to obtain a multi-digit number. For example, the decimal point is shifted eight places to the right to get from 3.8 to 380 000 000. The latter number is therefore expressed as 3.8×10^8.

Scientific notation can also be used to express very small quantities conveniently and concisely. To give one example, the mass of a proton is

0.000 000 000 000 000 000 000 000 001 67 kg

In case you don't feel like counting them, there are 26 zeros after the decimal point! In scientific notation, the mass of the proton can be expressed as 1.67×10^{-27} kg. The power of 10 is obtained by counting the number of places the decimal point in the number between 1 and 10 is shifted to the *left* to obtain the small number. The expression 1.67×10^{-27} means $\frac{1.67}{10^{27}}$.

In physics, scientific notation is generally used for numbers less than 0.01 and greater than 1000.

Quantities in scientific notation can be entered into your calculator using the EXP button. For example, to enter 425 000 000 000, you would enter 4.25×10^{11} as:

4.25 EXP 11.

Revision question A1.2

Express the following quantities in scientific notation:

(a) the radius of the Earth, 637 000 m

(b) the speed of light in a vacuum, 300 000 000 m s^{-1}

(c) the diameter of a typical atom, 0.000 000 000 3 m.

Significant figures

There is a degree of uncertainty in any physical measurement. The uncertainty can be due to human error or to the limitations of the measuring instrument.

Before 1964, when the first electronic quartz timing system was used in international events, stopwatches (accurate to the nearest 0.1 s) were used to measure running times. There was no point in having more accurate hand-held stopwatches because the timing was dependent on human judgement and reaction time, a minimum of about 0.1 s. Any measurement of running time by a hand-held timing device has an uncertainty of at least 0.2 s. The International Amateur Athletic Federation now requires that world record times in running events are measured to the nearest one-hundredth of a second.

In 1960, the women's Olympic 100 m sprint was won by Wyomia Tyus (USA) in a time of 11.0 s. In 1984, the same event was won by Evelyn Ashford (USA) in a time of 10.97 s. The 1960 event was not timed electronically. The uncertainty of the measurement of time is indicated by the number of significant figures quoted.

The Wyomia Tyus time of 11.0 s has three significant figures. There would have been no point expressing the time as 11.00 because the nature of the timing device and human judgement and reaction time provide no degree of certainty in the second decimal place. The expression of the time as 11.0 s is consistent with the small degree of uncertainty in the last significant figure. To express the time as 11 s would suggest that the time was measured only to the nearest second.

The Evelyn Ashford time of 10.97 s has four significant figures. This is a reflection of the accuracy of the electronic timing devices and suggests that there could be a small degree of uncertainty in the last figure. The computerised timing systems used today can measure times to the nearest 0.001 s. The last figure quoted in world records therefore has no degree of uncertainty of measurement.

In most physical measurements, the last significant figure shows a small degree of uncertainty. For example, the length of an Olympic competition swimming pool is correctly expressed as 50.00 m. The last zero has a small degree of uncertainty. A pool can still be used for Olympic competition if it is up to 3 cm too long.

Complicated by zeros

Two simple rules can be used to help you decide if zeros are significant.

- Zeros before the decimal point are significant if they are between non-zero digits. For example, all of the zeros in the numbers 4506, 27 034 and 602 007 are significant. The numbers therefore have four, five and six significant figures respectively. The zero in the number 0.56 is not significant.
- Zeros after the decimal point are significant if they follow a non-zero digit. For example, in the number 28.00, the two zeros are significant. The number has four significant figures. However, in the number 0.0028, the two zeros are not significant. They do not follow a non-zero digit and are present only to indicate the position of the decimal point. This number therefore has only two significant figures. The number 0.002 80 has three significant figures.

Sometimes, the number of significant figures in a measured quantity is not clear. For example, a length of 1500 m may have been measured to the nearest metre, the nearest 10 m or even the nearest 100 m. The two zeros are not between non-zero digits. The first rule given above, therefore, suggests that the length of 1500 m has only two significant figures. However, it could have two, three or four significant figures depending on how the length was measured. In order to avoid confusion, quantities such as this can be expressed in scientific notation. The length could then be expressed as 1.500×10^3 m, 1.50×10^3 m or 1.5×10^3 m, giving an indication of the uncertainty.

When scientific notation appears clumsy, as it would for numbers such as 100 or 10, it is generally assumed that the zeros are significant.

Calculating and significant figures

When quantities are multiplied or divided, the result should be expressed in the number of significant figures quoted in the least accurate quantity. For example, if you travelled a distance of 432 m in a car for 25 s, your average speed would be given by:

$$\begin{aligned}\text{average speed} &= \frac{\text{distance travelled}}{\text{time taken}} \\ &= \frac{432\text{ m}}{25\text{ s}} \\ &= 17.28\text{ m s}^{-1}.\end{aligned}$$

The result should be rounded off to two significant figures to reflect the uncertainty in the data used to determine the distance and time, and should be expressed as 17 m s^{-1}.

When quantities are added or subtracted, the result should be expressed to the minimum number of decimal places used in the data. For example, if you travelled three consecutive distances of 63.5 m, 12.2517 m and 32.78 m, the total distance travelled would be given by:

$$\begin{array}{r} 63.5\text{ m} \\ +\ 12.2517\text{ m} \\ +\ 32.78\text{ m} \\ \hline 108.5317\text{ m} \\ \hline \end{array}$$

The result should be rounded off to one decimal place as the minimum number of decimal places used in the data is one in the distance of 63.5 m.

Revision question A1.3

(a) How many significant figures are quoted in each of the following quantities?
- **(i) 566.2 kJ**
- **(ii) 0.000 32 m**
- **(iii) 602.5 kg**
- **(iv) 42.5300 s**
- **(v) 5.6×10^3 W**
- **(vi) 0.008 40 V**

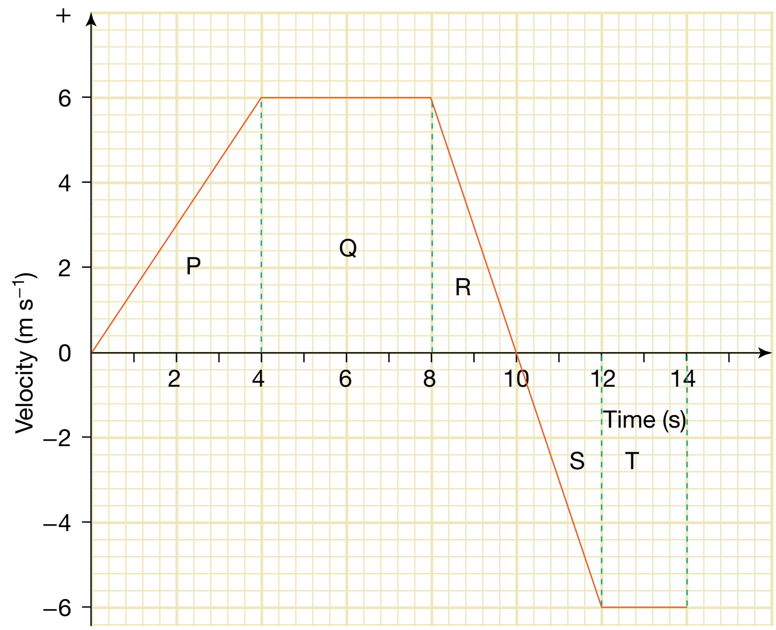
(b) Calculate each of the following quantities and express them to the appropriate number of significant figures:
- **(i) the area of a rectangular netball court that is 30.5 m long and 15.24 m wide**
- **(ii) the perimeter of a soccer pitch that is measured to have a length of 96.3 m and a width of 72.42 m.**

(c) A Commonwealth Games athlete completes one lap of a circular track in a time of 46.52 s. The radius of the track is measured to be 64 m. What is the average speed of the athlete?

Finding the area under a graph

There are several quantities related to forces and movement that need to be determined by calculating the area under a graph.

If the graph consists only of straight line sections, the task is simple. The area can be divided into triangles and rectangles. The areas of these shapes can be added together to determine the total area. The area under the graph in the figure below is found by adding areas P, Q, R, S and T.



It is important to remember each area represents a quantity that has units. The unit of the area under the graph in the figure to the left is the metre because the quantities being multiplied to find the area are m s^{-1} and s.

m $s^{-1} \times$ s = m

Areas under graphs can have direction. The area under the curve in the figure, for the interval from 10 s to 14 s, represents a negative quantity. During this interval, the object is moving in a 'reverse' direction and its displacement (relative to the origin) is decreasing.

The area under the graph in the figure is equal to:

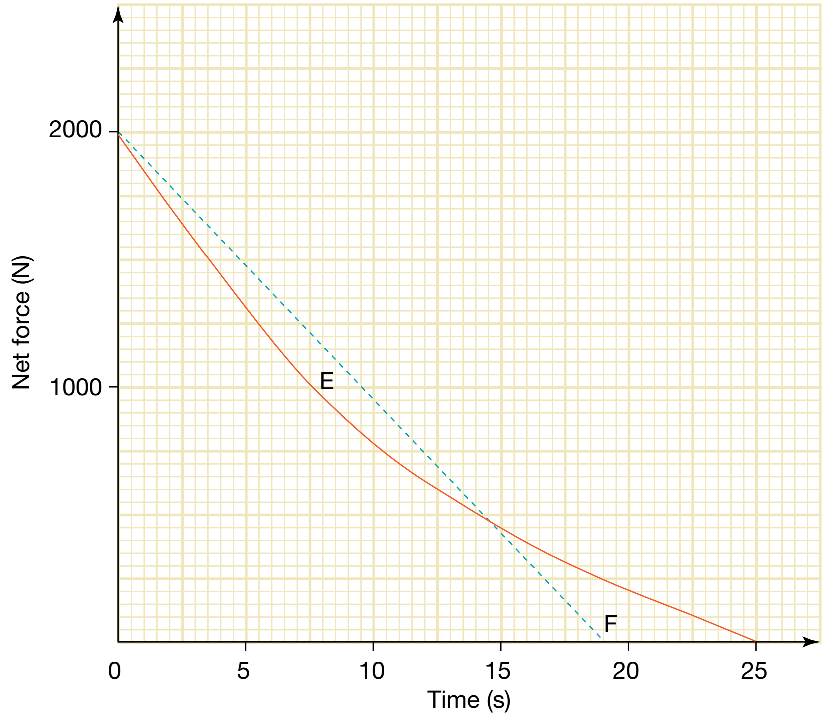
Area P + Area Q + Area R + Area S + Area T

$$= \tfrac{1}{2} \times 4\text{ s} \times 6\text{ m s}^{-1} + 4\text{ s} \times 6\text{ m s}^{-1} + \times 2\text{ s} \times 6\text{ m s}^{-1}$$
$$+ \tfrac{1}{2} \times 2\text{ s} \times -6\text{ m s}^{-1} + 2\text{ s} \times -6\text{ m s}^{-1}$$
$$= 12\text{ m} + 24\text{ m} + 6\text{ m} - 6\text{ m} - 12\text{ m}$$
$$= 24\text{ m}.$$

This area is equal to the displacement of the object during the 14 s time interval.

The figure below shows how the net force on a car changes with time. In this instance, the area under the curve cannot be divided into regular shapes like triangles and rectangles. The area under this curve (which has units of N s) can be estimated by one of the following methods:

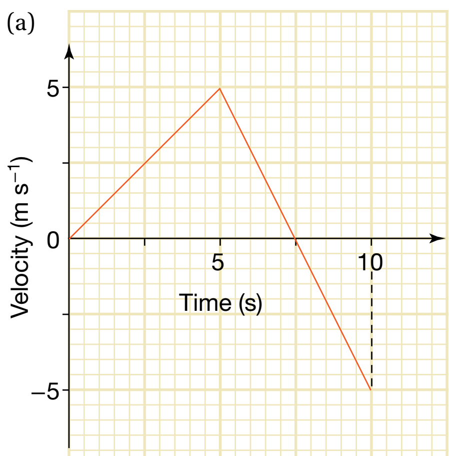
- counting the 'squares' between the curve and the horizontal axis. Find the area of each 'square' and multiply it by the number of squares. In the figure below, each small 'square' represents 25 N s. The number of squares under the graph is approximately 720. The area under the curve is thus estimated as 18 000 N s.
- drawing a regular shape that has the same area as the area under the curve. The area of the regular shape can be found by dividing it into triangles and rectangles. You need to make sure that the regular shape includes as much extra area (E) as it leaves out (F) (see the figure on next page).



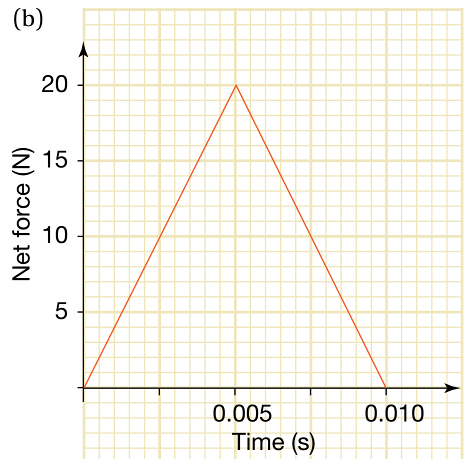
Revision question A1.4

Determine the area under each of the following graphs.

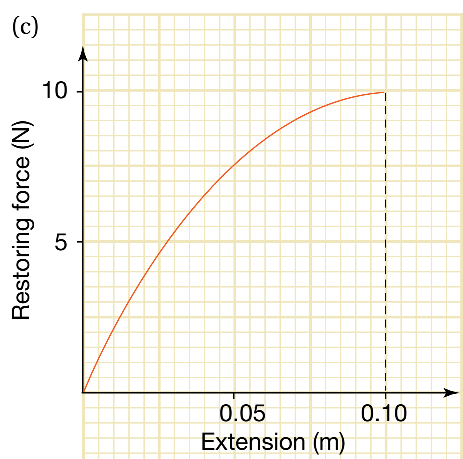
(a)



(b)



(c)



Direct variation

If one quantity is directly proportional to another, a change in one results in a change in the other by the same proportion. Consider, for example, the relationship described by the equation $y \propto x$. This type of relationship is known as a direct variation. The relationship can be written as:

$y = \mathrm{k}x$ where k is a constant of proportionality.

Thus,

$$y_1 = \mathrm{k}x_1$$

$$\text{and } y_2 = \mathrm{k}x_2$$

$\Rightarrow$ When $y \propto x$,

$$\frac{y_2}{y_1} = \frac{\mathrm{k}x_2}{\mathrm{k}x_1}$$

$$\Rightarrow \frac{y_2}{y_1} = \frac{x_2}{x_1}.$$

The ratio $\frac{y}{x}$ is constant. That is, if x is doubled, y doubles. If x is tripled, y triples. If x is halved, y halves.

Many relationships in physics involve direct variation or direct proportion. For example, the power, P, delivered to an electric appliance is directly proportional to the voltage, V, across it and the current, I, passing through it. In symbols:

$P \propto VI$.

If either V or I are doubled, P changes in the same proportion — that is, it doubles. If both V and I are doubled, P changes by a factor of four.

The net force acting on an object is related to the object's acceleration and mass by the equation:

$\boldsymbol{F}_{\text{net}} = m\boldsymbol{a}$.

This is another example of direct variation. The net force is directly proportional to the mass and acceleration of the object. In this case, the constant of proportionality is 1 and has no units.

When one quantity is directly proportional to the reciprocal of another, the relationship is defined as an inverse variation. For example, the electrical resistance R of a length of wire is directly proportional to the reciprocal of the cross-sectional area A of the wire. In symbols:

$$R \propto \frac{1}{A}$$

$\Rightarrow R = \frac{\mathrm{k}}{A}$ where k is a constant of proportionality.

R is said to be inversely proportional to A.

$$\text{If } R_1 = \frac{\mathrm{k}}{A_1}$$

$$\text{and } R_2 = \frac{\mathrm{k}}{A_2}$$

then

$$\mathrm{k} = R_1A_1 = R_2A_2.$$

The product of R and A is constant. If A is doubled, R is halved. If A is tripled, R is divided by three. If A is halved, R doubles.

Revision question A1.5

(a) The power delivered to an electrical device is directly proportional to the voltage across the device and the electric current flowing through the device. If the power delivered to the device is initially 20 W, what will it be if:

- **(i) the voltage is tripled**
- **(ii) the current is doubled**
- **(iii) the voltage and electric current are both tripled**
- **(iv) the voltage is doubled and the current is halved?**

(b) The kinetic energy E_k of an object is directly proportional to the mass m of the object and the square of the speed v of the object. The formula for kinetic energy is:

$$E_k = \frac{1}{2}mv^2.$$

(i) What is the constant of proportionality in this example of direct variation?

(ii) If the speed of an object was tripled, by what factor would its kinetic energy change?

(iii) If an object A has twice as much kinetic energy as an identical object B, what is the value of the following ratio:

$$\frac{\text{speed of object A}}{\text{speed of object B}}?$$

(c) The density ρ of a substance is described by the equation:

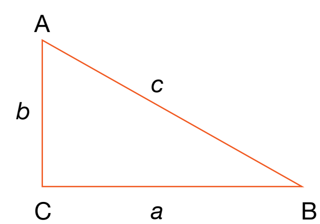
$\rho = \frac{m}{V}$ where m is the mass of the substance and V is its volume.

If a given mass of air with a density of 1.4×10^{-3} g cm^{-3} is compressed so that it occupies one-third of its original volume, what is its new density?

Using trigonometry

Trigonometric ratios can be used to find the sum or difference of vectors and to resolve vectors into components.

In the right-angled triangle ABC shown in the figure at right, the length of one side can be found if the lengths of the other two sides are known by using Pythagoras's theorem. Thus:



$$c^2 = a^2 + b^2.$$

Trigonometric ratios can be used to determine:

- an angle if the lengths of any two sides are known
- the length of an unknown side if one angle and the length of one other side are known.

In the right-angled triangle ABC:

$$\sin B = \frac{b}{c} \qquad \sin A = \frac{a}{c}$$

$$\Rightarrow b = c \sin B \qquad \Rightarrow a = c \sin A$$

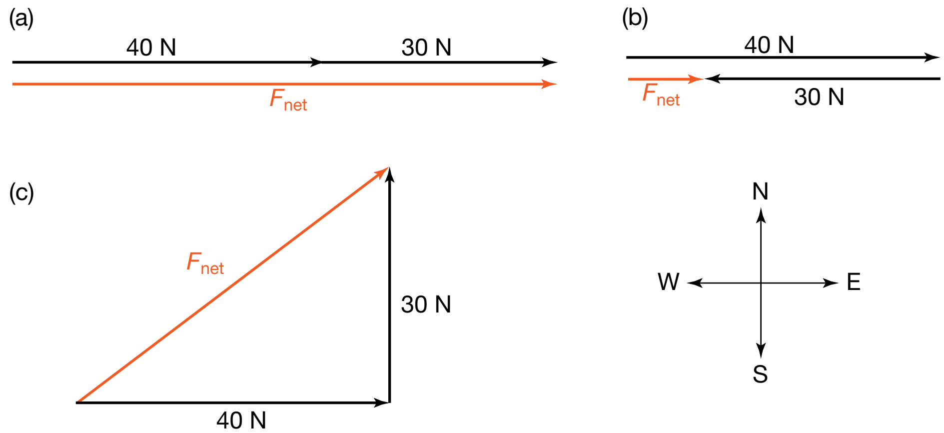
$$\cos B = \frac{a}{c} \qquad \cos A = \frac{b}{c}$$

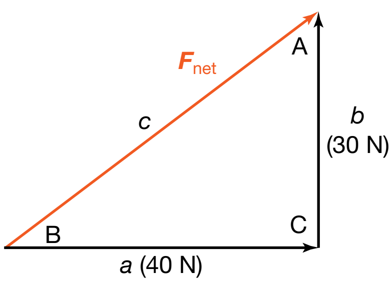
$$\Rightarrow a = c \cos B \qquad \Rightarrow b = c \cos A$$

$$\tan B = \frac{b}{a} \qquad \tan A = \frac{a}{b}$$

Adding vectors

When vector quantities such as forces are added together, direction needs to be taken into account as well as magnitude. The labelled arrows that represent vectors can be used to perform the addition by placing them 'head to tail'. When adding pairs of vectors, the labelled arrows are redrawn so that the 'tail' of the second arrow abuts the 'head' of the first arrow. The sum of the vectors is represented by the arrow drawn between the tail of the first vector and the head of the second. The diagrams on the following page illustrate how this method has been used to determine the net force in the three examples shown. The sum of the vectors (F_{net}) is represented by the brown coloured arrow in each case.





Determining the magnitude of a vector sum

The vectors in the diagrams above have been drawn to scale. That means that the length of the arrow representing the vector sum can be measured. The magnitude of the vector sum can then be calculated. The direction of the vector sum is given by the direction in which the third arrow points. If the vectors have been drawn to scale, the direction can be determined by measuring the appropriate angle with a protractor.

The magnitude of the vector sum can also be determined by using Pythagoras's theorem. The vector addition shown in example (c) above results in a right-angled triangle. The arrow representing the vector sum makes up the hypotenuse of a right-angled triangle, illustrated in the figure at left. The magnitude that it represents is given by:

$$c^2 = a^2 + b^2$$
$$= (40)^2 + (30)^2$$
$$= 2500 \quad \text{(calculating the sum of the squares of both sides)}$$
$$\Rightarrow c = 50 \text{ N.} \quad \text{(taking the positive square root of the sum of the squares)}$$

The direction of the net force can be found using trigonometric ratios.

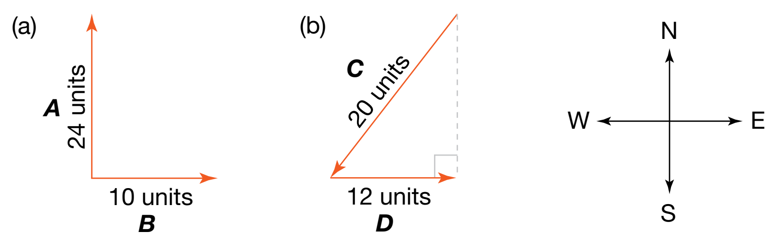
$$\tan \text{B} = \frac{30}{40}$$
$$= 0.75$$
$$\text{B} = 37°$$

The vector sum, and net force, is 50 N at an angle of N53°E (53° clockwise from north).

You will get the same result no matter in which order you add the vectors.

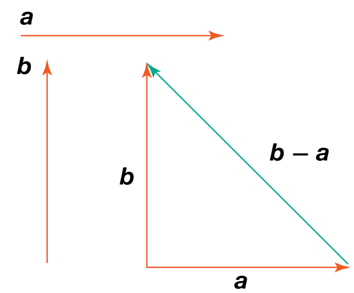
Revision question A1.6

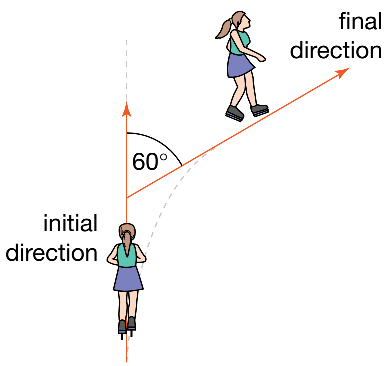
Find the sum of each of the pairs of vectors shown in (a) and (b) below.



Subtracting vectors

One vector can be subtracted from another simply by adding its negative. This technique is used in the 'As a matter of fact' box on page 167. It works because subtracting a vector is the same as adding the negative vector (just as subtracting a positive number is the same as adding the negative of that number). Another way to *subtract* vectors is to place them tail to tail as in the figure on the right. The difference between the vectors ***a*** and ***b*** (***b*** – ***a***) is given by the vector that begins at the head of vector ***a*** and ends at the head of vector ***b***.



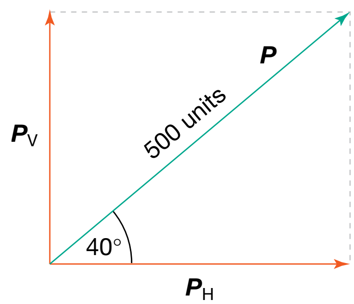


Revision question A1.7

An ice-skater moving at 20 m s^{-1} turns right through an angle of 60° as shown in the figure on the left while maintaining the same speed. What is the magnitude of her change in velocity?

Finding vector components

The magnitude of vector components can be determined using trigonometric ratios. The vector ***P*** in the figure at right can be resolved into vertical and horizontal components.

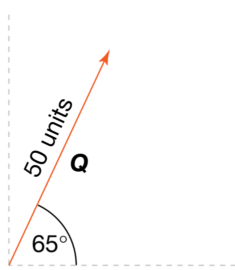


The magnitude of the horizontal component, labelled $\boldsymbol{P}_\mathrm{H}$, is given by:

$$P_\mathrm{H} = P\cos 40° \quad (\text{since } \cos 40° = \frac{P_\mathrm{H}}{P})$$
$$\Rightarrow P_\mathrm{H} = 500 \text{ units} \times 0.7660$$
$$= 383 \text{ units.}$$

The magnitude of the vertical component, labelled as $\boldsymbol{P}_\mathrm{V}$, is given by

$$P_\mathrm{V} = P\sin 40° \quad (\text{since } \sin 40° = \frac{P_\mathrm{V}}{P})$$
$$\Rightarrow P_\mathrm{V} = 500 \text{ units} \times 0.6428$$
$$= 321 \text{ units.}$$



Revision question A1.8

Determine the magnitude of the horizontal component and vertical component of the vector *Q* in the figure on the left.

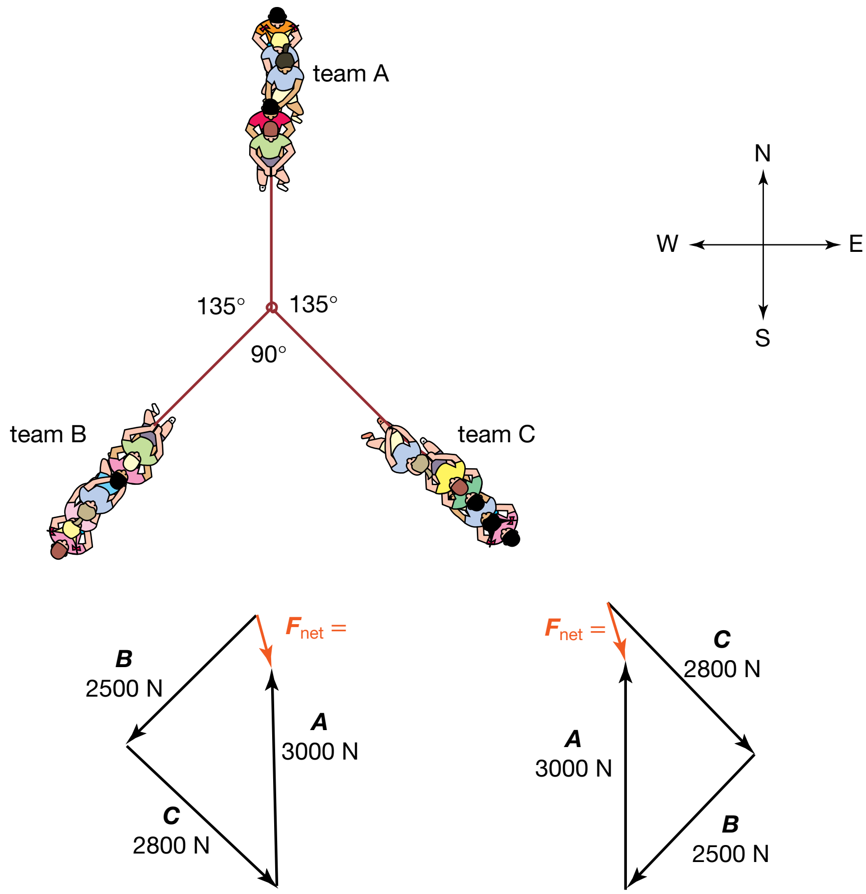
Adding three or more vectors

When three or more vectors are to be added together, they can be drawn to scale and placed 'head to tail' in any order. The sum of the vectors is represented by the arrow drawn between the tail of the first vector and the head of the last vector added.

Sample problem A1.1

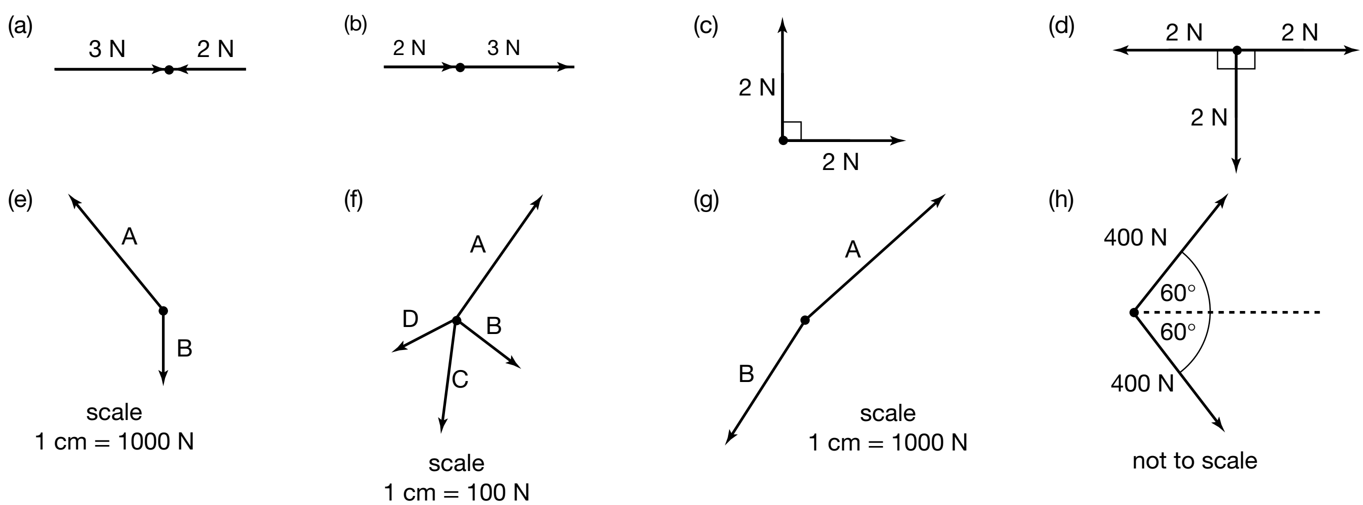
In a three-way 'tug of war', three teams (A, B and C) pull horizontally away from the knot joining the ropes with forces of 3000 N north, 2500 N south-west and 2800 N south-east respectively. Determine the net horizontal force exerted on the knot.

Solution: The figure below shows a diagram of the tug of war and two different ways of determining the net force on the knot. The order of adding the three vectors is not important as long as the magnitude and direction of each vector is not changed. The net force is 800 N in a direction 15° east of south.



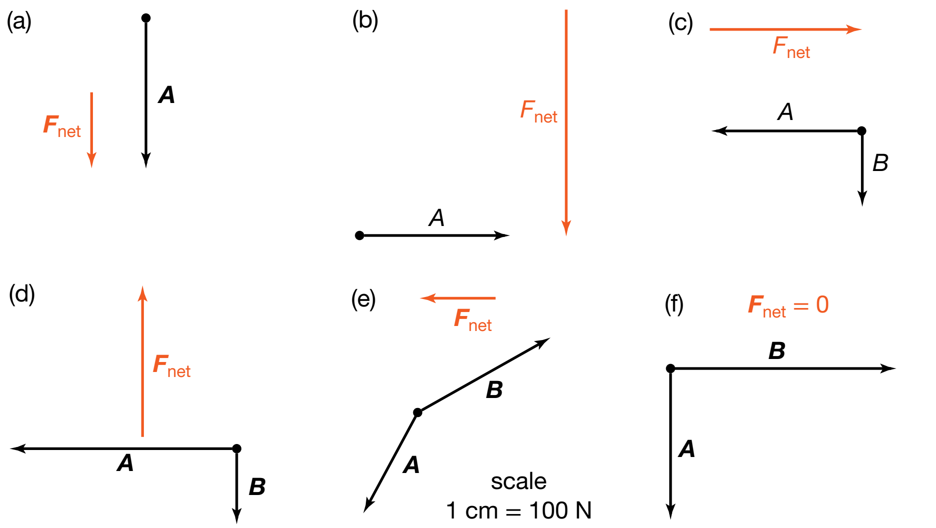
Revision question A1.9

Determine the net force in each of the situations illustrated in (a) to (h).



Revision question A1.10

In each of the illustrations below, the net force is shown along with all but one of the contributing forces. Use a vector diagram to determine the magnitude and direction of the missing force.



Appendix 2 PERIODIC TABLE OF THE ELEMENTS

Key

			Key
Period 1	1 Hydrogen **H** **1.0**	2 Helium **He** **4.0**	Atomic number Name Symbol Relative atomic mass

	Group 1 **Alkali metals**	Group 2 **Alkaline earth metals**	Group 3	Group 4	Group 5	Group 6	Group 7	Group 8	Group 9
			Transition metals						
Period 2	3 Lithium **Li** **6.9**	4 Beryllium **Be** **9.0**							
Period 3	11 Sodium **Na** **23.0**	12 Magnesium **Mg** **24.3**							
Period 4	19 Potassium **K** **39.1**	20 Calcium **Ca** **40.1**	21 Scandium **Sc** **45.0**	22 Titanium **Ti** **47.9**	23 Vanadium **V** **50.9**	24 Chromium **Cr** **52.0**	25 Manganese **Mn** **54.9**	26 Iron **Fe** **55.8**	27 Cobalt **Co** **58.9**
Period 5	37 Rubidium **Rb** **85.5**	38 Strontium **Sr** **87.6**	39 Yttrium **Y** **88.9**	40 Zirconium **Zr** **91.2**	41 Niobium **Nb** **92.9**	42 Molybdenum **Mo** **96.0**	43 Technetium **Tc** **(98)**	44 Ruthenium **Ru** **101.1**	45 Rhodium **Rh** **102.9**
Period 6	55 Caesium **Cs** **132.9**	56 Barium **Ba** **137.3**	57–71 Lanthanoids	72 Hafnium **Hf** **178.5**	73 Tantalum **Ta** **180.9**	74 Tungsten **W** **183.8**	75 Rhenium **Re** **186.2**	76 Osmium **Os** **190.2**	77 Iridium **Ir** **192.2**
Period 7	87 Francium **Fr** **(223)**	88 Radium **Ra** **(226)**	89–103 Actinoids	104 Rutherfordium **Rf** **(261)**	105 Dubnium **Db** **(262)**	106 Seaborgium **Sg** **(266)**	107 Bohrium **Bh** **(264)**	108 Hassium **Hs** **(267)**	109 Meitnerium **Mt** **(268)**

Lanthanoids

57 Lanthanum **La** **138.9**	58 Cerium **Ce** **140.1**	59 Praseodymium **Pr** **140.9**	60 Neodymium **Nd** **144.2**	61 Promethium **Pm** **(145)**	62 Samarium **Sm** **150.4**	63 Europium **Eu** **152.0**

Actinoids

89 Actinium **Ac** **(227)**	90 Thorium **Th** **232.0**	91 Protactinium **Pa** **231.0**	92 Uranium **U** **238.0**	93 Neptunium **Np** **(237)**	94 Plutonium **Pu** **(244)**	95 Americium **Am** **(243)**

Non-metals → (boundary line between Group 13 and Group 14)

Halogens ↓ Group 17 | Noble gases ↓ Group 18

Group 10	Group 11	Group 12	Group 13	Group 14	Group 15	Group 16	Group 17	Group 18
			5 Boron **B** **10.8**	6 Carbon **C** **12.0**	7 Nitrogen **N** **14.0**	8 Oxygen **O** **16.0**	9 Fluorine **F** **19.0**	10 Neon **Ne** **20.2**
			13 Aluminium **Al** **27.0**	14 Silicon **Si** **28.1**	15 Phosphorus **P** **31.0**	16 Sulfur **S** **32.1**	17 Chlorine **Cl** **35.5**	18 Argon **Ar** **39.9**
28 Nickel **Ni** **58.7**	29 Copper **Cu** **63.5**	30 Zinc **Zn** **65.4**	31 Gallium **Ga** **69.7**	32 Germanium **Ge** **72.6**	33 Arsenic **As** **74.9**	34 Selenium **Se** **79.0**	35 Bromine **Br** **79.9**	36 Krypton **Kr** **83.8**
46 Palladium **Pd** **106.4**	47 Silver **Ag** **107.9**	48 Cadmium **Cd** **112.4**	49 Indium **In** **114.8**	50 Tin **Sn** **118.7**	51 Antimony **Sb** **121.8**	52 Tellurium **Te** **127.6**	53 Iodine **I** **126.9**	54 Xenon **Xe** **131.3**
78 Platinum **Pt** **195.1**	79 Gold **Au** **197.0**	80 Mercury **Hg** **200.6**	81 Thallium **Tl** **204.4**	82 Lead **Pb** **207.2**	83 Bismuth **Bi** **209.0**	84 Polonium **Po** **(210)**	85 Astatine **At** **(210)**	86 Radon **Rn** **(222)**
110 Darmstadtium **Ds** **(271)**	111 Roentgenium **Rg** **(272)**	112 Copernicium **Cn** **(285)**		114 Flerovium **Fl** **(289)**	**Metals** ←	116 Livermorium **Lv** **(292)**		

64 Gadolinium **Gd** **157.3**	65 Terbium **Tb** **158.9**	66 Dysprosium **Dy** **162.5**	67 Holmium **Ho** **164.9**	68 Erbium **Er** **167.3**	69 Thulium **Tm** **168.9**	70 Ytterbium **Yb** **173.1**	71 Lutetium **Lu** **175.0**
96 Curium **Cm** **(247)**	97 Berkelium **Bk** **(247)**	98 Californium **Cf** **(251)**	99 Einsteinium **Es** **(252)**	100 Fermium **Fm** **(257)**	101 Mendelevium **Md** **(258)**	102 Nobelium **No** **(259)**	103 Lawrencium **Lr** **(262)**

Appendix 3 SOME USEFUL ASTRONOMICAL DATA

	Mean radius of orbit (au)	Mean radius of orbit (km)	Orbital period (years)	Equatorial radius (km)	Mass (kg)
Sun				6.95×10^{5}	1.99×10^{30}
Mercury	0.387	5.79×10^{7}	0.241	2.44×10^{3}	3.30×10^{23}
Venus	0.723	1.08×10^{8}	0.615	6.05×10^{3}	4.87×10^{24}
Earth	1.00	1.50×10^{8}	1.00	6.37×10^{3}	5.98×10^{24}
Moon	2.57×10^{-3}	3.84×10^{5}	27.32 days	1.74×10^{3}	7.35×10^{22}
Mars	1.52	2.28×10^{8}	1.88	3.40×10^{3}	6.42×10^{23}
Jupiter	5.20	7.78×10^{8}	11.9	7.15×10^{4}	1.90×10^{27}
Saturn	9.58	1.43×10^{9}	29.7	6.03×10^{4}	5.68×10^{26}
Titan	8.20×10^{-3}	1.22×10^{6}	15.9 days	2.58×10^{3}	1.35×10^{23}
Uranus	19.2	2.87×10^{9}	84.6	2.56×10^{4}	8.68×10^{25}
Neptune	30.1	4.50×10^{9}	166	2.48×10^{4}	1.02×10^{26}
Pluto	39.48	5.91×10^{9}	248	1.15×10^{3}	1.29×10^{22}

Alpha Centauri	4.37 light-years away
The Milky Way	1.50×10^{5} light-years across
Andromeda	2.30×10^{6} light-years away
Edge of observable universe	4.65×10^{10} light-years away

Source: Data derived from www.jpl.nasa.gov

Glossary

A

acceleration: the rate of change of velocity
active wire: a circuit wire connected to the 230 V rms supply at the switchboard
air resistance: the force applied to an object, opposite to its direction of motion, by the air through which it is moving
α particle: a relatively slow-moving decay product consisting of two protons and two neutrons. It is equivalent to a helium nucleus and so can be written as $^{4}_{2}He$. α particles carry a positive charge.
alternating current: (AC), refers to circuits where the charge carriers move backwards and forwards periodically
ammeter: a device used to measure current
ampere: (A), the unit of current
atomic number: the number of protons in the nucleus of an atom

B

baryons: hadrons with three quarks
battery: composed of two or more electrical cells in series in a single unit
big bang: the name for the dramatic beginning of the universe from an infinitely dense, small point
binding energy: the energy that is required to split a nucleus into individual nucleons

C

centre of mass: the centre of mass of an object is the point at which all of its mass can be considered to be
charge carrier: a charged particle moving in a conductor
circuit: an electric circuit is a closed loop of moving electric charge
circuit breaker: a device that carries out the same function as a fuse by breaking the circuit when the current through it exceeds a certain value
components: parts. any vector can be resolved into a number of components. When all of the components are added together, the result is the original vector
conduction: the transfer of heat through a substance as a result of collisions between neighbouring vibrating particles
conductor: the wire connecting the elements in an electric circuit
continuous variables: variables that take a numerical value. They can be represented by line graphs.
convection: the transfer of heat in a fluid (a liquid or gas) as a result of the movement of particles within the fluid
convection current: a movement of particles during the transfer of heat through a substance
conventional current: the movement of positive charges from the positive terminal of a cell through the conductor to the negative terminal
cosmic rays: very energetic charged particles that enter our atmosphere. They are mainly protons and originate from beyond the solar system.
cosmology: the study of how the universe began, has evolved and will end
coulomb: (C), the unit of electric charge

D

daughter nucleus: the nucleus remaining after an atom undergoes radioactive decay. The daughter nucleus is more stable than the original nucleus.
decay chain: also known as a decay series; the sequence of stages a radioisotope passes through to become more stable. At each stage, a more stable isotope forms. The chain ends when a stable isotope forms.
decay curve: a graph of the number of nuclei remaining in a substance versus time elapsed. The half-life of a substance can be determined by looking at the time that corresponds to half of the substance remaining.
decay equation: a representation of a decay reaction. It shows the changes occurring in nuclei and lists the products of the decay reaction.
dependent variables: variables that are determined by independent variables
diode: a device that allows current to pass through it in one direction
direct current: (DC), refers to circuits where the net flow of charge is in one direction only
discrete variables: variables that include different categories, such as colour. They can be represented only with column graphs, not line graphs.

displacement: a measure of the change in position of an object. It is a vector quantity.

distance: a measure of the length of the path taken by an object. It is a scalar quantity.

E

earth wire: wire used in power circuits as a safety device; it connects the case of the appliance being used to the earth

electric cell: supplies energy to a circuit from chemical reactions; it can be modelled by a motor with a supply of fuel

electric charge: a basic property of matter. It occurs in two states; positive (+) charge and negative (–) charge.

electric current: the movement of charged particles from one place to another

electric insulator: a material in which the electrons are bound tightly to the nucleus and are not free to travel through the material

electric shock: a violent disturbance of the nervous system caused by an electrical discharge or current through the body

electrocution: death brought about by an electrical shock

electromagnetic spectrum: the full range of wavelengths of all electromagnetic waves

electromotive force: a measure of the energy supplied to a circuit for each coulomb of charge passing through the power supply

electron: a negatively charged particle found around the nucleus of an atom

electron current: the term used when dealing with the mechanisms for the movement of electrons

electrostatic force: the force between two stationary charged objects

element: a substance that consists only of atoms of the same name

excited nucleus: a nucleus that does not have an ideal arrangement of protons and neutrons. An excited nucleus emits γ radiation to become more stable.

F

fibrillation: the disorganised, rapid contraction of separate parts of the heart so that it pumps no blood; death may follow

First Law of Thermodynamics: $\Delta U = Q - W$ or $Q = U + W$, where Q is the heat energy in joules, W is the work done in joules and U is the internal energy in joules

fission fragments: the products from a nucleus that undergoes fission. The fission fragments are smaller than the original nucleus.

force: a push or a pull. Force is a vector quantity.

frequency: a measure of how many times per second an event happens

friction: the force applied to the surface of an object when it is pushed or pulled against the surface of another object

fuse: a short length of conducting wire or strip of metal that melts when the current through it reaches a certain value, breaking the circuit

G

γ ray: the packet of electromagnetic energy released when a nucleus remains unstable after α or β decay. γ rays travel at the speed of light and carry no charge.

globular cluster: a very old, densely packed cluster of stars in the shape of a sphere

gravitational field strength: ($\boldsymbol{g}$), the force of gravity on a unit of mass

gravitational potential energy: the energy stored in an object as a result of its position relative to another object to which it is attracted by the force of gravity

H

hadrons: composite particles made up of either two or three quarks

half-life: the time taken for half of a group of unstable nuclei to decay

Hubble's constant: the constant of proportionality relating the speed that galaxies are receding from Earth and their distance from Earth

Hubble's Law: states that the speed of recession of galaxies is proportional to their distance from Earth

I

idealisation: an idealisation makes modelling a phenomenon or event easier by assuming ideal conditions that don't exactly match the real situation

impulse: the impulse of a force is the product of the force and the time interval over which it acts. Impulse is a vector quantity.

independent variables: variables that are changed in an investigation to observe their effect on another variable

instantaneous speed: the speed at a particular instant of time

instantaneous velocity: the velocity at a particular instant of time

insulators: materials that are poor conductors of heat

ion: a charged particle

isotopes: isotopes of an element are atoms containing the same number of protons but different numbers of neutrons

J

joule: (J), the SI unit of work or energy. One joule is the energy expended when a force of 1 newton acts through a distance of 1 metre.

K

kilowatt-hour: (kW-h), the amount of energy transformed by a 1000 W appliance when used for 1 hour

kinetic energy: the energy associated with the movement of an object. Like all forms of energy, kinetic energy is a scalar quantity

L

latent heat: the heat added to a substance undergoing a change of state that does not increase the temperature

leptons: the simplest and lightest of the subatomic particles. They are fundamental particles with no internal structure.

light-dependent resistor (LDR): a device that has a resistance which varies with the amount of light falling on it

light-emitting diode (LED): a small semiconductor diode that emits light when a current passes through it

load: a device where electrical energy is converted into other forms to perform tasks such as heating or lighting

M

mass number: the total number of nucleons in an atom

mechanical interaction: an interaction in which energy is transferred from one object to another by the action of a force

mesons: hadrons with two quarks

model: uses objects and phenomena that we can see and understand or have experienced to explain things that we cannot see

momentum: the product of the mass of an object and its velocity. It is a vector quantity.

N

negligible: a quantity that is negligible is so small that it can be ignored when modelling a phenomenon or an event

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

neutral: a neutral object carries an equal amount of positive and negative charge

neutral wire: in a circuit, the wire connected to the neutral link at the switchboard, which is connected to the earth

neutron: a nucleon with no charge

non-ohmic device: a device for which the resistance is different for different currents passing through it

normal reaction force: a force that acts perpendicularly to a surface as a result of an object applying a force to the surface

nuclear fission: the process of splitting a large nucleus to form two smaller, more stable nuclei

nuclear fusion: the process of joining together two nuclei to form a larger, more stable nucleus

nucleon: the collective name for the particles found in the nucleus of an atom

nucleus: the solid centre of an atom. Most of the mass of an atom is concentrated in the nucleus.

O

ohmic device: a device for which, under constant physical conditions such as temperature, the resistance is constant for all currents that pass through it

P

parallel: devices connected in parallel are joined together so that one end of each device is joined at a common point and the other end of each device is joined at another common point

period: the amount of time one cycle or event takes, measured in seconds

positron: a positively charged particle with the same mass as an electron

potential difference: the amount of electrical potential energy, in joules, lost by each coulomb of charge in a given part of a circuit

power: the rate of doing work, or the rate at which energy is transformed from one form to another

proton: a positively charged particle in the nucleus of an atom

Q

quarks: fundamental particles that combine to form hadrons

R

radiation: heat transfer without the presence of particles

radioisotope: an unstable isotope

red shift: the increase in wavelength that results from a light source moving away from the observer

residual current device: a device that operates by making use of the magnetic effects of a current to break a circuit in the event of an electrical fault

resistance: the resistance, R, of a substance is defined as the ratio of voltage drop, V, across it to the current, I, flowing through it

resistor: used to control the current flowing through, and the voltage drop across, parts of a circuit

S

scalar: quantities that specify magnitude (size) but not direction

series: devices connected in series are joined together one after the other

short circuit: can occur when frayed electrical cords or faulty appliances allow the current to flow from one conductor to another with little or no resistance. The current increases rapidly, causing the wires to get hot and potentially cause a fire.

specific latent heat of fusion: the quantity of energy required to change 1 kilogram of a substance from a solid to a liquid without a change in temperature

specific latent heat of vaporisation: the quantity of energy required to change 1 kilogram of a substance from a liquid to a gas without a change in temperature

speed: a measure of the rate at which an object moves over a distance. Speed is a scalar quantity.

strain potential energy: the energy stored in an object as a result of a reversible change in shape. It is also known as elastic potential energy.

strong nuclear force: the force that holds nucleons together in a nucleus of an atom. It acts over only very short distances

switch: stops or allows the flow of electricity through a circuit

synchrotron radiation: the electromagnetic radiation produced when electric charges are accelerated

T

temperature: a measure of the average translational kinetic energy of particles

thermal equilibrium: occurs when the temperature of two regions is uniform

thermistor: a device that has a resistance which changes with a change in temperature

V

vector: a vector quantity specifies direction as well as magnitude (size)

velocity: a measure of the time rate of displacement, or the time rate of change in position. Velocity is a vector quantity.

voltage divider: a device used to reduce, or divide, a voltage to a value needed for a part of the circuit

voltage drop: *see* potential difference

voltmeter: a device used to measure potential difference

W

weak nuclear force: the force that explains the transformation of neutrons into protons and vice versa

weight: the force applied to an object due to gravitational attraction

work: when energy is transferred to or from an object by the action of a force. Work is a scalar quantity.

Answers to numerical questions

eBookplus

Digital documents
Fully worked solutions and answers to all questions can be found in the Resources section of your eBookPLUS.

Chapter 1

Page 10
1.2. (a) 194.7 K
(b) −16 °C to −107 °C

Page 13
1.3. $W = -100$ J, $\Delta U = 100$ J

Page 15
1.4. 3500m J, where m is your mass in kg

Review questions
12. (a) $Q = 500$ J, $\Delta U = 500$ J, increase
(b) $Q = -250$ J, $W = -250$ J, $\Delta U = 0$, no change
(c) $Q = 0$ J, $W = -150$ J, $\Delta U = 150$ J, increase
(d) $Q = 0$ J, $W = -5$ J, $\Delta U = 5$ J, increase
17.

	A	B	C
Heat (+ is in)	0	+	+
Work (+ is out)	–	0	+
ΔU	+	+	+

18. (a) Cooking oil
(b) Ethylene glycol
19. (a) 400 kJ (b) 1200 kJ
21. 68 °C
22. 1.15×10^6 J
23. (a) 230 °C
(c) Liquid
(d) 160 kJ kg^{-1}
24. 6.1 MJ
25. 8.2 kg

Chapter 2

Page 27
2.1. 1.413×10^{27} W

Page 28
2.2. 6400 K

Review questions
6. 3×10^8 m s^{-1}, the speed of light
14. (a) 0.012 W
(b) 100 – 27 = 73 W
(c) 3300 K
15. (a) 12.8 times
(b) 1066 °C
16. 9.5×10^{-7} m or 950 nm
17. 5690 K
18. 1.0×10^{-5} m
19. (a) 9.4×10^{-6} m
(b) Far infrared
20. (a) 7250 K (b) 4140 K
21. (b) (i) 7500 K
(ii) 10 500 K
(c) (i) 0.4 μm
(ii) 0.52 μm
22. (a) 16 times
(b) The wavelength would be halved.
23. The colours of the stars are blue and infrared; the blue star is 16 times brighter.

Chapter 3

Page 36
3.1. (a) (i) 12–19 μm
(ii) 5–8 μm, 15–100 μm
(b) 12–15 μm

Page 37
3.2. (a) Lighter
(b) The molecule with carbon-12; being faster, it will more easily penetrate the surface.

Page 39
3.4. 30 W m^{-2} and 67 W m^{-2}
3.5. (a) (i) 0.02–0.06
(ii) 0.2–0.3
(iii) 0.1–0.2
(b) Methane: positive, clouds: negative

Page 41
3.7. (a) (i) Decrease the temperature
(b) (i) 1905–1915, 1935–1945
(c) 3. 1960–1965
(d) (i) Liquid oceans; high heat capacity means less volatile temperatures.

Review questions
22. 2.2×10^7 sq m
24. Water: 0.5 °C, sand: 2000 °C

Chapter 4

Page 52
4.1. 5.0 A
4.2. 3.0 s

Page 54
4.3. 14 800 J

Page 56
4.4. 12 V

Page 57
4.5. 0.60 W

Page 58
4.6. 0.175 A

Page 65
4.7. (a) 2.5 A
(b) 96 Ω

Review questions
5. 37.5 C
6. 0.045 A
7. 0.23 mA
8. 4.5×10^{-4} A
10. 4.2×10^3 C
11. 0.30 A
12. 8.0×10^{-5} m s^{-1}
13. 1.5 V
14. *(from top to bottom)*: 3.3 V, 6.0 V, 31.5 J, 1.02 J, 2.7 C, 31.3 C
15. 3.4×10^{-5} J
16. 6.0×10^{-5} C, 60 μC
17. (a) 0.25 A
(b) 3.3 A
(c) 1.05 A
(d) 5.0 A
18. (a) Each coulomb of charge transforms 240 J.
(b) 6.0×10^3 J
19. 4.3×10^4 J
20. 24 W
21. 90 s
22. 2.4 kW
23. 40.4 s
24. 1.5 V
25. 1080 J or 1.08×10^3 J
26. *(from top to bottom)*: 32 V, 48.4 V, 2.0 A, 3.0×10^{-3} A or 3.0 mA, 1.5 W, 33.3 W
27. (a) 39 ± 2 Ω
(b) 56 000 ± 5600 Ω
(c) 750 ± 37.5 kΩ
28. (b) 0
(c) ∞ (infinity)
(d) 32.5 Ω

29. 0.45 W
30. (a) 960 Ω
(b) 5.7 Ω
(c) 3.6 Ω
31. 1200 W
32. (a) (i) 5.0 kΩ
(ii) 1.0 kΩ
(b) (i) 25 °C
(ii) 50 °C
33. (a) 5000 Ω
(b) 200 °C

Chapter 5

Page 73
5.1. 13.9 kΩ

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5.2. 960 Ω

Page 78
5.3. 5.0 A

Page 79
5.4. 710 Ω

Page 81
5.5. Fixed resistor, 2.5 kΩ

Review questions
2. (a) 1.5 A away from junction
(b) 4.5 A into junction
(c) 1.1 A into junction
3. $V_a = 9.0$ V, $V_b = 9.0$ V, $V_c = 4.0$ V, $V_d = 0.0$ V
4. (a) 12.5 Ω
(b) 62 Ω
(c) 15.4 kΩ
5. $I_a = 1.0$ A, $V_1 = 4.0$ V, $V_2 = 2.0$ V, $R_2 = 2.0$ Ω
6. (a) 2.0 A
(b) 60 V
(c) 10 Ω
(d) 40 Ω
(e) 80 V
7. (a) 50 Ω
(b) 2.0 A
(c) 20 Ω, 40 V; 30 Ω, 60 V
8. (a) 12 Ω
(b) 1.0 A
(c) 3.0 Ω, 3.0 V; 5.0 Ω, 5.0 V; 4.0 Ω, 4.0 V
(d) 12 V
9. (a) 0.010 A
(b) First person, 10 V; second person, 15 V
10. (a) 12 Ω
(b) 3.0 Ω
(c) 10 Ω
(d) 12.1 Ω
11. $I_a = 1.5$ A, $V_1 = 6.0$ V, $V_2 = 6.0$ V, $I_1 = 1.0$ A, $I_2 = 0.5$ A, $R_2 = 12$ Ω
12. (a) 12 V
(b) 12 V
(c) 12 V
(d) 0.30 A
(e) 40 Ω
13. (a) 5.0 Ω
(b) 3.0 A
(c) 1.5 A
14. (a) 10 Ω
(b) 9.0 A
(c) 60 Ω, 1.5 A; 30 Ω, 3.0 A; 20 Ω, 4.5 A
15. (a) 6.0 Ω, 6.0 A; 18 Ω, 2.0 A; 9.0 Ω, 4.0 A
(b) 12 A
(c) 3.0 Ω
16. (a) G_1, G_2, G_3
(b) G_1, G_3
(c) G_1
18. (a) 6 mA
(b) 140 V
(c) 8.75 kΩ
19. (a) 30 V
(b) 6.0 mA
(c) 100 V
(d) 130 V
20. (a) 100 V
(b) 100 V
(c) 6 mA
(d) 26 mA
21. (a) 0.20 A
(b) 25 Ω, 5.0 V; 15 Ω, 3.0 V; 10 Ω, 2.0 V
(c) 25 Ω, 1.0 W; 15 Ω, 0.6 W; 10 Ω, 0.4 W
(d) 2.0 W
22. (a) 2.1 A
(b) 10 V across each resistor
(c) 25 Ω, 4.0 W; 15 Ω, 6.7 W; 10 Ω, 10 W
(d) 21.7 W
26. (a) 20 Ω
(b) 5 Ω
27. (a) 400 Ω
(b) 5000 Ω
28. (a) 3.0 V
(b) 3.0 V
29. 1.5 kΩ
30. (a) 4.0 V
(b) 3.0 V
(c) 16 V
32. (a) 6.0 kΩ
(b) 660 Ω
(c) 3.3 kΩ
(d) 2.5 kΩ

Chapter 6

Page 90
6.1. (a) 65 mA
(b) 3.5 kΩ

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6.2. (a) 10 mA
(b) 1.45 MJ
(c) $48.38

Page 96
6.3. (a) 0.76 A (or 0.8 A to 1 significant figure)
(b) 1.63 A
(c) 3.4 A

Review questions
7. $215
8. (a) 4.3 A
(b) 53 Ω
(c) $0.85
9. (b) 382 kg CO_2

Chapter 7

Page 103
7.1. (a) 1 and 1
(b) 95 and 146
(c) 63 and 89

Page 105
7.2. (a) ${}^{241}_{95}\text{Am} \rightarrow {}^{237}_{93}\text{Np} + {}^{4}_{2}\text{He}$
(b) ${}^{197}_{78}\text{Pt} \rightarrow {}^{197}_{79}\text{Au} + {}^{0}_{-1}\text{e}$
(c) ${}^{23}_{12}\text{Mg} \rightarrow {}^{23}_{11}\text{Na} + {}^{0}_{+1}\text{e}$

Page 108
7.3. 21 years

Page 116
7.4. Ba + Kr:
(a) 166.745 851 MeV
(b) $2.972\,280 \times 10^{-28}$ kg
(c) $2.675\,052 \times 10^{-11}$ J, 166.963 679 MeV
Xe + Sr:
(a) −178.136 720 MeV
(b) $0.003\,176\,52 \times 10^{-25}$ kg
(c) $2.858\,868 \times 10^{-11}$ J, 178.436 576 MeV

Review questions
1. (a) 30 protons, 36 neutrons,
(b) 90 protons, 140 neutrons
(c) 20 protons, 25 neutrons
(d) 14 protons, 17 neutrons
2. (a) ${}^{4}_{2}\text{He}$
(b) ${}^{13}_{7}\text{N}$
(c) ${}^{234}_{91}\text{Pa}$
3. (a) Gold: 79 protons, 118 neutrons
(b) Bismuth: 83 protons, 127 neutrons
(c) Lead: 82 protons, 128 neutrons
6. (a) β–
(b) β–
(c) α
7. (a) ${}^{226}_{86}\text{Ra} \rightarrow {}^{4}_{2}\alpha + {}^{222}_{86}\text{Rn} + \text{energy}$
(b) ${}^{214}_{84}\text{Po} \rightarrow {}^{4}_{2}\alpha + {}^{210}_{82}\text{Pb} + \text{energy}$
(c) ${}^{291}_{95}\text{Am} \rightarrow {}^{4}_{2}\alpha + {}^{237}_{93}\text{Np} + \text{energy}$
8. (a) ${}^{60}_{27}\text{Co} \rightarrow {}^{0}_{-1}\text{e} + {}^{60}_{28}\text{Ni} + \text{energy}$
(b) ${}^{90}_{38}\text{Sr} \rightarrow {}^{0}_{-1}\text{e} + {}^{90}_{39}\text{Y} + \text{energy}$
(c) ${}^{32}_{15}\text{P} \rightarrow {}^{0}_{-1}\text{e} + {}^{32}_{16}\text{S} + \text{energy}$

9. ${}^{24}_{12}\text{Mg}^* \rightarrow \gamma + {}^{24}_{12}\text{Mg}$

10. (a) ${}^{Z}_{A}\text{X} \rightarrow {}^{4}_{2}\alpha + {}^{Z-4}_{A-2}\text{D} + \text{energy}$

(b) ${}^{Z}_{A}\text{X} \rightarrow {}^{0}_{-1}\text{e} + {}^{Z}_{A+1}\text{E} + \text{energy}$

(c) ${}^{Z}_{A}\text{X}^* \rightarrow {}^{Z}_{A}\text{X} + \gamma$

(d) ${}^{27}_{13}\text{Al} + {}^{2}_{1}\text{H} \rightarrow {}^{28}_{14}\text{Si} + {}^{1}_{0}\text{n} + \text{energy}$

(e) ${}^{22}_{11}\text{Na} + {}^{4}_{2}\text{He} \rightarrow {}^{25}_{12}\text{Mg} + {}^{1}_{1}\text{H} + \text{energy}$

13. 8 α particles and 6 β particles are emitted.
14. (a) 7 α decays and 4 β decays
 (b) 6 α decays and 4 β decays
15. Astatine-218
16. No, the total changes in atomic number and mass number are identical.
17. 1.9 h
19. 17 190 years
20. 33 mg
21. (a) 27.0, 13.5, 6.75, 3.375, 1.69 kBq
 (c) (i) 23 kBq
 (ii) 25 kBq
22. 2.0 h
23. 1.6×10^{10}
27. 210 MeV
32. (a) 174 MeV
 (b) 3.09×10^{-28} kg
 (c) 2.78×10^{-11} J, 174 MeV
33. (a) 174 MeV
 (b) 3.10×10^{-28} kg
 (c) 2.79×10^{-11} J, 174 MeV
34. (a) (i) 17.6 MeV
 (ii) 3.14×10^{-29} kg
 (iii) 2.82×10^{-12} J, 17.6 MeV
 (b) (i) 4.03 MeV
 (ii) 7.19×10^{-30} kg
 (iii) 6.46×10^{-13} J, 4.03 MeV
 (c) (i) 22.4 MeV
 (ii) 3.99×10^{-29} kg
 (iii) 3.58×10^{-12} J, 22.4 MeV

Chapter 8

Page 125

8.4. $x = 12$, $y = 7$, $z =$ N

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8.6. (a) Zero
 (b) Double charmed bottom, +1

Review questions

5. 30 mesons, 216 baryons
6. Strange B meson ($s\bar{b}$), charge = zero; charm B meson ($c\bar{b}$), charge = +1; up B meson ($u\bar{b}$), charge = +1; down B meson ($d\bar{b}$), charge = zero

8. (a) –1
 (b) +2
10. 6
12. (a) Zero

Chapter 9

Review questions

24. 1.31×10^{26} m
25. 5.7×10^{-4} K
26. See answer at the foot of the page.*

Chapter 10

Page 154

10.1. (a) (i) 800 m
 (ii) 400 m north
 (iii) 0
 (b) (i) 16 km
 (ii) 5.7 km north-west
 (iii) 5.7 km south-east
 (iv) 0

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10.2. (a) 720 km
 (b) (i) 10 km h^{-1}
 (ii) 2.8 m s^{-1}
 (c) 12 s

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10.3. (a) 3.5 m s^{-1}
 (b) 1.2 m s^{-1} east

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10.4. (a) Approx. 16 m
 (b) Approx. 30 m

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10.5. (a) 15 m s^{-2}
 (b) (i) +70 km h^{-1} s^{-1}
 (ii) +19 m s^{-2}

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10.6. (a) 6.0 s
 (b) 36 m

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10.7. (a) 18 m
 (b) –16 m s^{-2}

Review questions

2. (a) 17 znotters
 (b) 13 znotters at an angle of 23° north of west (293° true)
 (c) Average velocity = 2 znotters znitter^{-1} at an angle of 23° north of west (293° true); average speed = 2.6 znotters znitter^{-1}
 (d) Znotters znitter^{-2}
3. 27.8 m s^{-1}
4. 5.4 km h^{-1}
5. (a) 88 km h^{-1}
 (b) 24 m s^{-1}

6. (a)

Event (m)	Average speed (m s^{-1})
100	10.4
200	10.4
400	9.26
800	7.93
1500	7.28
3000	6.81
5000	6.58
10 000	6.32

 (c) 1 h 36 min 37 s
 (d) Only Usain Bolt in the 100 m. This event is the only one that involves only straight line motion.
7. (a) 14.83 m s^{-1}
 (b) 170 min
 (c) 1.9 h
 (d) (i) 76 km h^{-1}
 (ii) 0 km h^{-1}
8. 3.7 h or 3 h 41 min
9. 3.3 m s^{-1}
10. (b) 89 km h^{-1}
12. (a) *B*, *C*
 (b) *B*, *D*
 (c) *A*, *E*
 (d) *A*, *E*
 (e) *D*
17. (a) (i) –40 km h^{-1}
 (ii) 40 km h^{-1} south (or –40 km h^{-1} north)
 (b) (i) –20 m s^{-1}
 (ii) –20 m s^{-1} in original direction
 (c) (i) +5 m s^{-1}
 (ii) –55 m s^{-1} in original direction
19. About 3 m s^{-2}
20. About 6 m s^{-2}
21. (a) 1.8 s
 (b) 5.0 s
22. (a) 2.7 s
 (b) 27 m s^{-1} (about 100 km h^{-1})
23. (a) 12 m s^{-1}
 (b) –6.0 m s^{-2}
24. (a) –8.0 m s^{-2}
 (b) 3.5 s
25. Not possible
26. 793 m
27. (a) 32 m s^{-1}
 (b) 50 m from the ground
28. (a) B
 (b) A, D, E
 (c) 40 s
 (d) 20 m north
 (e) 260 m

* 0.000 000 000 000 000 000 000 000 000 000 000 000 001 s and 0.000 000 000 000 000 000 000 000 000 000 000 01 s

(f) D
(g) E
(h) 3.3 m s^{-1}
(i) 6.0 m s^{-1} south
(j) Approx. 3 m s^{-1} north

29. (a) B, D, F
(b) +20 m
(c) 0.25 m s^{-1}
(d) 30 s
(e) It didn't.
(f) C, G
(g) The first half of interval C, the first half of interval E, and all of interval G
(i) 0.20 m s^{-2}
(j) 0.050 m s^{-2}

30. (a) 3.0 s
(b) 2.5 m s^{-2}
(c) 10 s
(d) 80 m

31. (a) The jet ski after 8.0 s

Chapter 11

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11.1. (a) 3.64 N
(b) Denver

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11.4. (a) (i) 1.7×10^4 N
(ii) 4.7×10^4 N
(b) (i) 0
(ii) 1.5×10^4 N perpendicular to the road's surface

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11.5. (a) 700 N
(b) 0.80 kg

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11.6. (a) 2.0 m s^{-2}
(b) 320 N

11.7. (a) 42 N
(b) 0.42 ms^{-2}
(c) 5.0 m s^{-1}

11.8. (a) 400 N
(b) 1800 N

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11.9. (a) 2.0 m s^{-2}
(b) 200 N
(c) 300 N

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11.10. (a) 1.8×10^4 kg m s^{-1}
(b) 2.5×10^4 kg m s^{-1}

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11.11. (a) 2.8×10^4 kg m s^{-1}
(b) 2.8×10^4 N s
(c) 2000 N

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11.12. (a) 5.5 m s^{-1}
(b) 5.0 m s^{-2}
(c) 2.5×10^2 N (245 N)

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11.13. 1.0 m

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11.14. (a) 7500 N
(b) (i) 800 N
(ii) 8300 N

Review questions

5. (a) 1.4×10^4 N
(b) 5.0×10^3 N
(c) 1400 kg

6. (a) Approx. 1.0 N
(b) Approx. 10 N
(c) If the teacher's mass is about 80 kg, then their weight is approx. 800 N.

7. Assume your mass is *m* kg.
(a) 10*m* N
(b) 3.6*m* N
(c) *m* kg

11. (a) 3 N east
(b) 1.4×10^2 N east

12. (a) 346 N east
(b) 53.6 N east

13. (b) Zero

19. (a) 1.8×10^2 N
(b) 100 N
(c) 0 N

21. (a) 6.6×10^6 N
(b) 2.9×10^7 N

23. (a) 700 N
(c) 700 N

24. (a) Zero
(b) 400 N
(c) 410 N
(d) 6.9×10^2 N

25. (a) Down the slope
(c) 300 N
(d) 292 N

26. (a) 7500 N
(b) 6.3 m s^{-2}
(c) 31 m s^{-1}
(d) 78 m

27. 6.9×10^6 N opposite to the direction of motion

28. 1.0×10^2 N

29. (a) 700 N
(b) 560 N
(c) 840 N

30. 1.6 m s^{-2}

31. 180 N

32. 6.0 m s^{-2}

33. (a) 42 N
(b) 19°

37. 0.87 m s^{-2}

38. (a) 0 m s^{-1}
(b) 10 m s^{-2}
(c) 5.0 N down

45. (a) 2.0 m s^{-2}
(b) 6.0 N
(c) 8.0 N
(d) 3.5 m s^{-2}

46. (a) 4.0 m s^{-2} to the right
(b) 160 N to the right
(c) 240 N to the left
(d) 240 N to the right
(e) No

47. (a) 3×10^3 N
(b) 8×10^2 N
(c) 8×10^2 kg m s^{-1}
(d) 1×10^4 kg m s^{-1}
(e) 6×10^2 N s
(f) 2 N s
(g) 10 kg m s^{-1}

48. (a) 0.84 kg m s^{-1} up
(b) 0.84 N s down
(c) No. The mass of the Earth is very large.
(d) 4.2×10^2 N up
(e) 4.2×10^2 N up

49. (a) 240 N s upwards
(b) 3.2×10^3 N upwards
(c) 0.5 m

50. (a) 2.3×10^4 N s opposite to the initial direction of motion of the car
(b) 2.9×10^5 N opposite to the initial direction of motion of the car
(c) 2.1×10^2 m s^{-2}

53. (a) Approx. 160 N s
(b) 2.7 m s^{-1}

54. (a) Approx. 100 N s upwards
(b) 0.67 m s^{-1}
(c) 1000 N

58. (b) Left: 24 kN, right: 96 kN

60. 356 kN

61. 1.8 kN

62. 1.6 m

Chapter 12

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12.1. (a) 15 kg m s^{-1} east
(b) 1.5 m s^{-1} east
(c) 2.5 kg m s^{-1} west
(d) 2.5 kg m s^{-1} east
(e) 2.5 N s
(f) Opposite in direction

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12.2. (a) 600 J (b) 120 J

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12.3. (a) 64 000 J
(b) (i) 900 J
(ii) 2×10^{-8} J

12.4. 2.0 m s^{-1}

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12.5. (a) 0.40 J (b) 1.6 J

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12.6. (a) (i) 12 N
(ii) 1.2 J
(iii) 1.2 kg
(b) 80 N m^{-1}

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12.7. 1.6 m

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12.8. (a) 0.40 J
(b) 1.3 m s^{-1}

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12.9. (a) 1.4 m
(b) 600 W

Review questions

2. (a) 0.30 m s^{-1}
(b) 0.60 m s^{-1}
3. (a) 40 kg
(b) 60 N s
(c) 60 N s
(d) Zero
4. (a) 1.7 m s^{-1}
(b) 120 N s
(c) 120 kg m s^{-1}
(d) 120 kg m s^{-1}
(f) 0.92 m s^{-1}
5. (a) 15 m s^{-1}
(b) 1.1×10^4 N s in the initial direction of motion of the car
(c) 420 N s opposite to the initial direction of motion of the car
(d) 1.1×10^5 N
8. 60 J
9. None
10. (a) Zero
(b) Zero
12. (a) Approx. 1×10^5 J
(b) Approx. 4×10^1 J
13. 90 J
14. (a) 2 kJ (b) 600 J
15. (a) 200 J (b) 200 J
17. (a) 3.2 J
(b) 1.0 J
(c) 0.64 m
18. (a) X: 40 N, Y: 20 N
(b) X: 4.0 J, Y: 2.0 J
19. (a) 240 J
(b) 20 m s^{-1}
20. (a) 2.4×10^5 N
(b) 1.6×10^2 m s^{-2}
(c) 9.7×10^2 m s^{-2}
21. (a) 1.9×10^3 J (1920 J)
(b) 10 N
(c) 3600 J
(d) 5000 J
22. (a) 3.2×10^4 J
(b) At B, 23 m s^{-1}; at C, 20 m s^{-1}
(c) 27 m
23. (a) 8.9×10^5 J
(b) 3.6×10^5 J
(c) 30 m s^{-1}
24. (a) 2.1 kJ (b) 0.15 m
25. 1.0 m s^{-1}
26. (b) 19 kN m^{-1}
(c) 60 J
(d) 60 J
(e) 0.20 m
31. 51%
33. 399 kN
34. 2.2×10^4 W
35. 50 W
36. (a) 3.2×10^3 J (b) 1.1 kW
(c) None
37. 14 kW
38. 36 W
39. (a) 4.6 m s^{-1}
(b) 1.7×10^3 W

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W

X

Y

Z