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VCE UNITS
1&2

Cambridge Senior Science

Physics

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Please be aware that this publication may contain images of Aboriginal and Torres Strait Islander people who are now deceased. Several variations of Aboriginal and Torres Strait Islander terms and spellings may also appear; no disrespect is intended. Please note that the terms 'Indigenous Australians' and 'Aboriginal and Torres Strait Islander peoples' may be used interchangeably in this publication.

Cambridge University Press & Assessment acknowledges the Australian Aboriginal and Torres Strait Islander peoples of this nation. We acknowledge the traditional custodians of the lands on which our company is located and where we conduct our business. We pay our respects to ancestors and Elders, past and present. Cambridge University Press & Assessment is committed to honouring Australian Aboriginal and Torres Strait Islander peoples' unique cultural and spiritual relationships to the land, waters and seas and their rich contribution to society.

About the authors

Dr Sydney Boydell has had a long association with VCE Physics, including involvement in course design; classroom teaching; and setting, vetting and marking the examinations. He has taught at VCE level in Australia and the UK, and has over 25 years experience teaching at first-year university level. He currently lectures in Science Education and is the author of two VCE physics titles in the Cambridge Checkpoints series as well as two HSC titles for New South Wales.

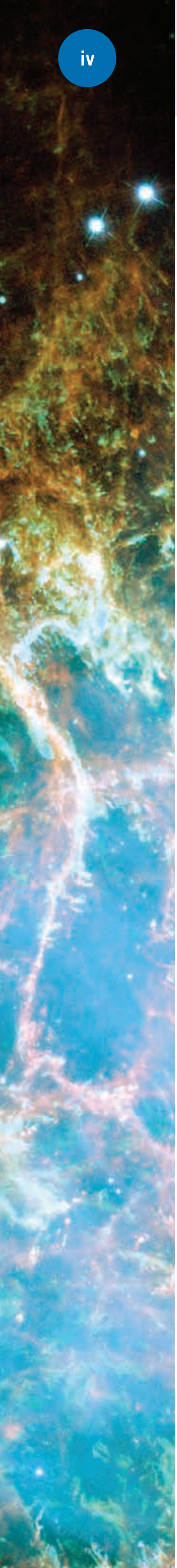
Dr Eddy de Jong has been involved with science and physics education at the secondary and tertiary level for many years. He has taught science at all levels, senior HSC/VCE Physics and university physics. He was involved in the Victorian Gifted Students Physics Network. Eddy has had a long association with Year 12 Physics, including involvement in course design; classroom teaching; and setting, vetting and marking the examinations. He is a successful author of numerous science and physics texts, including the Cambridge Victorian Science Years 7–10. He is passionate about seeing young minds engaging with science and physics and aims to instil in students a sense of curiosity while developing their critical thinking skills.

Christopher Dale is a young, enthusiastic and accomplished science and physics teacher who brings a unique perspective to the profession. Chris started his career as a physiotherapist and worked briefly in the private and public sector before moving to teaching. Chris started his teaching career in Western Australia, and is currently involved in marking VCE Physics exams and Head of Physics at a leading independent school. Outside of the classroom, Chris competes in running at a national level in and has competed in Commonwealth Games, World Championship and Olympic trials for Australia.

Andrew Hansen has been a Physics Assessor for VCAA for over 10 years, including Chief Assessor (Physics). He trained in biophysics and instrumental science before becoming a cardiac technologist at St Vincent's Hospital and then entering the medical technology industry. He then gained a Master of Education and has been teaching at a government secondary school for more than 15 years, including positions as Head of Science and Leader in Digital Learning.

Mary Macmillan (formerly Willox) has recently retired after more than 35 years' experience teaching physics in Melbourne and in the UK, including HSC/VCE, A-Level and International Baccalaureate. She has an ongoing interest in the broader curriculum, in particular teaching for effective learning, developing a range of generic life skills through classroom activities and encouraging students to see physics in their everyday lives. Following her passion for physics, Mary retrained mid-career as a radiographer, worked in magnetic resonance imaging at the Florey Institute in Melbourne, but soon returned to the fun of the physics classroom.

Authors' acknowledgement
The authors wish to thank Dr David Mills and Bruce Walsh for their help in checking the manuscripts for this series.



Contents

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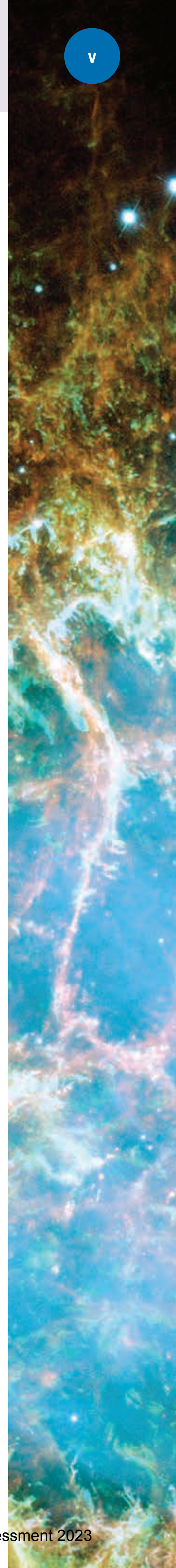
The online material summarised in Appendix 1 will be found in the Interactive Textbook and teacher resources.
Answers to all questions are available in the Interactive Textbook and the teacher resources.



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Overview: How to use this resource

The Cambridge Education Australia and New Zealand website has more information and demos for this title.

This overview guides you through all the components of the **print and PDF textbooks**, the **Interactive Textbook (ITB)**, and the teacher resources in the **Online Teaching Suite (OTS)**. Users of the award-winning *Cambridge Science 7–10 for the Victorian Curriculum* will recognise some similarities with this senior science resource, including the hosting of the digital material on the Edjin platform, which was developed from *Cambridge HOTmaths* and is already being used successfully by thousands of teachers and students across Victoria.

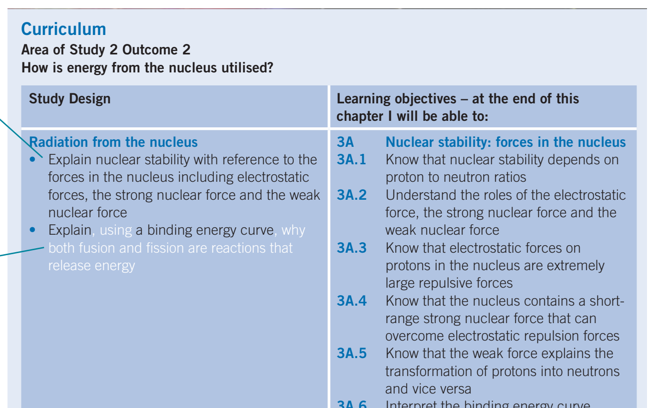
Print book features

Learning objectives

In the Curriculum table at the start of each chapter, the Study Design dot points are translated into Learning objectives, describing what students should be able to do by the end of the chapter:

Black text indicates the portion of the dot point covered by the section shown in the second column

White text indicates the portion of the dot point covered by other sections


Curriculum
Area of Study 2 Outcome 2
How is energy from the nucleus utilised?

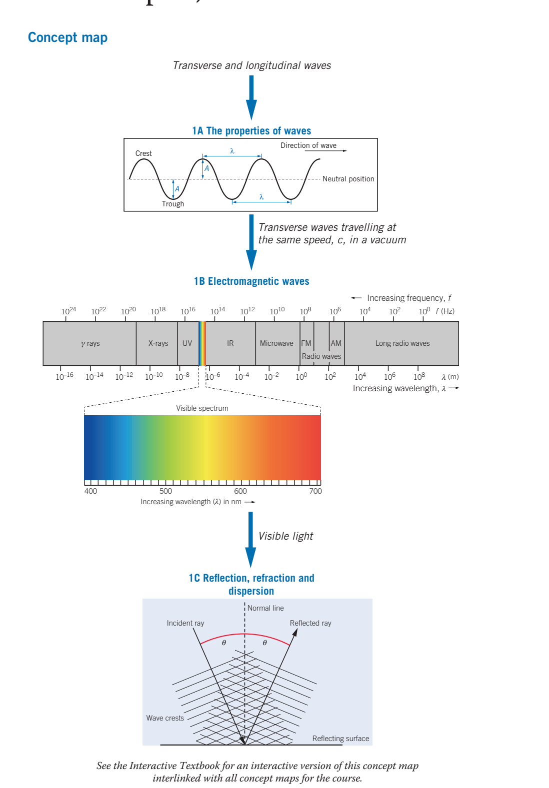
Study Design	Learning objectives – at the end of this chapter I will be able to:
Radiation from the nucleus • Explain nuclear stability with reference to the forces in the nucleus including electrostatic forces, the strong nuclear force and the weak nuclear force • Explain, using a binding energy curve, why both fusion and fission are reactions that release energy	**3A Nuclear stability: forces in the nucleus** **3A.1** Know that nuclear stability depends on proton to neutron ratios **3A.2** Understand the roles of the electrostatic force, the strong nuclear force and the weak nuclear force **3A.3** Know that electrostatic forces on protons in the nucleus are extremely large repulsive forces **3A.4** Know that the nucleus contains a short-range strong nuclear force that can overcome electrostatic repulsion forces **3A.5** Know that the weak force explains the transformation of protons into neutrons and vice versa **3A.6** Interpret the binding energy curve

Learning objectives are turned into Success Criteria (achievement standards) at the end of the chapter and are assessed in the Chapter review and tracked in the Checklists

Relevant Study Design dot points are repeated at the start of each section in the chapter, and an overall curriculum grid is provided in the teacher resources.

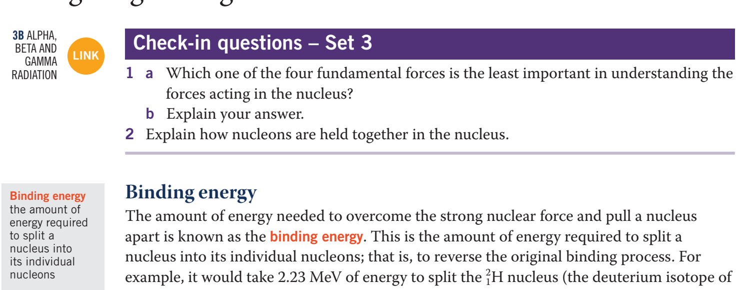
Concept maps

Concept maps display each chapter's structure with annotations emphasising interconnectedness, providing a great memory aid. The versions in the ITB are hyperlinked and offer an alternative way of navigating through the course. An overall concept map of Units 1&2 is also provided on page xiv.



Links

The interconnectedness of topics in Physics is demonstrated through links between sections, displayed in the margins. In the ITB, these are hyperlinks that provide a second alternative way of navigating through the course.


3B ALPHA, BETA AND GAMMA RADIATION LINK

Check-in questions – Set 3

1 a Which one of the four fundamental forces is the least important in understanding the forces acting in the nucleus?
b Explain your answer.
2 Explain how nucleons are held together in the nucleus.

Binding energy

Binding energy the amount of energy required to split a nucleus into its individual nucleons

The amount of energy needed to overcome the strong nuclear force and pull a nucleus apart is known as the **binding energy**. This is the amount of energy required to split a nucleus into its individual nucleons; that is, to reverse the original binding process. For example, it would take 2.23 MeV of energy to split the $^{2}_{1}H$ nucleus (the deuterium isotope of

Chapter sections

Chapters are divided into numbered sections, each with a consistent set of features.

Engage

At the start of each section, these boxes provide points of interest for the topic, emphasising its place in Physics. This material, though not assessable, can be used as examples of applications.

Explain

This icon marks the start of essential content that is assessed.

Glossary

Scientific terms are highlighted in the text, definitions are given in the margin of the print and PDF textbooks, or on mouseover in the ITB, and the terms are listed at the start of each chapter and section.

Check-in questions

Each section in the chapter has one or more sets of check-in questions, for formative assessment. Full answers are provided in the digital resources.

Skills

Skills boxes in every section provide advice and guidance on how to answer and prepare for questions, especially in examinations. The ITB has video versions of these, which provide extra comments and an alternative medium of delivery.

Study Design coverage for section

Glossary terms in the section

1B Electromagnetic waves

Study Design:

- Identify all electromagnetic waves as transverse waves travelling at the same speed, *c*, in a vacuum as distinct from mechanical waves that require a medium to propagate

Glossary:
Electric field
Electromagnetic radiation
Electromagnetic spectrum
Electromagnetic wave

ENGAGE

How do we understand light?

The electromagnetic spectrum, which includes visible light, plays a crucial role in our lives. Through photosynthesis, light sustains all humankind. There have also been revolutionary applications in medicine, culture, communications, energy, weather forecasting, remote sensing, scientific research and our understanding of the Universe. For example, the recently launched James Webb Space Telescope allows us to see light from the fringes of the Universe and billions of years into the past.

EXPLAIN

What is light?

VIDEO 1B–1
WHAT IS LIGHT

Electric field
a physical field that creates a force on all charged particles within the field. Produced by charged particles and changing magnetic fields. A changing electric field also produces a changing

Electromagnetic theory, Maxwell's crowning achievement, predicted that accelerating charges should generate waves – waves made up of changing electric and magnetic fields. The changing **electric field** causes a changing **magnetic field**, which in turn generates a changing electric field – and so on. The wave produced in this way doesn't need a medium to propagate, unlike mechanical waves such as sound, which do require a medium to propagate. These waves travel through a vacuum at the speed of light, *c*, 3.00×10^8 m s^{-1}. The electric and magnetic fields are always at right angles to each other, as shown in Figure 1B–2 below. The waves are also always transverse because the electric and magnetic fields are always perpendicular to the direction of travel of the waves.

Glossary definitions

Terms in the glossary

Check-in questions – Set 1

1 What are the relative orientations of the electric vibrations, the magnetic vibrations, and the velocity of a light wave?
2 Convert 800 nm into metres.
3 What kinds of electromagnetic waves have a wavelength of 0.10 nm?
4 State the regions of greatest and smallest frequency of the electromagnetic spectrum.

1A SKILLS

Multichoice questions on definitions

Refer to the definition first. Check the options for an answer that can be reworded to fit the definition. If stuck, eliminate unlikely options.

Calculation questions

Identify the relevant formula. If necessary, transform the equation so that the subject of the equation is the desired quantity. Always check that your answer is a reasonable quantity. For example, if your answer to a speed question is greater than the speed of light in a vacuum ($v = 3 \times 10^8$ m s^{-1}), then it must be incorrect.

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Charts, diagrams and tables

Detailed charts integrating text and diagrams, and illustrated tables, feature throughout the print books. In the ITB, many of these are available as animated slide-show presentations for students to use, with copies for teachers to display on data projectors or whiteboards.

Climate the long-term weather patterns or average weather in an area, typically over a period of 30 years

Such global warming, even of only one or two degrees, causes significant changes in the **climate** – the local, regional and global average weather patterns over Earth's surface. These changes can include land, sea and air temperature increases, higher sea levels, loss of ice from glaciers and Arctic and, Antarctic ice caps, and more frequent extreme weather events like cyclones, heatwaves, bushfires, droughts and floods. Patterns of rainfall can also shift, making land less suitable (or more suitable) for agriculture and animal habitats. Sea level rises would make some lower lying parts of the planet uninhabitable; for example islands like the Maldives and delta communities such as the Nile and in Bangladesh.

WORKSHEET 2B–1 THERMAL ENERGY, ELECTRO-MAGNETIC RADIATION AND GLOBAL WARMING

Earth's energy budget

'Budget' is used here in the sense of a reckoning of inputs (incoming energy) and outputs (outgoing energy). Almost all the energy in Earth's climate system comes from solar radiation (a tiny amount comes from Earth's interior). Figure 2B–6, published by NASA in 2009 and based on 10 years of data, outlines what happens to the incoming solar radiation and the radiation emitted and reflected by Earth.

Figure 2B–6 Earth's energy budget, calculated by NASA in 2009, based on the means of 10 years of data. The units are watts per square metre of the Earth's surface, i.e. power per square metre, or energy per second per square metre.

Table 1B–1 *Continued*

Spectrum region and approximate wavelength and frequency range	Applications	Illustrated examples
Infrared (IR) 1 mm – 700 nm and 300 GHz – 430 THz	• Thermal imaging (including night vision goggles) • Remote controls (e.g. for domestic TVs) • Heat lamps in IR saunas • IR astronomy • Optical fibre signals	Night vision goggles 
Visible 700 nm – 400 nm and 4.3×10^{14} Hz – 7.5×10^{14} Hz	• Vision • Lighting • Optical astronomy • Laser applications – surgery, pointers, cutters, communication • Phototherapy (for seasonal affective disorder (SAD), jaundice) • Photosynthesis (growth of plants)	Laser eye surgery 
Ultraviolet (UV) 400 nm – 10 nm and 7.5×10^{14} Hz – 3×10^{16} Hz	• Vitamin D generation in the skin • UV astronomy • Medical and food sterilisation	UV food and drink sterilisation 
X-rays 10 nm – 10 pm and 3×10^{16} Hz – 3×10^{19} Hz	• X-ray astronomy • Industrial scanning for quality control • Medical imaging (including computerised tomography (CT) scans) • Medical therapies (cancer treatment) • X-ray security imaging • Detection of art forgeries	Luggage X-ray scanners 

Section questions

Summative assessment is provided at the end of each section, with full answers provided in the digital resources.

Section 2B questions

Multiple-choice questions

1 A key characteristic of a blackbody is that
A it has a dark-coloured surface.
B it absorbs all radiation frequencies falling on it.
C it has a temperature above 0 K.

Chapter reviews

Summaries: Students are encouraged to make their own set of summary notes, to help them assimilate the material. Model summaries are provided in the teacher resources, to be given to those who need help. Creating summaries can also be turned into an assessment task, with the models serving as the answer.

Checklists and **Success criteria:** The learning objectives from the front of the chapter are listed again in the form of success criteria linked to the **multiple-choice** and **short-answer questions** that follow. The checklists are printable from the ITB, and students can tick off their achievement manually. If they do the questions in the ITB, they are ticked automatically when the questions are marked or self-assessed.

Chapter 1 review

Summary

Create your own set of summary notes for this chapter on paper or in a digital document. A model summary is provided in the Teacher Resources, which can be used to compare with yours.

Checklist

In the Interactive Textbook, the success criteria are linked from the review questions and will be automatically ticked when answers are correct. Alternatively, print or photocopy this page and tick the boxes when you have answered the corresponding questions correctly.

Success criteria – I am now able to:		Linked questions
1A.1	Recognise wave motion and give examples	14☐, 15☐, 18☐, 19☐, 20☐

Multiple-choice questions

Use the following information to answer Questions 1 and 2.

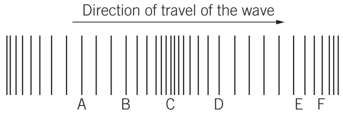
A transverse wave is travelling to the right. One particle of the wave, A, is located one-quarter of a wavelength to the left of another particle, B. The wave amplitude is 2.0 m.

1 Which one of the following statements is correct?
A A is always lower than B by 1.0 m
B A is always higher than B by 1.0 m.
C When A is at the crest of the wave motion, B will be in a trough.
D When A is located halfway between a crest and a trough, B will be either at a crest or at

Short-answer questions

Use $c = 3.00 \times 10^8\ m s^{-1}$

13 A sketch of the wave crests of a longitudinal wave is shown below. The wave is travelling to the right.



a Which of the letters in the diagram best identifies the position of a compression (place where wave crests group up the most)? (1 mark)
b Which of the letters in the diagram best identifies the position of a rarefaction (place where wave crests spread out the most)? (1 mark)

Unit revision exercises

Each Unit has a revision exercise in the print book, with both multiple-choice and short-answer questions.

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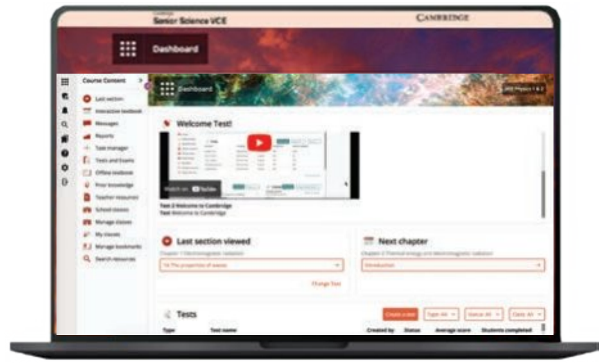
Interactive Textbook features



The digital version of the textbook is hosted on the Edjin platform, offering easy navigation, excellent on-screen display and multimedia assets, as well as auto-marking of multiple-choice questions, and workspaces for other questions with self-assessment and confidence rating tools. The different kinds of digital assets are listed below:

- Printable **Worksheets** with extra questions and activities (and content in some cases) are provided for all chapters, marked by an icon in the margin, as shown on the right.

WORKSHEET 1A–1 THE PROPERTIES OF WAVES

- **Videos** are provided for all chapters, and are of two kinds: **concept videos** demonstrate or illustrate important theory, while **skills and example videos** work through the textbook's skills and example boxes, providing extra explanation and guidance. Some videos are provided in the print pages as QR codes for immediate access and review.

VIDEO 1A–1 THE PROPERTIES OF WAVES

- **Animated slide-show presentations** (in PowerPoint Show format) are provided of many charts, diagrams and tables, and marked by an icon in the margin as shown at right, enabling them to be explored interactively.
- **Answers** (suggested responses) to questions are provided as printable documents in the teacher resources and, if enabled by the teacher, below the ITB question workspaces.
- **'Scorcher' quizzes** on terms and definitions let students test themselves.
- **Prior knowledge** can be tested with an auto-marked quiz with questions from the Years 9 and 10 *Cambridge Science for the Victorian Curriculum.*

Online Teaching Suite features (teacher resources)

The OTS provides Edjin's learning management system, which allows teachers to set tasks, track progress and scores, prepare reports on individuals and the class, and give students feedback. The assets include:

- **Curriculum Grid** and **teaching programs**
- Editable and printable **Chapter tests** with answers
- **Checklists** with linkage to the success criteria for the chapter question sets and tests
- A **question bank** and test generator, with answers
- **Practice exams** and **assessment tasks**, with answers
- Editable versions of **Worksheets** in the Interactive Textbook, and answers to them
- Editable versions of the PowerPoint files in the Interactive Textbook
- Downloadable, editable and printable **practicals**
- Editable and printable chapter **summaries** (model answers for the chapter summary activity)
- **Teacher notes** on selected content with additional theory explanation and suggestions for further activities and resources
- **Curated links** to internet resources such as videos and interactives.

Exam generator

The Online Teaching Suite includes a comprehensive bank of exam-style and actual VCAA exam questions to create custom trial exams to target topics that students are having difficulty with. Features include:

- Filtering by question-type, topic and degree of difficulty
- Answers provided to teachers
- VCAA marking scheme
- Multiple-choice questions that will be auto-marked if completed online
- Tests that can be downloaded and used in class or for revision.

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Overview: Aboriginal and Torres Strait Islander knowledge, cultures and history

The VCE Physics Study Design includes aspects of Aboriginal and Torres Strait Islander knowledge, cultures and history. This overview is a guide to coverage in this resource.

Aboriginal and Torres Strait Islander peoples' world views are highly integrated: each aspect of culture, history and society connects with all other aspects. Each community has their own personalised system of thinking, doing and knowing based on sharing culture and adapting to the environment around them.

In order to gain an understanding of any system, Indigenous or not, time and effort is needed to appreciate it. That time is limited in this course; and it is wrong to try and generalise the Indigenous culture of Australia, or even of Victoria. Instead, the coverage in the resource should be taken as a collection of examples, and students should read up on or engage with their local Indigenous community to understand their cultural aspects.

This textbook includes examples of Aboriginal and Torres Strait Islander knowledge, cultures and history and in the Unit 2 Options in the Interactive Textbook there is coverage of *Option 2.15: How can physics explain traditional artefacts, knowledge and techniques?*

In addition, for students, the Interactive Textbook includes an introductory guide prepared by First Nations consultants advising on approaches to studying Aboriginal and Torres Strait Islander knowledge, cultures and history, with links to further reading.

For teachers, the teacher resources include a guide to approaches to teaching Aboriginal and Torres Strait Islander knowledge, cultures and history in the VCE Physics course, with links to internet resources.

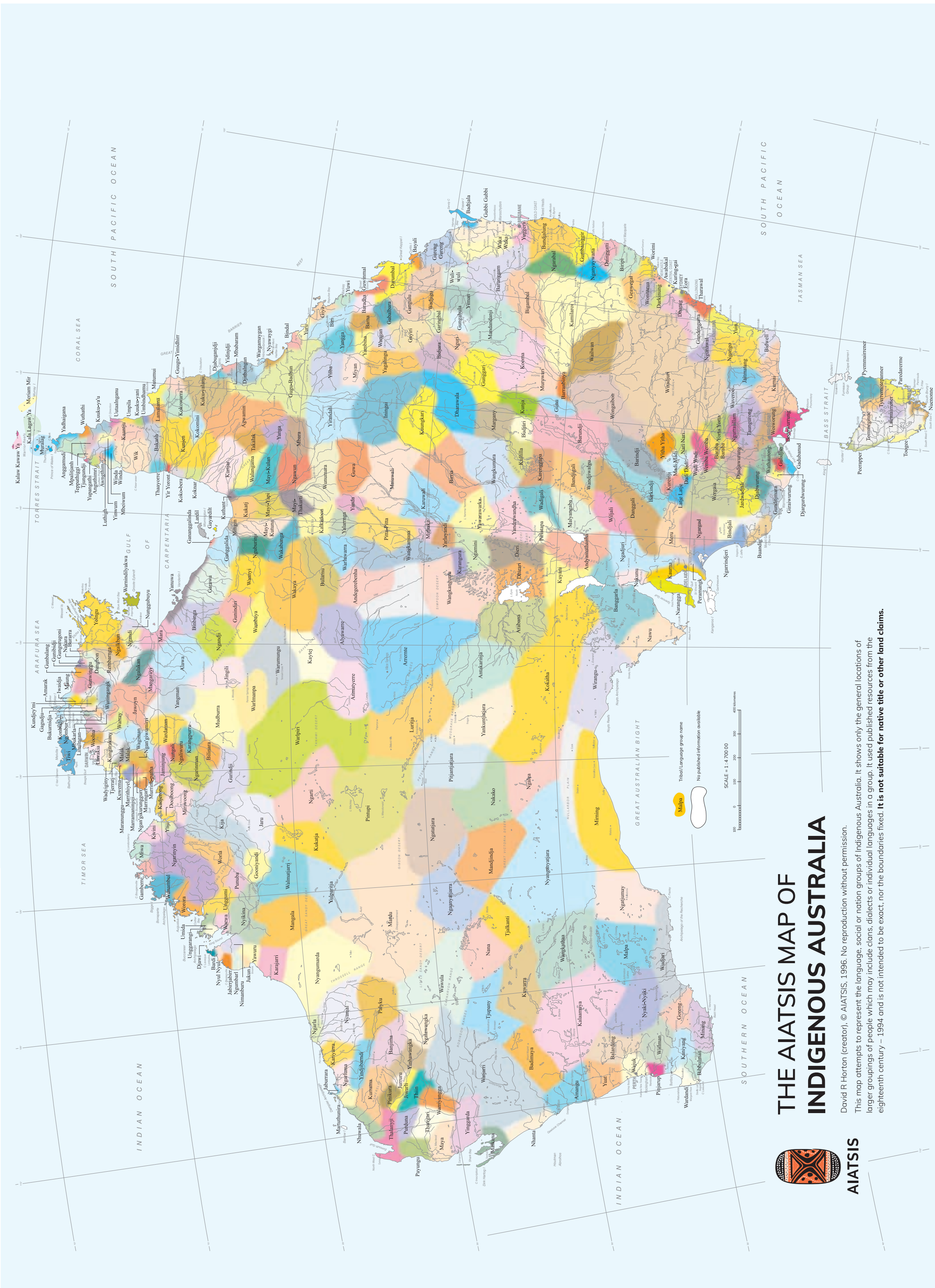
Guide to terms used in this resource

Language is very important in discussing Indigenous issues, especially given the past history of deliberately offensive usage in Australia, where language was used to oppress and control.

Indigenous First Australians and First Peoples of any country	Respectful usage requires a capital I.
First Australians, First Nations or First Peoples Indigenous people of Australia	These terms have become more common in recent years, with 'Indigenous' as the adjective.
Aboriginal an Aboriginal person is someone who is of Aboriginal descent, identifies as being Aboriginal and is accepted as such by the Aboriginal community with which they originally identified	One of the reasons that 'First Nations' and allied forms have become more common is that the term 'Aboriginal' was sometimes used disrespectfully, and still is in some circles.
Aboriginal and Torres Strait Islander peoples the Australian Indigenous population includes Aboriginal People, Torres Strait Islander People, and people who have both Aboriginal and Torres Strait Islander heritage. The term 'Aboriginal and Torres Strait Islander' encompasses all three	While this is still used in official circles and is in the name or title of many organisations and documents, it is tending to be replaced by 'First Australians' and similar terms, especially in everyday use. This is partly because the abbreviation 'ATSI' is considered disrespectful by Indigenous people, who regard it as lazy not to use a full title. The abbreviation should not be used to refer to people.

Cambridge University Press & Assessment acknowledges the Australian Aboriginal and Torres Strait Islander peoples of this nation. We acknowledge the traditional custodians of the lands on which our company is located and where we conduct our business. We pay our respects to ancestors and Elders, past and present.

Map of Indigenous peoples of Australia



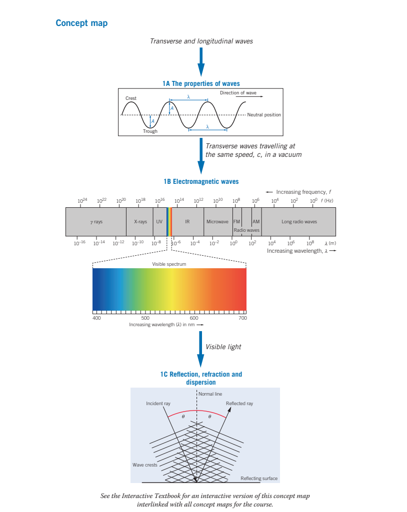
This map attempts to represent the language, social or nation groups of Aboriginal Australia. It shows only the general locations of larger groupings of people which may include clans, dialects or individual languages in a group. It used published resources from the eighteenth century – 1994 and is not intended to be exact, nor the boundaries fixed. It is not suitable for native title or other land claims. David R Horton (creator), © AIATSIS, 1996. No reproduction without permission. To purchase a print version visit: https://shop.aiatsis.gov.au/

AIATSIS Map of Indigenous Australia, showing the general locations of larger language, social or nation groups. To zoom in on detail especially in Victoria, access the map in the Interactive Textbook.

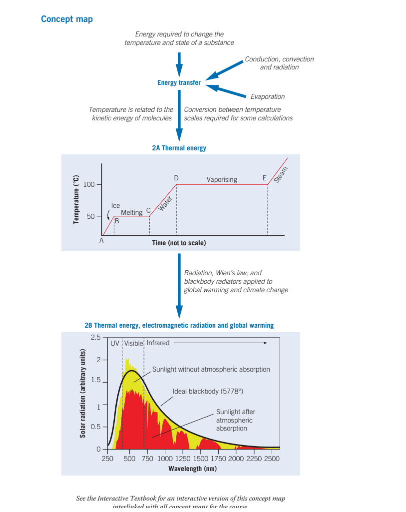
Concept maps for Units 1&2

This spread displays the concept maps for Chapters 1–9. Access the digital versions in the ITB and click on hyperlinks to explore the interconnections of the topics.

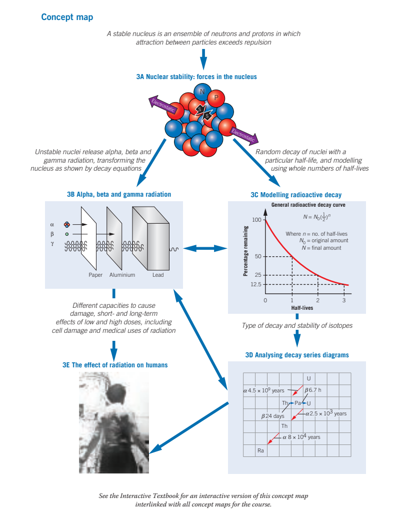
Chapter 1 Electromagnetic radiation



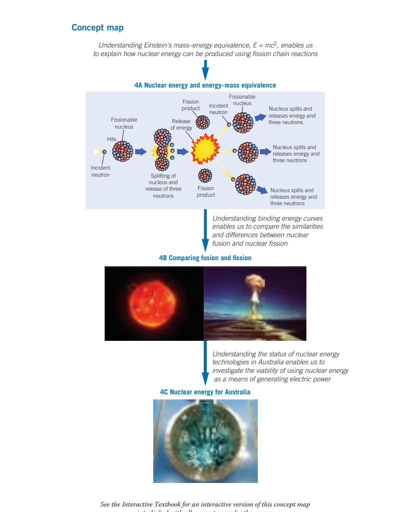
Chapter 2 Thermal energy and electromagnetic radiation



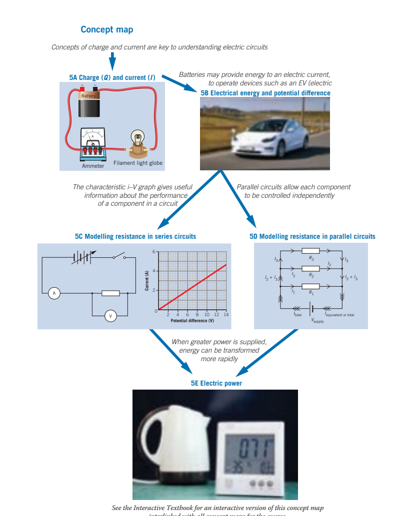
Chapter 3 Radiation from the nucleus



Chapter 4 Nuclear energy



Chapter 5 Electricity and energy transfer



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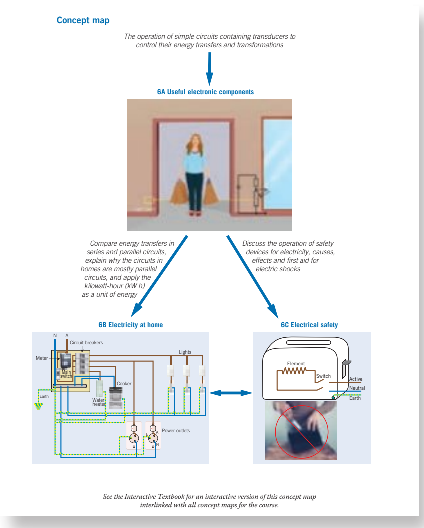
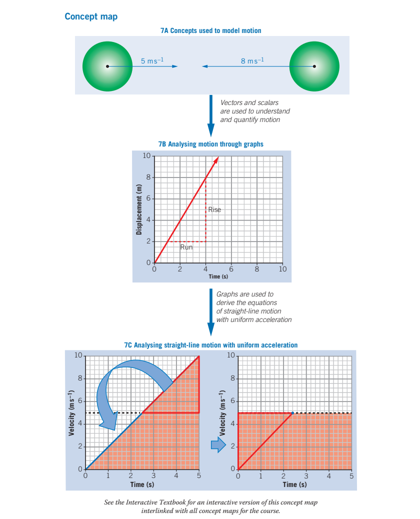
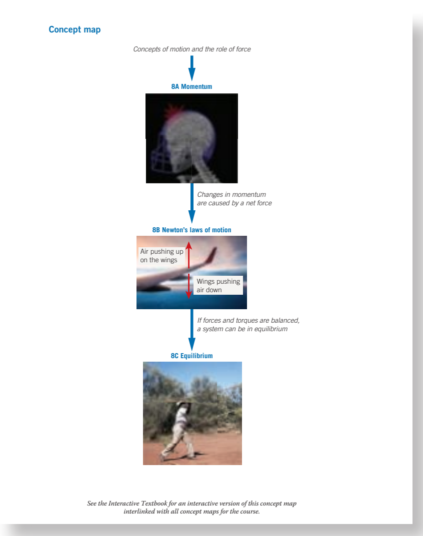
Chapter 6 Using electricity



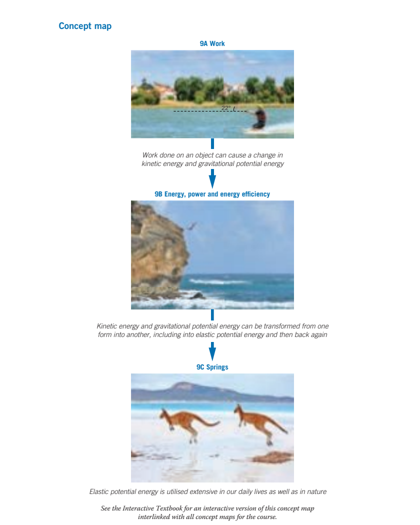
Chapter 7 Modelling motion



Chapter 8 Forces and motion



Chapter 9 Energy and motion



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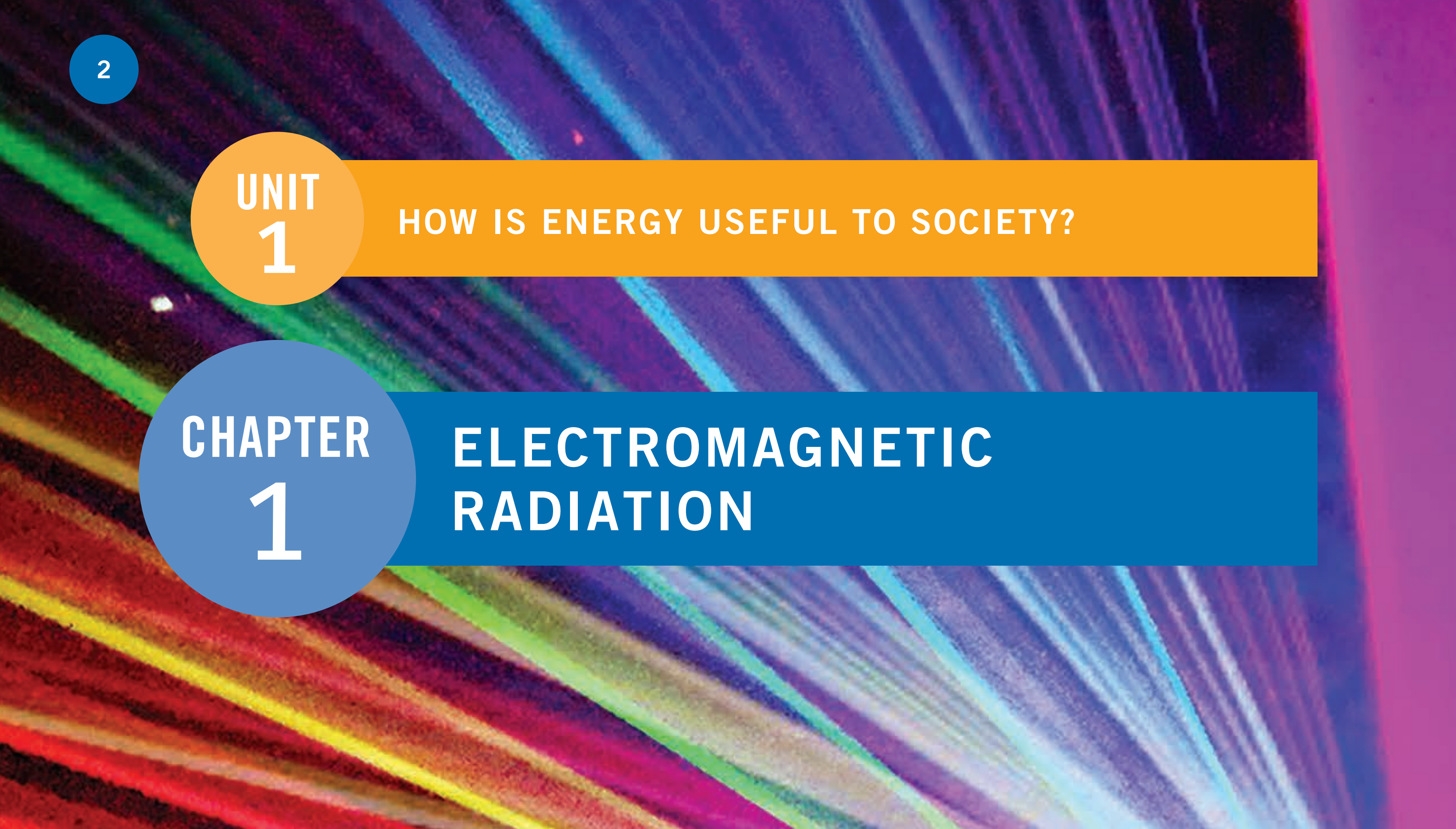

UNIT 1 HOW IS ENERGY USEFUL TO SOCIETY?

CHAPTER 1 ELECTROMAGNETIC RADIATION

Aboriginal and Torres Strait Islander peoples should be aware this Chapter contains images of people who have, or may have, passed away.

Introduction

Just over 8 minutes after it leaves the Sun, light reaches Earth. That light brings with it the energy that enables life to flourish on this planet. Visible light alone enables photosynthesis, the foundation of food production. As well as vision, humankind makes use of all regions of the electromagnetic spectrum.

These uses include revolutionary lifesaving applications in medicine, high-speed internet connectivity using optical fibres and wireless, dazzling laser light shows, abundant renewable energy, accurate weather forecasting, remote sensing, GPS navigation systems, scientific research and increasing our wider understanding of the Universe. It is little wonder that light is celebrated each year on 16 May, the International Day of Light. The date is the anniversary of the first operational laser.

Aboriginal and Torres Strait Islander peoples' understanding of the nature of light appears to have started 60 000 years ago. Their knowledge of how light behaves enabled them to spear fish in water (using refraction – this example is covered in the chapter), construct effective housing (reflection and absorption) and use highly refracting ochres for ceremonial purposes.

Further understanding of light was reached, notably, by Ptolemy of Alexandria in the second century and more accurately by Ibn al-Haytham of Basra in his renowned *Book of Optics* in the eleventh century. Further key developments were made by James Clerk Maxwell and Thomas Young in the nineteenth century and Albert Einstein in the early twentieth century.

This chapter will begin by looking at the basic properties of all waves before moving into an introduction of electromagnetic waves and the electromagnetic spectrum as a whole, including applications in society. The chapter concludes by looking at the phenomena of reflection and refraction of light as well as their application in explaining other natural phenomena, such as colour dispersion in a prism and the formation of rainbows and mirages.

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Curriculum

Area of Study 1 Outcome 1
How are light and heat explained?

Study Design	Learning objectives – at the end of this chapter I will be able to:
Electromagnetic radiation • Identify the amplitude, wavelength, period and frequency of waves • Calculate the wavelength, frequency, period and speed of travel of waves using: $\lambda = \frac{v}{f} = vT$ • Explain the wavelength of a wave as a result of the velocity (determined by the medium through which it travels) and the frequency (determined by the source)	**1A The properties of waves** **1A.1** Recognise wave motion and give examples **1A.2** Understand that wave motion transfers energy without transferring matter **1A.3** Distinguish between transverse and longitudinal waves **1A.4** Use amplitude (A), speed (v), frequency (f), period (T) and wavelength (λ) to describe the motion of waves **1A.5** Explain the wavelength of a wave as a result of the velocity (determined by the medium through which it travels) and the frequency (determined by the source) **1A.6** Solve numerical problems using: $\lambda = \frac{v}{f} = vT$
• Identify all electromagnetic waves as transverse waves travelling at the same speed, c, in a vacuum as distinct from mechanical waves that require a medium to propagate • Compare the wavelength and frequencies of different regions of the electromagnetic spectrum, including radio, microwave, infrared, visible, ultraviolet, X-ray and gamma, and compare the different uses each has in society • Describe electromagnetic radiation emitted from the Sun as mainly ultraviolet, visible and infrared	**1B Electromagnetic waves** **1B.1** Describe all electromagnetic waves as transverse vibrations of electric and magnetic fields that travel at speed, c, in a vacuum **1B.2** Describe electromagnetic radiation emitted from the Sun as mainly UV, visible and IR **1B.3** Recall approximate wavelength and frequency ranges of the radio, microwave, infrared, visible, ultraviolet, X-ray and gamma ray regions **1B.4** Give examples of the different societal uses of regions of the electromagnetic spectrum from radio through to gamma rays

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Study Design	Learning objectives – at the end of this chapter I will be able to:
• Investigate and analyse theoretically and practically the behaviour of waves including: ▸ refraction using Snell's Law: $n_1\sin(\theta_1) = n_2\sin(\theta_2)$ and $n_1v_1 = n_2v_2$ ▸ total internal reflection and critical angle including applications: $n_1\sin(\theta_c) = n_2\sin(90°)$ • Investigate and explain theoretically and practically colour dispersion in prisms and lenses with reference to refraction of the components of white light as they pass from one medium to another • Explain the formation of optical phenomena: rainbows; mirages • Investigate light transmission through optical fibres for communication	**1C Reflection, refraction and dispersion** **1C.1** Use a ray model with wave crests to describe reflection and refraction of light **1C.2** Define refractive index of transparent substances **1C.3** Use the equation: $n_1v_1 = n_2v_2$ **1C.4** Carry out practical investigations involving Snell's law **1C.5** Apply Snell's law to analyse qualitative and quantitative refraction situations of visible light **1C.6** Qualitatively, using a ray model, explain the formation of images **1C.7** Carry out practical investigations involving total and partial internal reflection **1C.8** Apply Snell's law to predict the critical angle at media interfaces **1C.9** Carry out practical investigations involving dispersion of visible light **1C.10** Qualitatively analyse situations involving dispersion of visible light in prisms and lenses **1C.11** Qualitatively explain the formation of rainbows and mirages using a ray model of light **1C.12** Apply Snell's law to analyse qualitatively and quantitatively the operation of optical fibres for communication

Glossary

Amplitude, A
Chromatic distortion
Colour dispersion
Compression
Critical angle
Electric field
Electromagnetic radiation
Electromagnetic spectrum
Electromagnetic wave
Frequency, f
Gamma ray
Infrared (IR)
Longitudinal wave
Magnetic field
Medium
Microwave
Monochromatic
Normal
Optical fibre
Partial internal reflection
Period, T
Radio wave
Rarefaction
Reflection
Refraction
Refractive index, n
Snell's law
Total internal reflection
Transverse wave
Ultraviolet (UV)
Visible light
Wavelength, λ
X-ray

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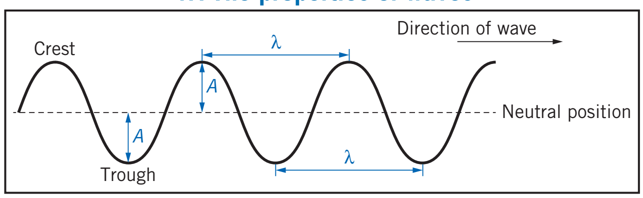
Concept map

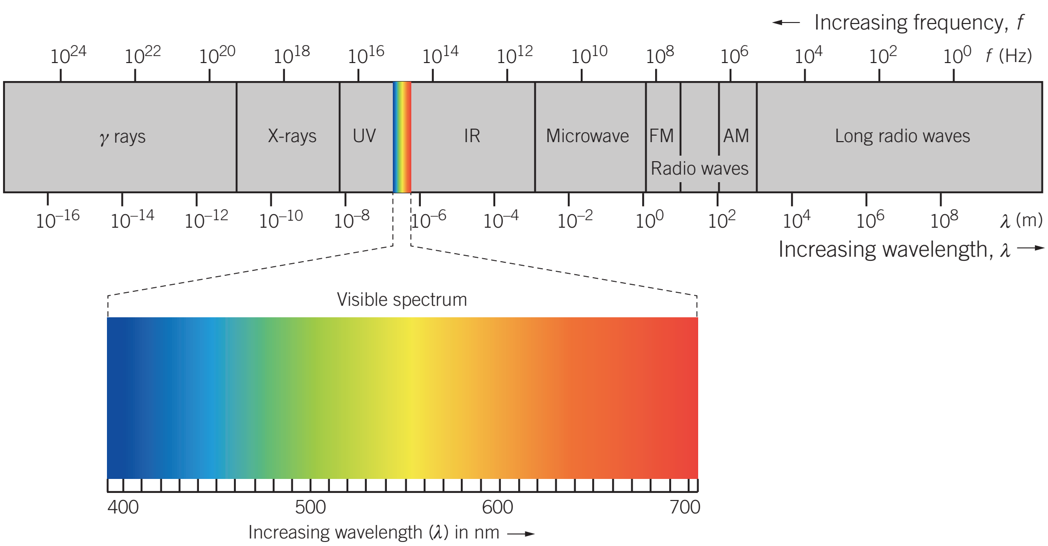
Transverse and longitudinal waves

1A The properties of waves



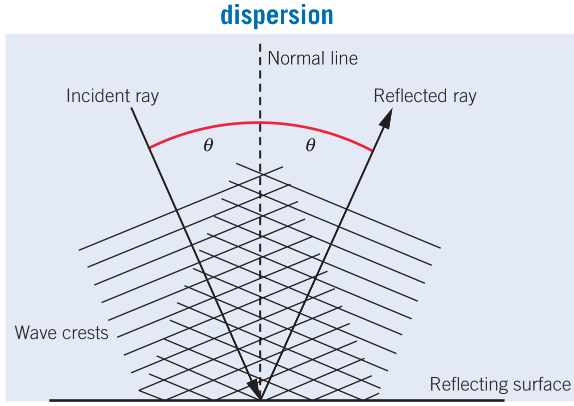
Transverse waves travelling at the same speed, c, in a vacuum

1B Electromagnetic waves



Visible light

1C Reflection, refraction and dispersion



See the Interactive Textbook for an interactive version of this concept map interlinked with all concept maps for the course.

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1A The properties of waves

Study Design:

- Identify the amplitude, wavelength, period and frequency of waves
- Calculate the wavelength, frequency, period and speed of travel of waves using $\lambda = \frac{v}{f} = vT$
- Explain the wavelength of a wave as a result of the velocity (determined by the medium through which it travels) and the frequency (determined by the source)

Glossary:

Amplitude, A
Compression
Frequency, f
Longitudinal wave
Medium
Period, T
Rarefaction
Transverse wave
Wavelength, λ

ENGAGE

What are waves?

Waves are all around us and affect many aspects of our lives. Sound waves are used to communicate and to enrich our culture. Ultrasound is used by bats to navigate, by doctors to image our internal organs, by dentists to our clean teeth, and there are a host of other cleaning technologies. Water waves range from tiny ripples to gigantic ocean waves and tsunamis, both entertaining us and threatening our lives. Movements in Earth's crust cause seismic waves that travel as fast as 5 km s^{-1} in solid rock. Matter waves are central to quantum mechanics. Light waves, the focus of most of this chapter, travel through a vacuum at 300 000 km s^{-1}. When astronomers observe distant stars, they are looking at objects that sent out their light billions of years ago and do not exist anymore.

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EXPLAIN

The nature of waves

The source of all waves is a vibration of some kind. Mechanical waves vibrate particles of a **medium**. The vibrations then spread though the medium. Non-mechanical waves, such as light waves, do not require a medium. Their vibrations are electrical and magnetic, and they can travel through both transparent materials and a vacuum, such as the space between the Sun and Earth. You can recognise waves by their vibrations and the fact that they transfer energy without transferring matter. A good example of a simple mechanical wave can be seen when a slinky spring is shaken at a steady rate, as shown in Figure 1A–1.

Medium
a substance or material that can carry the vibrations of a wave

Transverse wave
a wave in which vibrations are perpendicular to the direction of travel

Longitudinal wave
a wave in which vibrations are parallel to the direction of travel

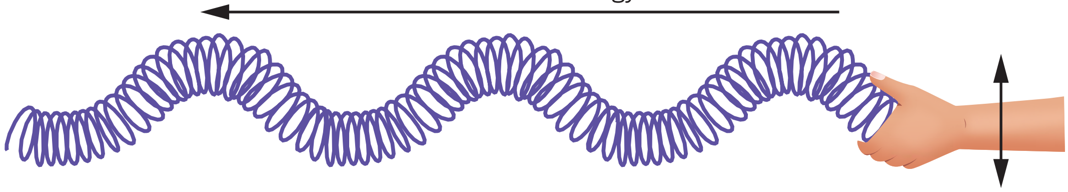

Figure 1A–1 Transverse wave in a slinky spring

VIDEO 1A–1
THE NATURE OF WAVES

If you look carefully at the movement of the spring, you will notice that although the wave moves to the left, the individual coils of the spring do not move left (or right); they just vibrate up and down. Waves like this are called **transverse waves**. Another everyday example of transverse waves are water waves, such as ocean swells or ripples in a pond where the water particles move more or less up and down as the wave moves along. There are other kinds of waves where the particles vibrate parallel to the direction of travel of the wave; these are called **longitudinal waves**. These can also be shown by shaking a slinky parallel to its length. Sound waves are also examples of this kind of wave. You can set up a longitudinal wave in a slinky spring as shown in Figure 1A–2. The vibrations create regions of **compression**, where the particles of the slinky are more closely spaced, and **rarefactions**, where the particles are more spread out.

Compression
in longitudinal waves, a region where particles are most closely spaced

Rarefaction
in waves, a region where particles are most spread out

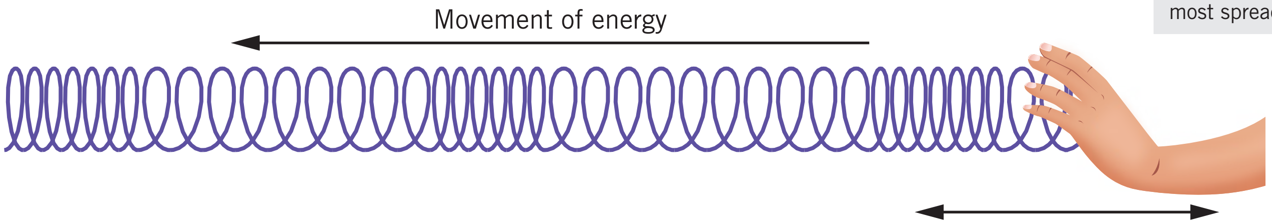

Figure 1A–2 Longitudinal wave in a slinky spring

In the example of the slinky spring waves, the energy input from the shaking hand at one end appears as energy at the other end of the spring. However, the particles of the slinky spring simply vibrate in the one place to and fro and do not travel from one end of the spring to the other end, but the vibrations do.

Check-in questions – Set 1

1 What is the difference between a transverse and a longitudinal wave?
2 What is the difference between a mechanical and a non-mechanical wave?
3 How does a mechanical wave motion transfer energy from one place to another?

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Describing waves

Amplitude, A
a measure of the size of vibrations in a wave as the maximum distance a point in the wave vibrates away from the neutral position; generally measured in metres (m)

Frequency, f
the number of wavelengths of a wave that pass a fixed point in a second; measured in hertz (Hz)

Wavelength, λ
the distance between repeated parts of a wave shape; measured in metres (m)

Period, T
the time it takes for a wave to move one wavelength in the direction of travel; measured in seconds (s)

The key terms describing waves are **amplitude**, **frequency**, **wavelength**, **period** and speed. Figure 1A–3 shows these terms applied to a transverse wave in a slinky spring.

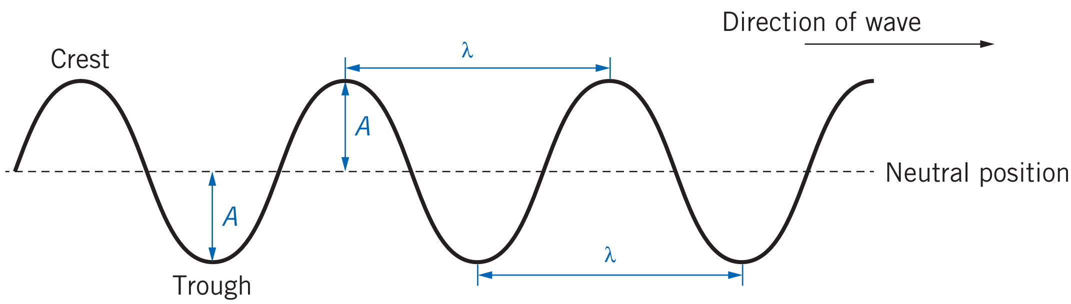

Figure 1A–3 Idealised sinusoidal transverse wave

- Amplitude, A, is a measure of the size of the wave vibrations; it is the maximum displacement from the neutral (mid-point) position. It is generally measured in metres.
- Wavelength, λ, is the distance between repeated parts of the wave shape. It is also measured in metres.
- Speed, v, is the speed of the wave as it moves. It is different from the transverse speed of the particles of the medium. It is measured in metres per second (m s^{-1}). The speed of a wave is determined by the properties of the medium through which it travels.
- Period, T, is the time for the wave shape to move one wavelength in the direction of travel. It is measured in seconds.
- Frequency, f, is equal to the number of wave shapes that pass a point every second. It is equal to $\frac{1}{T}$ and is measured in hertz (Hz). The frequency of a wave is only determined by the source that generates it and does not depend on the nature of medium.

The wavelength, λ, of a wave depends only on the nature of the medium through which the wave moves and is related to the speed, v, and frequency, f, of the wave. If a wave is travelling at a speed of v m s^{-1}, then every second the wave will travel a distance of v m from a fixed point. At the same time, if the frequency of the wave is f Hz, then every second, f wave shapes go past the same fixed point. Hence, in each second the wave travels a distance v m from a fixed point and f wave shapes go past the same point, so in symbols the length of each wave shape is:

Formula 1A–1 The wave equation

$$\lambda = \frac{v}{f} = vT$$

Where:

λ = Wavelength of the wave (m)
v = Speed of the wave (m s^{-1})
f = Frequency of the wave (Hz)
T = Period of the wave (s)

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This equation shows the relationship between wavelength, frequency, speed and period and applies to all types of waves. The frequency of a wave depends only on the source of the wave and not on the medium, whereas the speed of the wave depends on the nature of the medium. Using this relationship, since frequency is constant between media, the wavelength must also depend on the nature of the medium to make up for changes in the speed of the wave in different media. For example, if a wave increases speed going from one medium to another, then from Formula 1A–1 the wavelength must also increase in the medium by the same amount since f does not change between media. This shows that while f does not depend on the medium, wavelength and the speed of the wave do depend on the medium. Usually Formula 1A–1 will be written in the form $v = f\lambda$ and is referred to as the wave equation.

WORKSHEET 1A–1 THE PROPERTIES OF WAVES

Check-in questions – Set 2

1 Define the amplitude of a transverse wave in a slinky spring.
2 State the wave equation with the period (T) as the subject.
3 What determines the speed of a wave?

Worked example 1A–1 Period and frequency of a wave

Find the period and frequency of a water wave of wavelength 8.0 m and speed 5.0 m s^{-1}.

Solution

Using $\lambda = \frac{v}{f}$ to find the frequency and making f the subject gives:

$$f = \frac{v}{\lambda} = \frac{5.0}{8.0} = 0.625 \text{ Hz}$$

Using the definition of f to find the period gives:

$$T = \frac{1}{f} = \frac{1}{0.625} = 1.6 \text{ s}$$

1A SKILLS

Multichoice questions on definitions
Refer to the definition first. Check the options for an answer that can be reworded to fit the definition. If stuck, eliminate unlikely options.

Calculation questions
Identify the relevant formula. If necessary, transform the equation so that the subject of the equation is the desired quantity. Always check that your answer is a reasonable quantity. For example, if your answer to a speed question is greater than the speed of light in a vacuum ($v = 3 \times 10^8$ m s^{-1}), then it must be incorrect.

VIDEO 1A–2 SKILLS: CALCULATION QUESTIONS

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Section 1A questions

Multiple-choice questions

1 Which of the following characteristics is particularly associated with wave motion?

A vibrations which are longitudinal to the direction of motion

B the transfer of matter from one place to another

C vibrations which transfer energy from one place to another

D vibrations which are transverse to the direction of motion

2 Which of the following statements best describes the frequency of a moving transverse wave?

A The frequency of the wave is related to the time it takes a wave to travel any fixed distance.

B The frequency of the wave is related to the time it takes a wave crest to travel one wavelength.

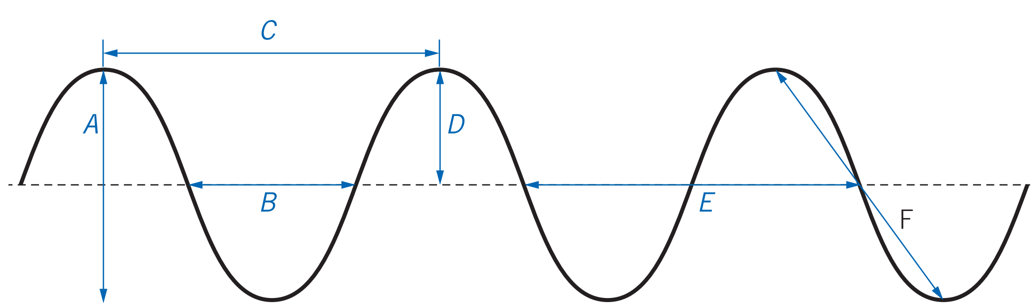
C The frequency of the wave is inversely related to the time it takes a wave crest to travel one wavelength.

D The frequency of the wave is equal to the time it takes a wave crest to travel one wavelength.

Short-answer questions

Use the following information to answer Questions 3 and 4.

The sketch below shows a side-on view of a wave in a rope. It is a transverse wave, and is moving from left to right.



3 Which one or more of the arrows labelled *A* to *F* best describes the size of the amplitude of the wave shown?

4 Which one or more of the arrows labelled *A* to *F* best describes the size of the wavelength of the wave shown?

5 Calculate the speed of a wave of frequency 3.0×10^9 Hz and wavelength 2.5 cm.

6 Calculate the frequency of a wave of speed 56 mm s^{-1} and wavelength 1.4×10^{-5} m.

7 Calculate the wavelength of a wave of speed 16 km s^{-1} and period 0.40 s.

8 Calculate the speed of a wave of wavelength 4.4×10^{-8} m and period 1.1×10^{-5} s.

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1B Electromagnetic waves

Study Design:

- Identify all electromagnetic waves as transverse waves travelling at the same speed, *c*, in a vacuum as distinct from mechanical waves that require a medium to propagate
- Compare the wavelength and frequencies of different regions of the electromagnetic spectrum, including radio, microwave, infrared, visible, ultraviolet, X-ray and gamma, and compare the different uses each has in society
- Describe electromagnetic radiation emitted from the Sun as mainly ultraviolet, visible and infrared

Glossary:
Electric field
Electromagnetic radiation
Electromagnetic spectrum
Electromagnetic wave
Gamma ray
Infrared (IR)
Magnetic field
Microwave
Radio wave
Ultraviolet (UV)
Visible light
X-ray

ENGAGE

How do we understand light?

The electromagnetic spectrum, which includes visible light, plays a crucial role in our lives. Through photosynthesis, light sustains all humankind. There have also been revolutionary applications in medicine, culture, communications, energy, weather forecasting, remote sensing, scientific research and our understanding of the Universe. For example, the recently launched James Webb Space Telescope allows us to see light from the fringes of the Universe and billions of years into the past.

Figure 1B–1 One of the first released images from NASA's new James Webb Space Telescope, the world's largest and most powerful space telescope. Captured in infrared light, the image shows the edge of a young star-forming region called NGC 3324 in the Carina Nebula.

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But what is the nature of light? How fast does it travel? What is it made of? The famed physicist Isaac Newton thought it was made up of tiny particles. Some of his scientific opponents thought it was a kind of wave, but thought that waves needed a medium to vibrate, and no one could find one. But in 1862, Scottish physicist James Clerk Maxwell proposed that waves made up of vibrating electric and magnetic fields could travel in a vacuum at 3.00×10^8 m s^{-1} as a transverse wave without the need for a medium.

EXPLAIN

What is light?

VIDEO 1B–1 WHAT IS LIGHT

Electric field
a physical field that creates a force on all charged particles within the field. Produced by charged particles and changing magnetic fields. A changing electric field also produces a changing magnetic field.

Magnetic field
a physical field that creates a force on moving charged particles and magnetic materials within the field. Produced by changing electric fields and magnetic materials. A changing magnetic field also produces a changing electric field.

Electromagnetic wave
a transverse wave made up of perpendicular changing electric and magnetic fields, which can propagate through space without the need of a medium

Electromagnetic theory, Maxwell's crowning achievement, predicted that accelerating charges should generate waves – waves made up of changing electric and magnetic fields. The changing **electric field** causes a changing **magnetic field**, which in turn generates a changing electric field – and so on. The wave produced in this way doesn't need a medium to propagate, unlike mechanical waves such as sound, which do require a medium to propagate. These waves travel through a vacuum at the speed of light, c, 3.00×10^8 m s^{-1}. The electric and magnetic fields are always at right angles to each other, as shown in Figure 1B–2 below. The waves are also always transverse because the electric and magnetic fields are always perpendicular to the direction of travel of the waves.

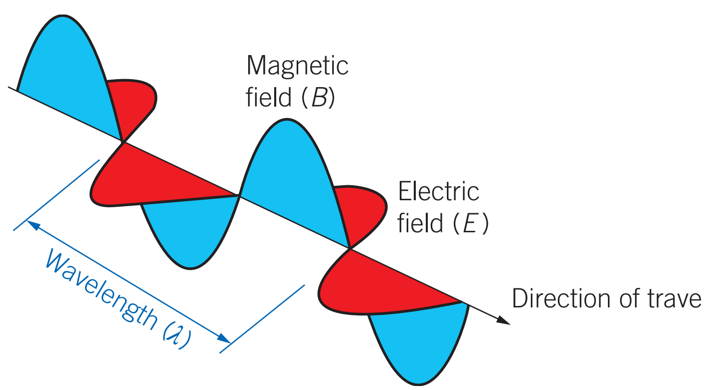

Figure 1B–2 Diagram of an electromagnetic wave

The wavelength is shown in Figure 1B–2 and is the same for the electric field and the magnetic field. All **electromagnetic waves** obey the wave equation ($v = f\lambda$), and have the same speed in a vacuum, equal to c. In other media, electromagnetic waves travel more slowly; for example, the speed of green light in water is 2.25×10^8 m s^{-1}. In a vacuum, the wave equation for electromagnetic waves can be written as:

Formula 1B–1 The wave equation for electromagnetic waves

$$c = f\lambda$$

Where:

c = Speed of light in vacuum (3.00×10^8 m s^{-1})
f = Frequency of the wave (Hz)
λ = Wavelength of the wave (m)

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The electromagnetic spectrum

Maxwell predicted that there could be a whole family of electromagnetic waves with a range of wavelengths and frequencies. He was right. We now call this the **electromagnetic spectrum**. The electromagnetic spectrum is shown in Figure 1B–3.

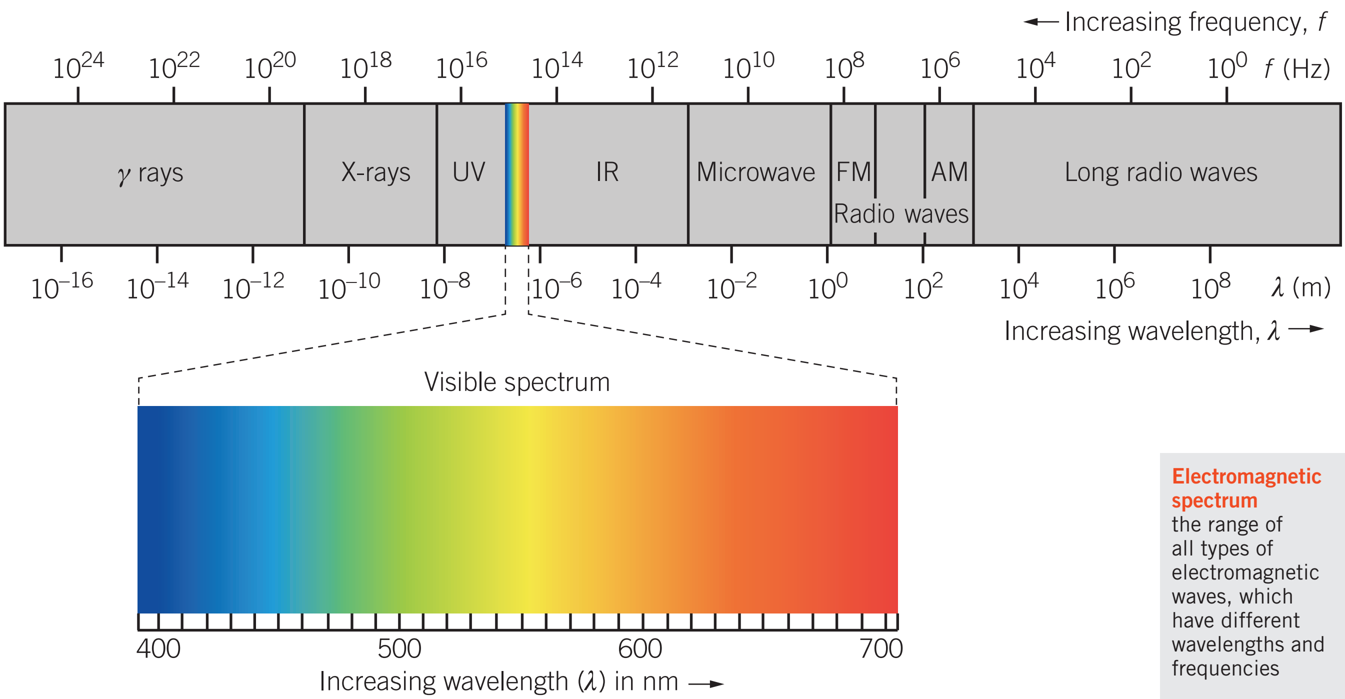

Figure 1B–3 The electromagnetic spectrum. Visible light forms only a narrow wavelength window of the whole spectrum.

Figure 1B–3 shows the relationship between wavelength and frequency for electromagnetic waves, that frequency increases (moving right to left in the diagram) with decreasing wavelength. This behaviour can be explained by Formula 1B–1 since the speed of light in a vacuum, c, is constant and $c = f\lambda$. So, increasing or decreasing frequency, f, must result in a corresponding decrease or increase in wavelength, λ, and since f is determined by the source, a large range of electromagnetic waves with different wavelengths and properties can be produced. The electromagnetic spectrum is broken up into approximate regions based on wavelength with the longest wavelength waves being **radio waves** and the shortest being **gamma rays**. Between them, in order of decreasing wavelength (increasing frequency), are **microwave**, **infrared (IR)**, **visible light**, **ultraviolet (UV)** and **X-ray**. Labelling the different regions is important because it helps identify and separate the different processes that create electromagnetic waves. It also allows for broader classification of properties, which is helpful when looking at applications.

Visible light
the region of the electromagnetic spectrum between 400 nm to 700 nm; it is the only region that can be detected by our eyes

Ultraviolet (UV)
the region of the electromagnetic spectrum between visible light and X-rays

X-ray
the region of the electromagnetic spectrum between UV and gamma rays; they have the second shortest wavelengths and second highest frequencies

Electromagnetic spectrum
the range of all types of electromagnetic waves, which have different wavelengths and frequencies

Radio wave
the region of the electromagnetic spectrum with the longest wavelength and lowest frequencies

Gamma ray
the region of the electromagnetic spectrum with the shortest wavelengths and highest frequencies

Microwave
the region of the electromagnetic spectrum with the longest wavelength the region of the electromagnetic spectrum with after radio waves

Infrared (IR)
the region of the electromagnetic spectrum between microwaves and red light; produced by sources of heat and is not visible to the human eye but can be detected as warmth on the skin

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Check-in questions – Set 1

1 What are the relative orientations of the electric vibrations, the magnetic vibrations, and the velocity of a light wave?
2 Convert 800 nm into metres.
3 What kinds of electromagnetic waves have a wavelength of 0.10 nm?
4 State the regions of greatest and smallest frequency of the electromagnetic spectrum.

Societal uses of the electromagnetic spectrum

The electromagnetic spectrum has an amazing range of uses, and every region is useful. The Study Design requires you to be familiar with the wavelength and frequency ranges of radio, microwave, infrared, visible, ultraviolet, X-ray and gamma ray radiations. Table 1B–1 shows some common uses for each, but there are many more (see Table 1B–2 on page 18 for an explanation of the units you will encounter in this table and throughout the chapter).

Table 1B–1 Common applications of the electromagnetic spectrum

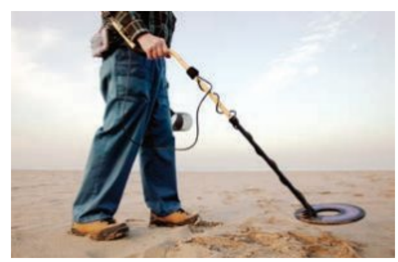
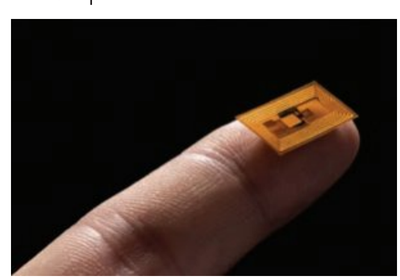
Spectrum region and approximate wavelength and frequency range	Applications	Illustrated examples
Radio > 1 m and < 300 MHz	• A wide range of communication technologies, including AM and FM radio, TV, CB radios, mobile phones • Radioastronomy gives information about the Universe otherwise unobtainable • Aircraft and ship navigation (radio direction finding) • Global positioning systems (GPS) • Metal detectors • Magnetic resonance imaging (MRI) • Radio frequency identification (RFID)	Metal detector  RFID chip 
Microwaves 1 m – 1 mm and 300 MHz – 300 GHz	• Heating in microwave ovens • Radar • Remote sensing; microwave radiation penetrates clouds, haze, dust and most rain; their wavelengths are unaffected by scattering unlike optical wavelengths • Microwave astronomy • Communications (including mobile phones)	Microwave oven 

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Table 1B–1 *Continued*

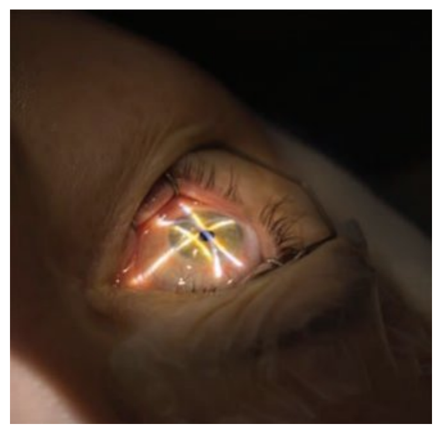
Spectrum region and approximate wavelength and frequency range	Applications	Illustrated examples
Infrared (IR) 1 mm – 700 nm and 300 GHz – 430 THz	• Thermal imaging (including night vision goggles) • Remote controls (e.g. for domestic TVs) • Heat lamps in IR saunas • IR astronomy • Optical fibre signals	Night vision goggles 
Visible 700 nm – 400 nm and 4.3×10^{14} Hz – 7.5×10^{14} Hz	• Vision • Lighting • Optical astronomy • Laser applications – surgery, pointers, cutters, communication • Phototherapy (for seasonal affective disorder (SAD), jaundice) • Photosynthesis (growth of plants)	Laser eye surgery 
Ultraviolet (UV) 400 nm – 10 nm and 7.5×10^{14} Hz – 3×10^{16} Hz	• Vitamin D generation in the skin • UV astronomy • Medical and food sterilisation	UV food and drink sterilisation 
X-rays 10 nm – 10 pm and 3×10^{16} Hz – 3×10^{19} Hz	• X-ray astronomy • Industrial scanning for quality control • Medical imaging (including computerised tomography (CT) scans) • Medical therapies (cancer treatment) • X-ray security imaging • Detection of art forgeries	Luggage X-ray scanners 

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Table 1B–1 *Continued*

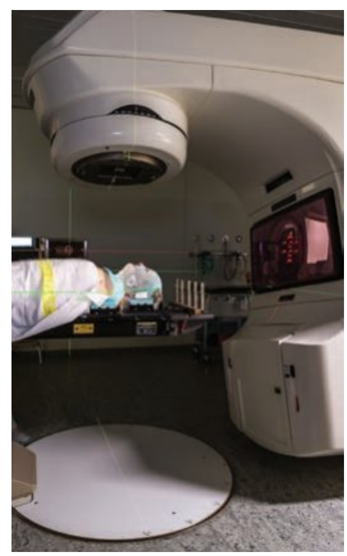
Spectrum region and approximate wavelength and frequency range	Applications	Illustrated examples
Gamma rays < 10 pm and > 3×10^{19} Hz	• Medical and food sterilisation • Medical imaging (PET scanners) • Medical therapy (cancer treatment) • Gamma ray astronomy • Industrial fault finding and tracing • Electrostatic discharging	PET scanners and radiotherapy  Radiotherapy 

Table 1B–1 shows that each region of the electromagnetic spectrum has its own useful and different applications in society. Generally, longer wavelength waves such as radio and microwave are used more for applications such as communications and radar. This is because they carry lower energy and are safer and their longer wavelengths allow them to travel around (diffract) buildings easier. At the other end of the spectrum, the shorter wavelength regions such as UV, X-ray and gamma ray aren't used for communications or radar. Instead, they are used in applications such as sterilisation of equipment, medical imaging and treatment of cancer. This is because, at these short wavelengths, the waves have much higher energy density and aren't as safe for living organisms. They can potentially cause serious harm to humans in large doses. Interestingly, each region of the spectrum is useful for different kinds of astronomy. This is because looking at each spectrum separately allows us to identify and detect different objects and processes occurring in space.

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Light from the Sun

Almost all of the energy that Earth receives from the Sun arrives as **electromagnetic radiation**. The idealised graph in Figure 1B–4 shows the distribution of radiation intensity by wavelength along with the percentage of total energy emitted in the ultraviolet, visible light, near infrared, far infrared and other regions of the solar spectrum.

Electromagnetic radiation another term commonly used to refer to electromagnetic waves

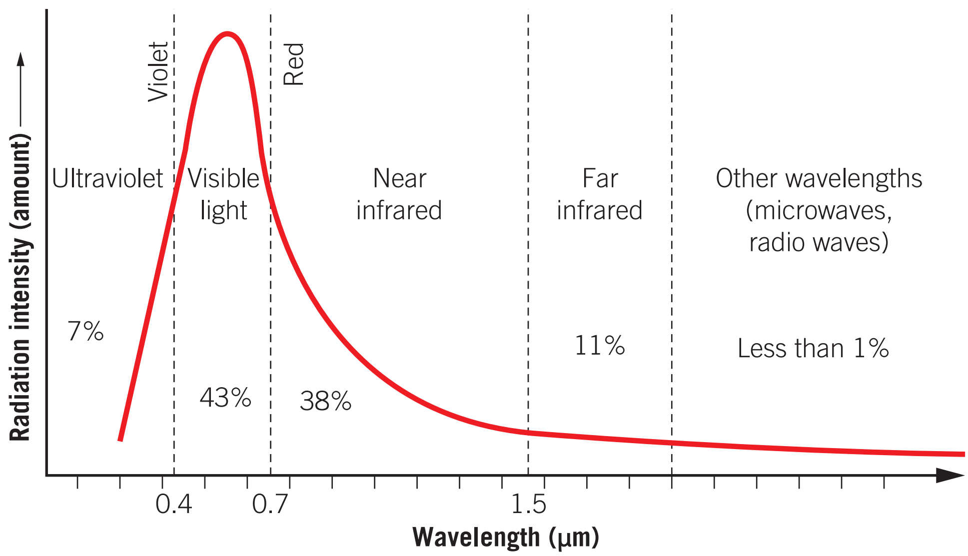

Figure 1B–4 Idealised solar spectrum

As the graph in Figure 1B–4 shows, the majority of electromagnetic radiation that Earth receives is infrared (48%) and visible light (44%), with an additional 7% from ultraviolet, leaving a tiny 1% from other wavelengths. The main contribution to warming the planet comes from infrared radiation. We can detect visible light with our eyes, infrared with our skin and ultraviolet with instruments (and, if excessive, with subsequent skin damage). Understanding the wavelength distribution helps us make best use of solar radiation and avoid its dangers. Positive benefits include absorbing visible and IR in solar cells, treating SAD (seasonal affective disorder) with visible light, the formation of vitamin D by the action of UV in our skin and photosynthesis (where the best wavelengths are blue light at about 435 nm and red light at about 650 nm). Negative effects include the formation of skin damage and cancers by UV and the effect of too much blue wavelength light on sleep patterns.

WORKSHEET 1B–1 ELECTRO-MAGNETIC WAVES

Check-in questions – Set 2

1 What named region of the spectrum would be used in these situations?
   a a mobile phone
   b a baggage scanner at an airport
   c a TV remote control
   d vitamin D generation in the skin
   e optical astronomy
2 Identify the type of electromagnetic rays with the following properties.
   a have the greatest energy density
   b are used to broadcast TV signals
   c have the highest frequency
   d have the longest wavelength
3 Rank the three main types of electromagnetic radiation received by Earth by radiation amount.

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VIDEO 1B–2
SKILLS: UNITS AND CONVERSIONS

1B SKILLS

Units

Because the electromagnetic spectrum has such a wide range of values, it is essential to know the following SI prefixes, which you will also meet in many other places. Converting between them is an essential skill in this course. The 1B Skills video shows more examples of calculations.

Table 1B–2 Common SI prefixes, their values compared to the base unit and examples.

Name	Value (times base unit)	Example
tera (T)	10^{12}	THz, terahertz
giga (G)	10^{9}	GHz, gigahertz
mega (M)	10^{6}	MHz, megahertz
kilo (k)	10^{3}	km, kilometre
(Base unit, no prefix)	10^{1}	metre, hertz, gram, etc.
centi (c)	10^{-2}	cm, centimetre
milli (m)	10^{-3}	mm, millimetre
micro (μ)	10^{-6}	μm, micrometre
nano (n)	10^{-9}	nm, nanometre
pico (p)	10^{-12}	pm, picometre

To convert units with a prefix into the base unit, multiply by the value of the prefix. For example, to convert 30 GHz into hertz, use the prefix from Table 1B–2 as follows:

$$\begin{aligned} 30\text{ GHz} &= 30 \times 10^{9}\text{ Hz} \\ &= 3.0 \times 10^{10}\text{ Hz} \end{aligned}$$

To convert 550 nm into metres, use the table again as follows:

$$\begin{aligned} 5.5 \times 10^{-7}\text{ m} &= 5.5 \times \frac{10^{-7}}{10^{-9}} \\ &= 5.5 \times 10^{2}\text{ nm} \\ &= 550\text{ nm} \\ &= 550 \times 10^{-9}\text{ m} \\ &= 5.5 \times 10^{-7}\text{ m} \end{aligned}$$

To convert quantities in the opposite direction, i.e. from the base unit into units with a prefix, divide by the value of the prefix.

Section 1B questions

Multiple-choice questions

Take $c = 3.00 \times 10^{8}\text{ m s}^{-1}$

1 When electromagnetic radiation from the Sun arrives at the surface of Earth, it warms the surfaces that it falls on. The best explanation of this is that

A light particles have travelled from the Sun's surface to Earth's surface.

B electromagnetic waves have managed to cross the nearly empty space between Earth and the Sun by vibrating the few particles that exist between Earth and the Sun.

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C electromagnetic waves carry energy from the surface of the Sun to the surface of Earth; they do not need a medium for transmission.

D light from the Sun does not warm the surface of Earth; the warming effect is entirely from other mechanisms.

2 Often people in remote situations carry a PLB (personal locator beacon) transmitter, shown here. These operate at 406 MHz and use electromagnetic radiation. Which one of the following characteristics describes PLB radiation?

A it requires a medium for its transmission

B it is a transverse wave motion

C it does not require a medium for its transmission

D it is a mixture of transverse and longitudinal waves

3 PLB radiation differs from visible light in which one of the following ways?

A one is a transverse wave motion and the other is not

B it has a different wavelength

C it has a different period

D PLB radiation cannot travel through a vacuum

Short-answer questions

4 Arrange the following components of visible light in order of increasing wavelength: yellow, green, violet, red.

5 Rank the following colours in order of increasing frequency: green, ultraviolet, red, yellow.

6 Refer to the information given in Question 2 and identify the region of the spectrum that PLB radiation occupies. Calculate the period and wavelength of these waves. Give your answer in ns and cm.

7 A scientist has a 500 nm laser for some experiments and would like a laser with double the frequency. Find the wavelength that this new laser would have and the region that it would occupy in the electromagnetic spectrum.

8 SAD can be treated with phototherapy using electromagnetic radiation of frequency 6.4×10^{14} Hz. Identify this radiation in the electromagnetic spectrum.

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1C Reflection, refraction and dispersion

Study Design:

- Investigate and analyse theoretically and practically the behaviour of waves including:
  - refraction using Snell's Law: $n_1\sin(\theta_1) = n_2\sin(\theta_2)$ and $n_1v_1 = n_2v_2$
  - total internal reflection and critical angle including applications: $n_1\sin(\theta_c) = n_2\sin(90°)$
- Investigate and explain theoretically and practically colour dispersion in prisms and lenses with reference to refraction of the components of white light as they pass from one medium to another
- Explain the formation of optical phenomena: rainbows; mirages
- Investigate light transmission through optical fibres for communication

Glossary:
Chromatic distortion
Colour dispersion
Critical angle
Monochromatic
Normal
Optical fibre
Partial internal reflection
Reflection
Refraction
Refractive index
Snell's law
Total internal reflection

ENGAGE

Applications of light

There can be little doubt that the role of light in photosynthesis and vision is crucial for most living things. There are also many applications of light in many other areas, as discussed earlier in this chapter.

Figure 1C–1 A vivid rainbow after a summer storm

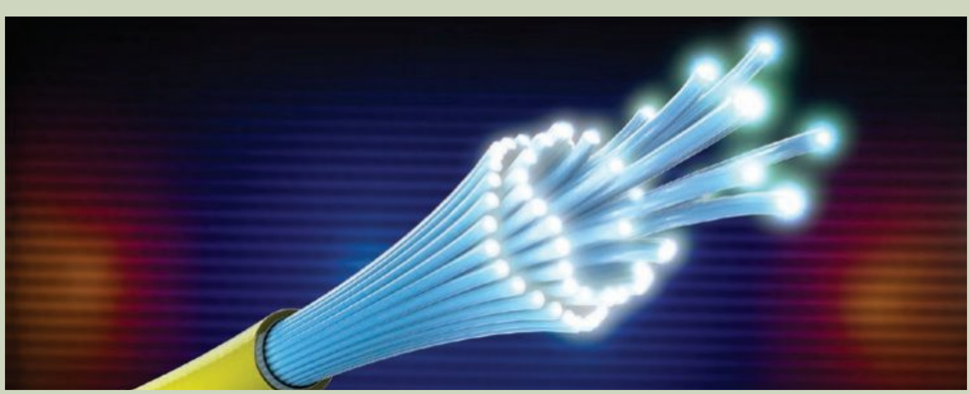

Figure 1C–2 Bundled optical fibres

All light applications require an understanding of the behaviour of light. In this section, you will focus on understanding reflection, refraction and dispersion of visible light and applications of these concepts to the phenomena of rainbows, mirages and optical fibres.

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EXPLAIN

Visualising light paths

Although light is made up of vibrating electric and magnetic fields, these vibrations are far too fast and the wavelengths are too small for us to represent them accurately. Take green light, for example, with a wavelength of 550 nm (5.5×10^{-7} m). It has an extremely high frequency of 5.45×10^{14} Hz. Even if you could 'see' such vibrations and wavelengths, a diagram of a parallel beam of light would give an arrangement like that shown in Figure 1C–3.

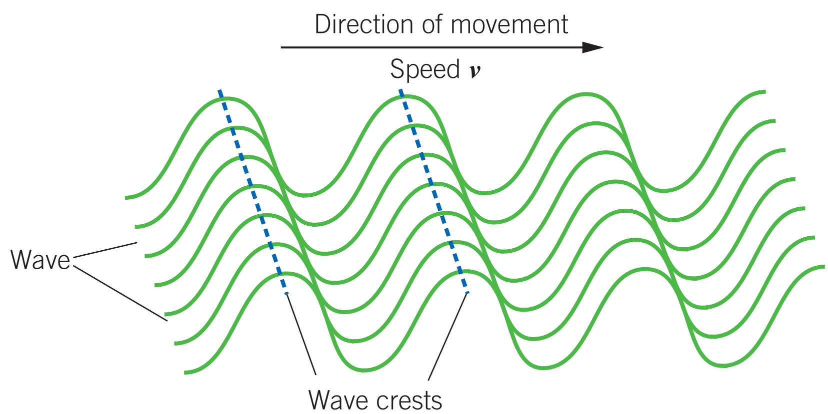

Figure 1C–3 Waves and wave crests

Sometimes diagrams include the wave crests to help describe what is happening in terms of the wave properties of light. However, a simple arrow or ray is often used to represent the path of a light beam.

Reflection of light

In common with other kinds of waves, such as water waves and sound waves, light reflects when it meets a surface between two media. Sometimes the **reflection** is total, and sometimes partial. If the surface is smooth, the reflected beam is at the same angle that it strikes the surface. This is shown in Figure 1C–4.

Reflection
a change in the direction of the wave crest as it meets the surface between two media that results in the wave travelling back into the medium it came from

Normal
an imaginary line that extends from the surface of an object and is perpendicular to the tangent of the surface at that point

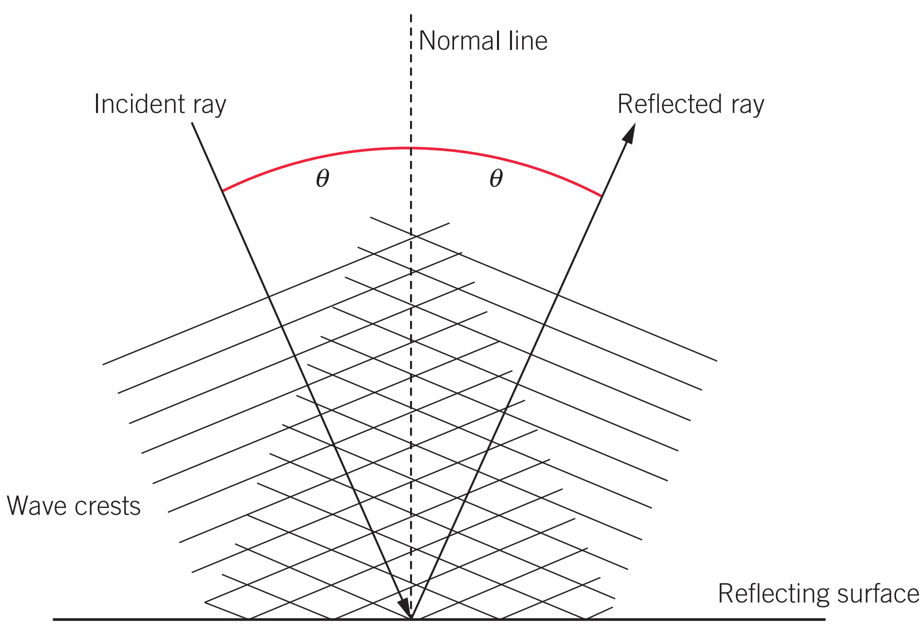

Figure 1C–4 Wave crests reflecting off a flat surface at an angle θ

The angle is usually measured between the direction of travel of the wave and the **normal**, an imaginary line perpendicular to the surface. In Figure 1C–4 the angle is θ.

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Speed of light in transparent materials

When light is travelling through a medium other than a vacuum, its speed is less than 3.00×10^8 m s^{-1}. The actual speed depends on the medium. In water, for example, it travels at 2.25×10^8 m s^{-1}.

A beam of light moving from air into a glass block at right angles is shown in Figure 1C–5 (using rays) and in Figure 1C–6 (using wave crests, shown as horizontal lines).

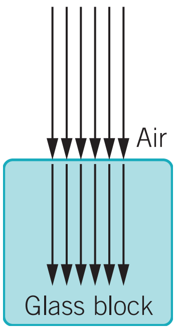

Figure 1C–5 Ray diagram

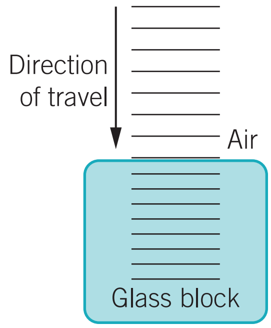

Figure 1C–6 Wave crest diagram

Table 1C–1 Speed of light in various media

Medium	Speed of light (m s^{-1})
Air	3.00×10^8
Water	2.25×10^8
Typical plate glass	1.98×10^8
Plastic spectacle lens	1.74×10^8
Diamond	1.24×10^8

The ray diagram gives only the direction of the light, whereas the wave representation shows that the wavelength of the light has changed on entering the glass.

Worked example 1C–1 Wavelength of light in a medium

In a type of glass the speed of light is $v = 2.00 \times 10^8$ m s^{-1}, and in air the speed is $c = 3.00 \times 10^8$ m s^{-1}. A ray of light has a frequency of 6.00×10^{14} Hz.

Calculate in nm:

a the wavelength of the light in air
b the wavelength of the light in the glass

Solution

a Using $c = f\lambda$ with λ as the subject gives:

$$\lambda = \frac{c}{f} = \frac{3.00 \times 10^8}{6.00 \times 10^{14}} = 5.00 \times 10^{-7}\,\text{m} = 500\,\text{nm}$$

b Using $v = f\lambda$ with λ as the subject gives:

$$\lambda = \frac{c}{f} = \frac{2.00 \times 10^8}{6.00 \times 10^{14}} = 3.33 \times 10^{-7}\,\text{m} = 333\,\text{nm}$$

1A THE PROPERTIES OF WAVES LINK

Notice that, as you learned in Section 1A, when the light moves from one medium to the next, the wavelength may change but the frequency does not. The reason frequency depends only on the source is that the rate at which wave crests arrive and leave the surface between the two media must be the same, leading to the formula in the next box.

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Formula 1C–1 The wave equation at the surface of a medium

$$f = \frac{v_1}{\lambda_1} = \frac{v_2}{\lambda_2}$$

Where:

f = Frequency of the wave (Hz)

v_1 = Speed of the wave in the first medium ($m\,s^{-1}$)

λ_1 = Wavelength of the wave in the first medium (m)

v_2 = Speed of the wave in the second medium ($m\,s^{-1}$)

λ_2 = Wavelength of the wave in the second medium (m)

Refraction of light

Most light rays do not arrive at surfaces at right angles, but at some other angle, and the light beam changes direction, as shown in Figure 1C–7. This is called **refraction**. As with reflected rays, the reference line for the direction of the light is the normal line.

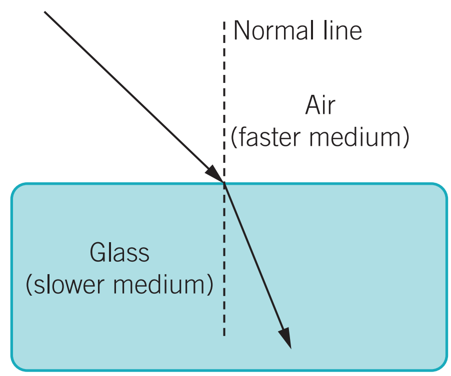

Figure 1C–7 Refracted light ray

Refraction the change in direction of a wave moving from one medium (or vacuum) to another medium (or vacuum) caused by the wave changing speed

Refractive index a measure of how much slower light travels through a medium compared to a vacuum; given the symbol n

The wave properties of light explain why the ray changes direction when it passes from one transparent medium to another with different properties, as illustrated in Figure 1C–8. When the wave crests reach the slower medium, they slow down and bunch up because the wavelength of the waves become shorter. This changes the direction of the waves. The ray entering the medium with the slower speed bends towards the normal. Rays going the other way, from a slower medium to a faster medium, bend away from the normal line.

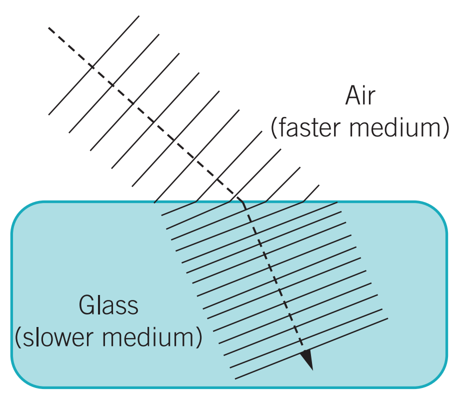

Figure 1C–8 Wave crests diagram of refraction of light through glass

The amount of refraction that occurs as light passes from one medium into another is related to how fast light moves in one medium compared with the other. In order to compare how much one medium will refract light compared to another, it is important to define the **refractive index**, n, of a medium as:

Formula 1C–2 The refractive index

$$n = \frac{c}{v}$$

Where:

n = Refractive index of the medium

v = Speed of light in the medium ($m\,s^{-1}$)

c = Speed of light in a vacuum ($3 \times 10^8\ m\,s^{-1}$)

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The refractive index has no units and measures how fast light moves in a medium compared to air (or a vacuum). A higher value means light moves slower, and in air (or a vacuum) the refractive index is $n_{air} = 1$, which is also the smallest the refractive index of a medium can be. Light travels slower in all transparent media other than air (or a vacuum) so the refractive index will always be greater than 1. (You can check how the refractive index formula works for different media by replacing v with each speed listed in Table 1C–1.)

Generally the more dense a medium is, the slower light travels through it and the higher the refractive index will be. For example, plate glass has a refractive index of 1.5 which means that light travels 1.5 times slower in plate glass than in air. The refractive index is useful because it allows different materials to be easily compared and also because it is related to how much light refracts as it moves from one medium to another, as discussed next.

Aboriginal and Torres Strait Islander peoples' understanding of light

Aboriginal and Torres Strait Islander peoples' understanding of the nature of light appears to have started 60 000 years ago. Their knowledge of how light behaves enabled them to spear fish in water (refraction) and construct effective housing (reflection and absorption).

Figure 1C–9 Accurate spear fishing requires understanding the paths of light through water.

Check-in questions – Set 1

1 Define the refractive index, n, of a transparent material.
2 What is the minimum value of the refractive index of a material?
3 Calculate the refractive index of a material in which the speed of light is 1.5×10^8 m s^{-1}.
4 When a ray of light enters a medium of greater refractive index, which way will the ray refract?
5 When a ray of light moves from a medium of lower speed into a medium of greater speed, which way will it refract relative to the normal line?

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Snell's law

The amount of refraction is measured by comparing the angle the ray makes with the normal before (θ_1) and after (θ_2) it crosses the media boundary as shown in Figure 1C–10.

Sometimes θ_1 is called the *angle of incidence* and θ_2 the *angle of refraction*. The mathematical link between the angles θ_1 and θ_2, the refractive indices n_1 and n_2 and the speeds of light v_1 and v_2 is named **Snell's law** after Willebrord Snell, one of its early discoverers. It is most easily remembered and used in its symmetric forms, shown in the formula box below.

It doesn't matter which medium you call medium 1 or medium 2, and it doesn't matter if the ray of light is reversed – the angles will be the same.

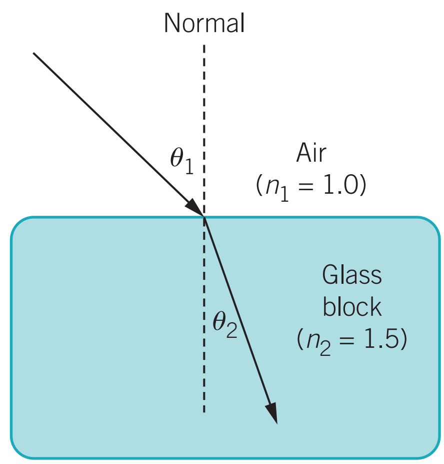


Figure 1C–10 Snell's law can be used to find the angle of incidence and the angle of refraction.

Snell's law
a law that describes mathematically the link between the angle of refraction, the angle of incidence and the refractive indices of each medium

Formula 1C–3 Using Snell's law

$$n_1 \sin \theta_1 = n_2 \sin \theta_2 \quad \text{and} \quad n_1 v_1 = n_2 v_2$$

Where:

n_1 = Refractive index of the first medium

θ_1 = Angle of incidence

v_1 = Speed of light in the first medium ($m\,s^{-1}$)

n_2 = Refractive index of the second medium

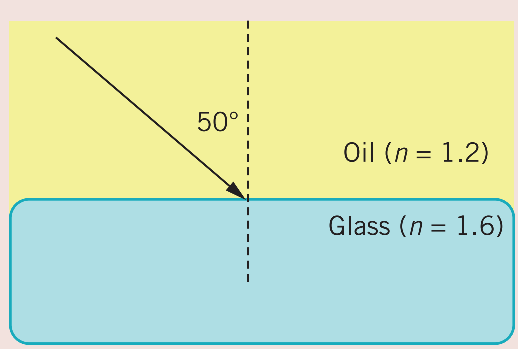
θ_2 = Angle of refraction or emergence

v_2 = Speed of light in the second medium ($m\,s^{-1}$)

Worked example 1C–2 Application of Snell's law

A thin ray of light shines on a glass block (refractive index = 1.6), as shown below. The glass block is immersed in oil with a refractive index of 1.2. Describe the direction of the light ray as it travels from the oil into the glass.

Solution



Using Snell's law, $n_1 \sin \theta_1 = n_2 \sin \theta_2$, with $\sin \theta_2$ as the subject, where:

$\theta_1 = 50°$

$n_1 = 1.2$

$n_2 = 1.6$

Gives:

$$\sin \theta_2 = 1.2 \times \frac{\sin(50°)}{1.6}$$

$$= 0.575$$

$$\theta_2 = 35°$$

Therefore, the ray bends towards the normal, making an angle of 35° with it.

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Optical illusion due to refraction 1: the 'bent' pencil

Objects under water viewed from the air often appear distorted or in the wrong place. A classic illusion is the 'bent pencil', as shown in Figure 1C–11.

Figure 1C–11 Apparent bending of a pencil under water

This can be explained by a ray diagram, as shown in Figure 1C–12.

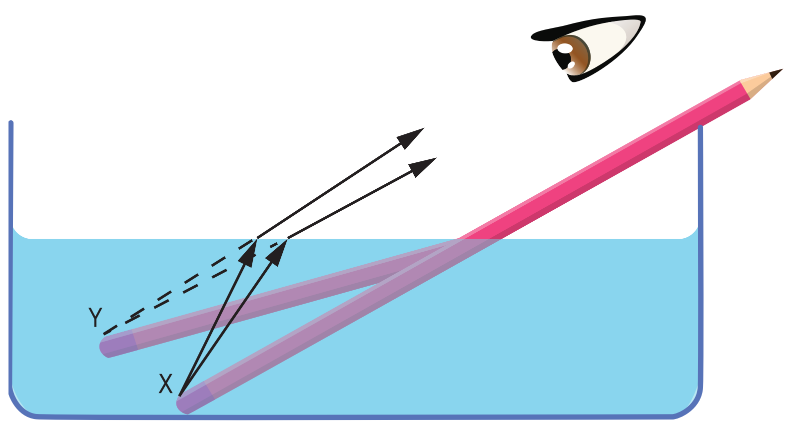

Figure 1C–12 Rays of light from an underwater pencil bend on entering the air.

The pencil is actually at point X, but rays of light from there bend away from the normal as shown. Hence, they appear to come from point Y, nearer the surface. What the eye sees is an *image* of the pencil. This happens for all the underwater parts of the pencil. The same principle applies to spear fishing, as shown in the ray diagram in Figure 1C–13. Because the fish appears to be closer to the surface, the fisher has to aim low, as shown. Of course, gravity has to be allowed for as well!

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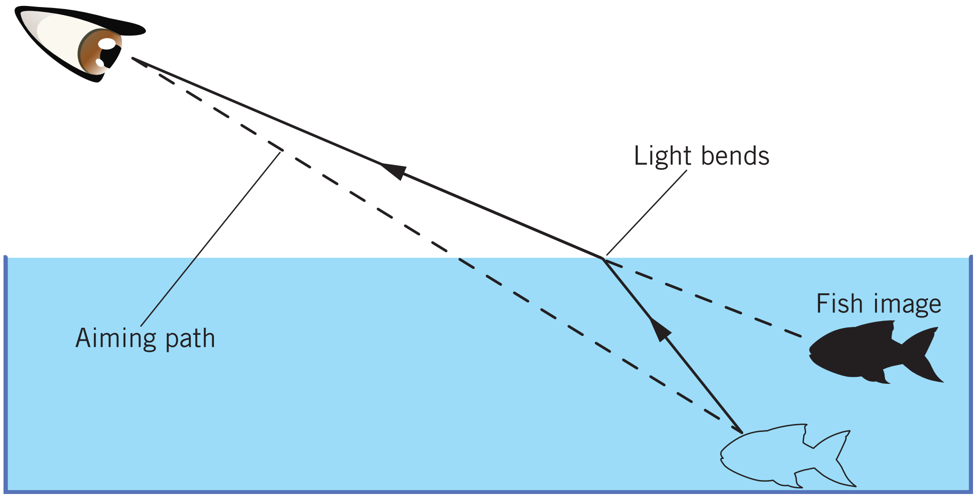

Figure 1C–13 Spear fishers must adjust their aim for refraction in order to catch fish.

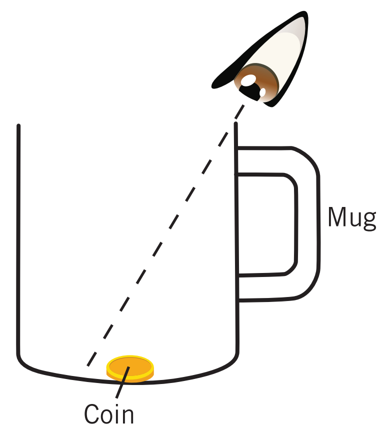

Figure 1C–14 Viewing the coin in an empty mug

Optical illusion due to refraction 2: 'floating' a coin

Place a coin at the bottom of a mug with opaque sides. Move your head to the side so that you just cannot see the coin, as in Figure 1C–14.

Now ask someone else to slowly fill the mug with water. The coin will appear to slowly float into view. But what in fact you are seeing, once again, is an image of the coin. See Figure 1C–15.

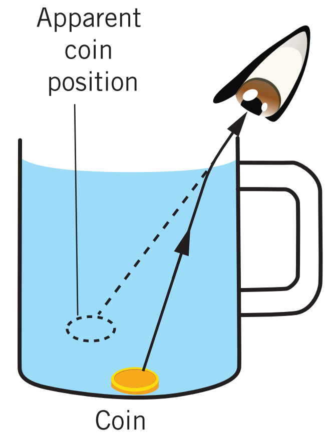

Figure 1C–15 The coin appears to be floating in a mug full of water due to refraction.

Partial internal reflection

As mentioned previously, when light comes into contact with the surface between two media, it is reflected. The reflection will happen at any angle of incidence even when the light is perpendicular to the surface (although it is hard to see in this case because only about 4% is reflected). This means that every time a light ray crosses the surface between different media, only part of the light ray reaches the second medium, and the other part of the light ray is reflected internally back into the first medium, even if most of it travels across the surface. In the case when some of an incident light ray crosses the surface, the reflected ray is said to have undergone **partial internal reflection**, because the light has been split between a ray that crosses the surface and a reflected ray, which are both only a part of the incident ray. An example of partial internal reflection is shown in Figure 1C–16.

Partial internal reflection reflection of light at an interface where some of the light has also refracted across the surface

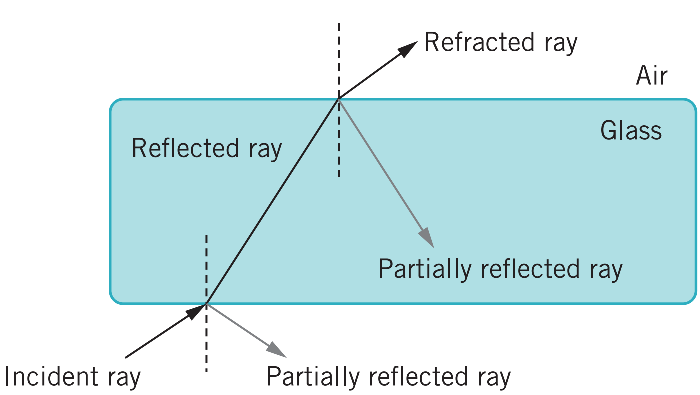

Figure 1C–16 Example of partial internal reflection

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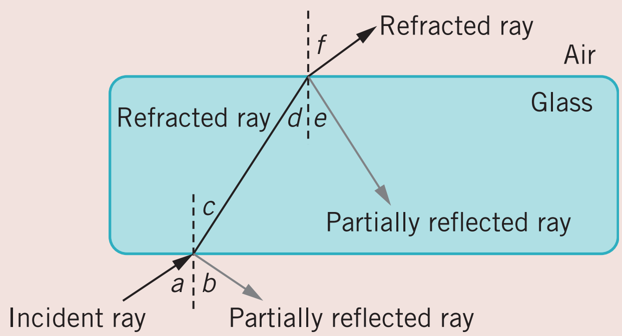
Worked example 1C–3 Partial internal reflection and refraction

The diagram below shows a glass block in air with a light ray entering it (labelled 'incident ray'). Angles *a, b, c, d, e* and *f* are labelled.



a Angles *a* and *b* are equal. Explain why.
b Angles *d* and *e* are equal. Explain why.
c Angles *c* and *d* are equal, because of geometric properties. Use this fact to explain why angles *a* and *f* are equal.

Solution

a Angle *b* is a partial reflection of angle *a*.
b Angle *e* is a partial reflection of angle *d*.
c Applying Snell's law to the incident ray gives the ratio:

$$\frac{\sin a}{\sin c} = \frac{n_{\text{glass}}}{n_{\text{air}}}$$

Applying Snell's law to the refracted ray as it leaves the glass also gives the ratio:

$$\frac{\sin f}{\sin d} = \frac{n_{\text{glass}}}{n_{\text{air}}}$$

Comparing the two equations gives:

$$\frac{\sin a}{\sin c} = \frac{\sin f}{\sin d}$$

Since it is given that angle $c = d$ because of geometric properties, from the equation above angles *a* and *f* are equal.

Total internal reflection

When light rays move from a medium with high refractive index into one with a lower refractive index, the ray refracts away from the normal, as shown in Figure 1C–17, and there is partial internal reflection at the oil–glass interface.

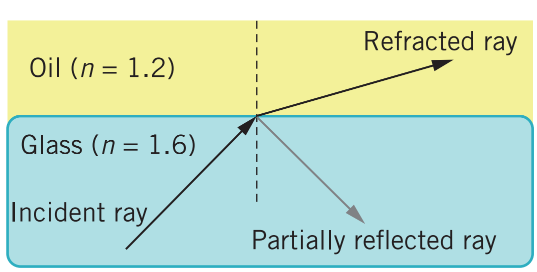


Figure 1C–17 Light ray bending away from the normal

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The angle of the refracted ray in the lower n medium will always be greater than the angle of the incident ray in the higher n medium. In fact, there is a maximum angle that the incident ray can have if the refracted ray is to emerge from the glass. This angle is the critical angle, and as it is approached, the refracted ray approaches an angle of 90° with the normal and weakens. When the **critical angle** is reached, the refracted ray disappears and perfect reflection takes place at the interface. As the incident ray's angle to the normal increases further, the interface continues to behave like a perfect mirror. This is **total internal reflection**. Note that this can only occur when the light is incident on a boundary with a medium of smaller refractive index.

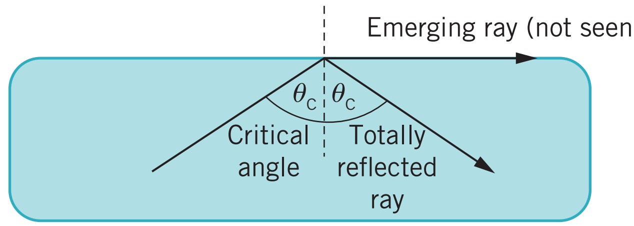

Figure 1C–18 The critical angle is where total internal reflection occurs

Critical angle depends on the refractive index of the medium but is the angle that an incident ray of light will fully reflect at the surface of the medium

Total internal reflection the phenomenon where all the light at a surface is reflected with no refraction. It occurs when light moves from a medium of higher refractive index to a medium of lower refractive index at an angle of incidence greater than or equal to the critical angle.

The key equation for the critical angle is:

Formula 1C–4 Total internal reflection

$$n_1 \sin \theta_c = n_2 \sin 90° = n_2$$

Where:

n_1 = Refractive index of the first medium
n_2 = Refractive index of the second medium
θ_c = Critical angle of incidence

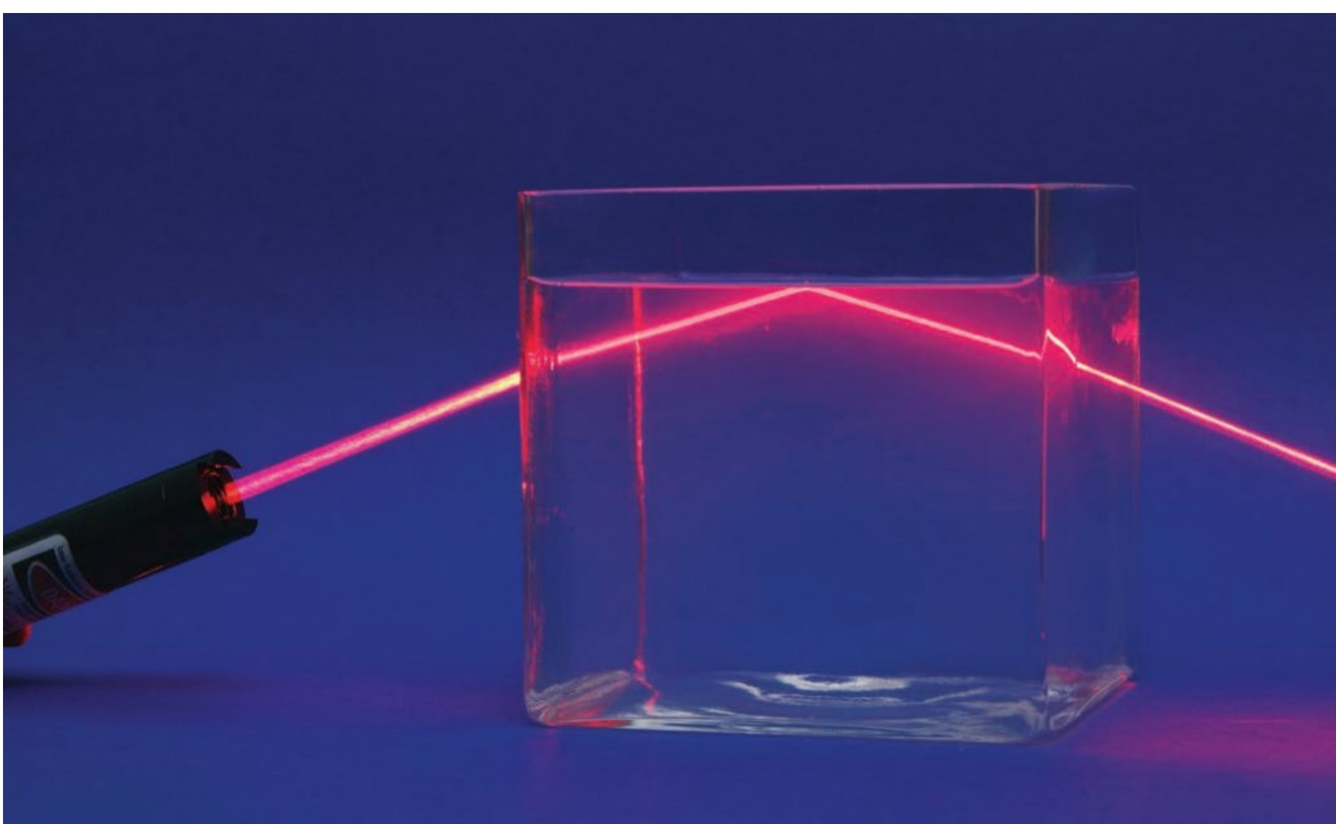

Figure 1C–19 A demonstration of total internal reflection using a laser beam and fish tank

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You may have noticed this 'mirror' behaviour of water while swimming under water, or looking up at the underside of the water surface in a fish tank, as shown in Figure 1C–20.

Figure 1C–20 Underwater reflection of a fish in the surface of the water

Worked example 1C–4 Critical angle calculation

What is the critical angle when light moves from a medium with n = 1.6 into a medium with n = 1.2?

Solution

Use Snell's law and set the emerging angle to 90°.
Making $\sin\theta_c$ the subject gives:

$$\sin\theta_c = 1.2 \times \frac{\sin(90°)}{1.6}$$
$$= \frac{1.2}{1.6}$$
$$= 0.75$$
$$\theta_c = 48.5°$$

Check-in questions – Set 2

1 When does internal reflection occur?
2 When does internal reflection become total?
3 Define the critical angle.

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Colour dispersion

Newton conducted a famous experiment where he passed a beam of sunlight through a triangular prism to produce a spectrum, as shown in Figure 1C–21. The colour separation occurs at both surfaces of the prism.

Newton identified seven distinct 'types' of light (he believed light consisted of tiny particles) as red, orange, yellow, green, blue, indigo and violet. We now know that the spectrum is continuous and the colours blend smoothly into each other. We call this separation of white light **colour dispersion**. In further experiments, he attempted to break up (disperse) the individual colours into yet more colours of light, but this did not happen. However, he knew that the different colours refracted differently. The explanation for this phenomenon is that different wavelengths of light travel at different speeds and so have slightly different refractive indices within a medium such as glass. This difference in speeds causes each colour to refract a different amount and exit at a different position along the prism's surface. A second refraction occurs when each colour leaves the surface of the glass and this together with the first refraction causes the effect of colour dispersion that can be seen in a glass prism. Today we use the different refractive indices of the different colours to predict the paths of light through prisms.

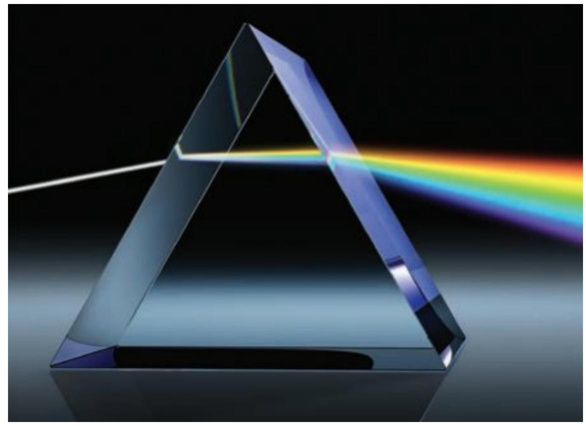

Figure 1C–21 Triangular glass prism dispersing a narrow beam of white light coming from the left, into a spectrum on the right

Colour dispersion the phenomenon in which white light is split into different light components as it moves from air (or a vacuum) into a medium such as glass

Table 1C–2 Typical wavelengths and refractive indices for glass for different colours of light

Colour	Wavelength (nm)	Refractive index
Red	640	1.509
Yellow	589	1.511
Green	509	1.515
Blue	486	1.517
Violet	434	1.521

Colour dispersion in lenses

Dispersion can lead to problems with coloured images formed by lenses. This is sometimes called **chromatic distortion**. For sharp accurate images all the colours need to come to a focus at the same distance from the lens. Such a 'perfect' lens is shown schematically in Figure 1C–22.

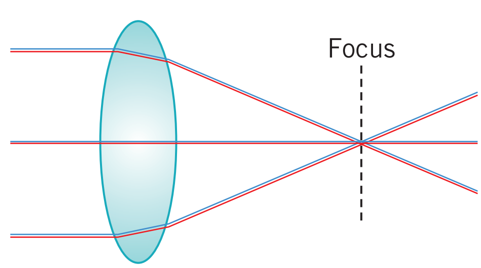

Figure 1C–22 Perfect lens without chromatic distortion; showing just red and blue light rays

Chromatic distortion image distortion caused by light of different colours focusing at different points of an image

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In the lens shown in Figure 1C–22, you can see that the blue and red light rays focus at the same place, at the same distance from the lens. For most lenses, however, the refractive indices of the various colours are different, which means they don't focus at the same place or distance, as shown in Figure 1C–23. Figure 1C–24 shows the result on a colour image.

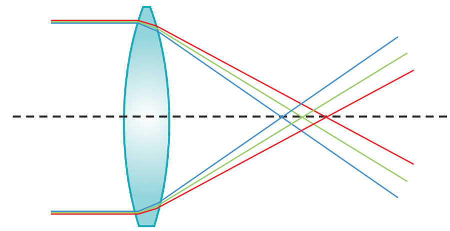

Figure 1C–23 Different refraction of different colours

High-quality cameras use a lens combination to reduce this effect. A combination of two lenses with different refractive indices can minimise chromatic distortion, as shown in Figure 1C–25.

Figure 1C–24 Severe chromatic distortion

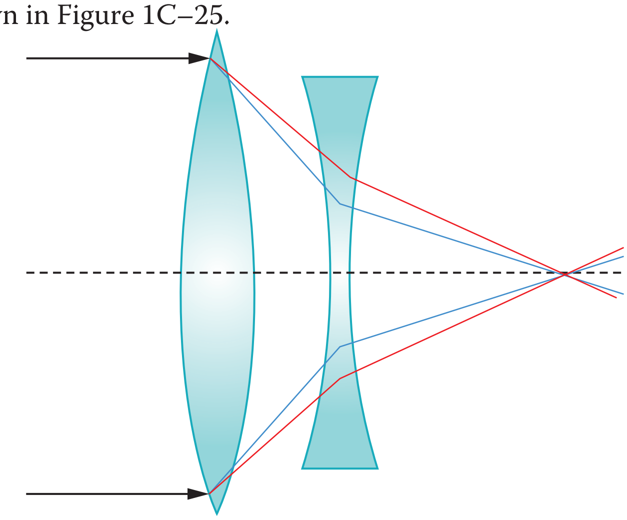

Figure 1C–25 Chromatic distortion can be reduced by combining different lenses.

Mirages

Is the water on the road in Figure 1C–26 real or a mirage?

Figure 1C–26 Mirage of water on hot bitumen road Notice how the bottom of the truck and its headlights seem to be reflected in what looks like water.

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This is an example of a mirage where the upside-down image of the bottom of the truck, under where the road surface should be, leads us to think that there must be water there. It is caused by refraction of light in the layers of air above the hot road. Layers near the road are hotter than the layers further away and this affects the refractive index; the hotter layers have a lower refractive index. So, rays travelling downwards (as shown in Figure 1C–27) bend away from the normal, eventually internally reflecting and travelling upwards. The observer's eye traces the ray back to an image of the vehicle underneath the actual vehicle, as shown.

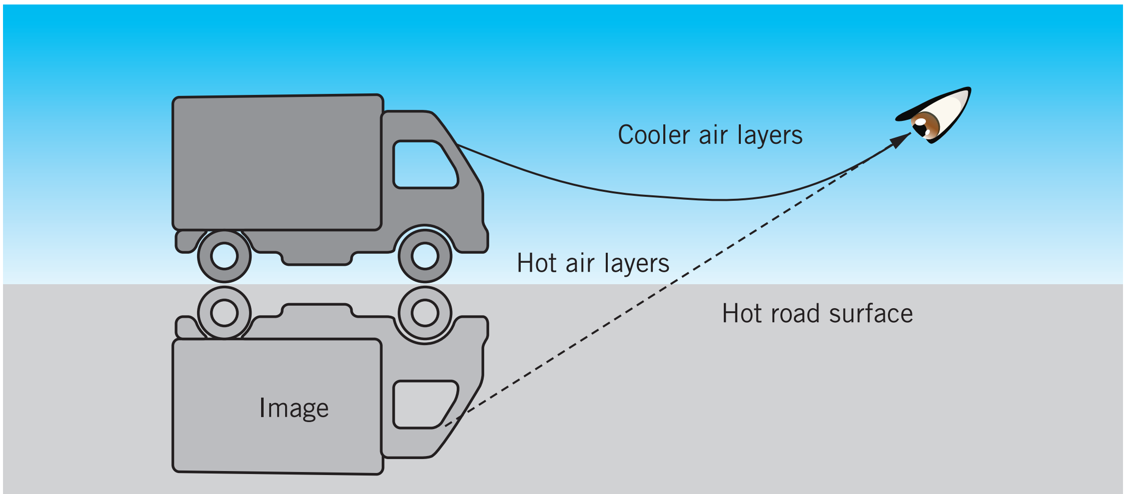

Figure 1C–27 Formation of 'underneath' mirage

Over cool surfaces, such as the ocean, where the layers of air are warmer further away from the water, different types of mirages form. This is shown in Figure 1C–28.

Figure 1C–28 Mirage of boat floating in the sky

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Here, light rays from a boat over the horizon that have been internally reflected are refracted back down to an observer. The observer traces the rays back to the image of a boat apparently floating in the sky. An outline of the light ray paths is shown in Figure 1C–29.

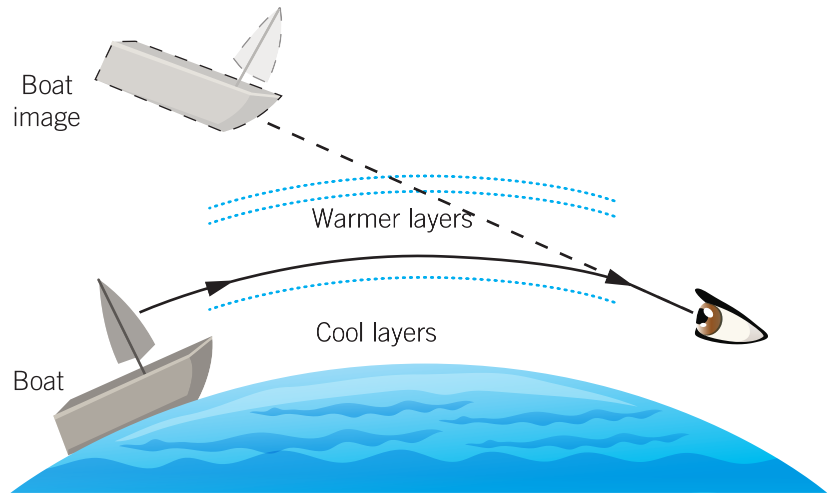

Figure 1C–29 Formation of 'floating' mirage

Check-in questions – Set 3

1 When does chromatic dispersion occur?
2 What is the cause of many mirages?

Optical fibres

Optical fibre a flexible transparent fibre made from glass and plastic that can carry digital signals by using the phenomenon of total internal reflection within

Total internal reflection is a key principle of **optical fibre** technology.

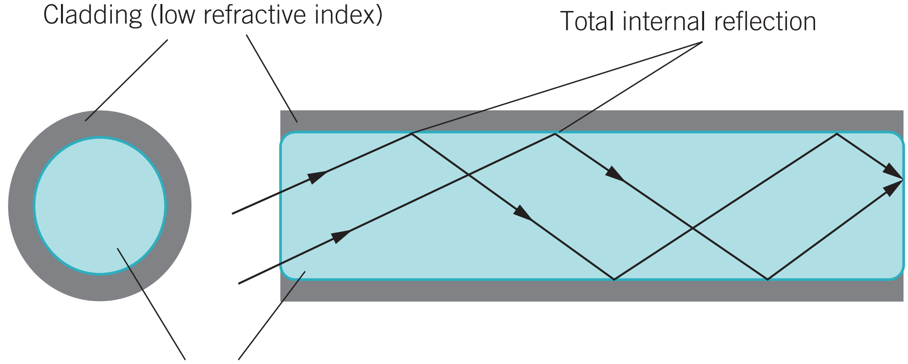

Figure 1C–30 Total internal reflection in an optical fibre

Light rays enter the optical fibre at the left and are kept in the core by successive total internal reflections. These are limited to a narrow range of angles. Rays outside this range would be rapidly attenuated. Because the total internal reflections are almost perfect and almost loss free, the intensity of the light signal is maintained over many kilometres. There are some losses due to absorption in the glass fibre, but they are small. The Australian NBN optical fibre network has 'repeaters' every 40–50 km to maintain the intensity of the signals.

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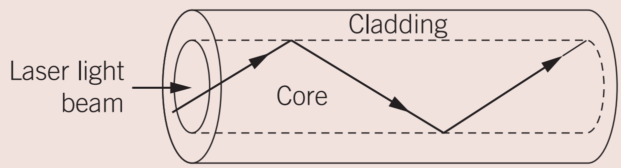
Worked example 1C–5 Application of total internal reflection

Optical fibres can be made from two layers of materials with different refractive indices. In the diagram below, **monochromatic** laser light enters the fibre. The critical angle needs to have a value of 82° to maintain total internal reflection in the core. The core material has a refractive index of 1.66.



For the fibre to operate as designed, what should the refractive index of the cladding be?

Solution

For the fibre to operate as designed, the refractive index of the cladding must be less than the refractive index of the core. Using the formula for total internal reflection with n_{cladding} as the subject gives:

$$n_{\text{cladding}} = n_{\text{core}} \sin \theta_c$$
$$= 1.66 \times \sin (82°)$$
$$= 1.64$$

So, for the fibre to operate as designed, the cladding must have a refractive index of 1.64.

Monochromatic composed of a single frequency of light or other radiation

Rainbows

Rainbows are formed from dispersion and partial internal reflection of the Sun's rays inside water droplets. The brightest rainbow is formed when there is just one partial reflection inside the rain droplets reflecting the Sun's rays back to the observer, as shown in Figure 1C–31. You can see where the dispersion is occurring in the droplet.

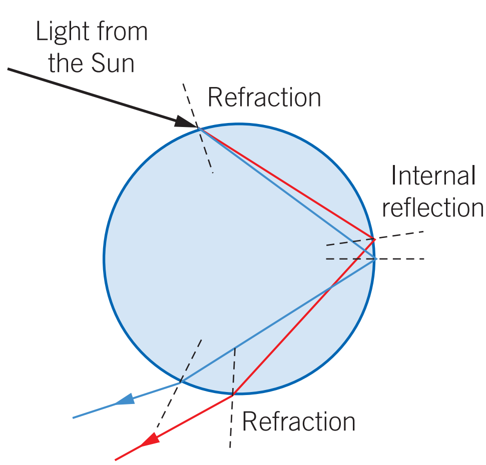


Figure 1C–31 Rainbow formation inside water droplets

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Rainbows are most easily seen with your back to the Sun. The eye traces back the blue light to water droplets at the bottom of the rainbow's arc and the red to the top; the other colours are in between. However, a weaker return ray of sunlight also occurs when there are two internal reflections inside the water droplets, as shown in Figure 1C–32. This forms a 'secondary' rainbow, higher and fainter than the main rainbow, with the colours reversed. This secondary rainbow is fainter than the primary rainbow because of two partial internal reflections.

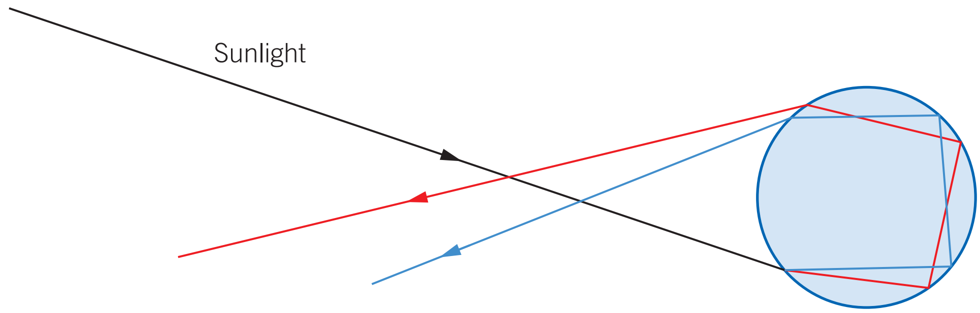

Figure 1C–32 Secondary rainbow formation inside water droplets: ray diagram (top) and resulting image (bottom)

WORKSHEET 1C–1 REFLECTION, REFRACTION AND DISPERSION

Check-in questions – Set 4

1 What is the name of the optical principle that ensures light signals remain inside the core of an optical fibre?
2 How many internal reflections from single raindrops occur in the formation of primary rainbows?
3 How many internal reflections from single raindrops occur in the formation of secondary rainbows?
4 How many refractions from single raindrops occur in the formation of primary or secondary rainbows?

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1C SKILLS

VIDEO 1C–1 SKILLS: REFRACTION AND DISPERSION

1 It is essential to be able to apply Snell's law to the refracted paths of light rays in this section. Make sure you can identify the 'normal' direction in all situations and are able to make the relevant quantity the subject of Snell's law.
2 You should also be able to identify situations where the critical angle is involved and total internal reflection occurs, especially in the case of optical fibres.
3 Ensure that you can identify the order of colours in situations involving colour dispersion and know that the violet end of the spectrum is refracted more than the red end.
4 In explaining optical phenomena such as mirages and rainbows, you should be able to sketch light ray paths that cause the phenomena involved.

Section 1C questions

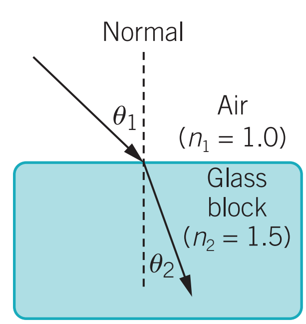
Multiple-choice questions

1 Which of the following statements best describes *colour dispersion*?
  - A when laser light disperses into different colours
  - B when the frequency of light increases during refraction
  - C when light slows down after passing through a triangular prism
  - D when light rays of different wavelengths travel at different speeds in a medium

2 When light waves reflect at a surface (such as a flat mirror), the wave crests change
  - A direction and wavelength but not speed.
  - B direction but not speed.
  - C frequency and wavelength.
  - D direction and speed.

3 A light beam is travelling through an unknown liquid with a refractive index of 1.75. Which of the following is closest to the speed of light in the liquid?
  - A 1.7×10^8 m s^{-1}
  - B 2.3×10^8 m s^{-1}
  - C 3.0×10^8 m s^{-1}
  - D 5.3×10^8 m s^{-1}

4 A narrow ray of light passes from air into a glass block. The angle θ_1 is equal to 43°.



The angle θ_2 will be closest to
  - A 27°
  - B 34°
  - C 43°
  - D 65°

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5 For a ray of light moving from one medium to another to bend away from the normal, the speed must

A stay the same and the refractive index must increase.

B decrease and the refractive index must decrease.

C increase and the refractive index must decrease.

D stay the same and the refractive index must decrease.

6 The critical angle occurs when light

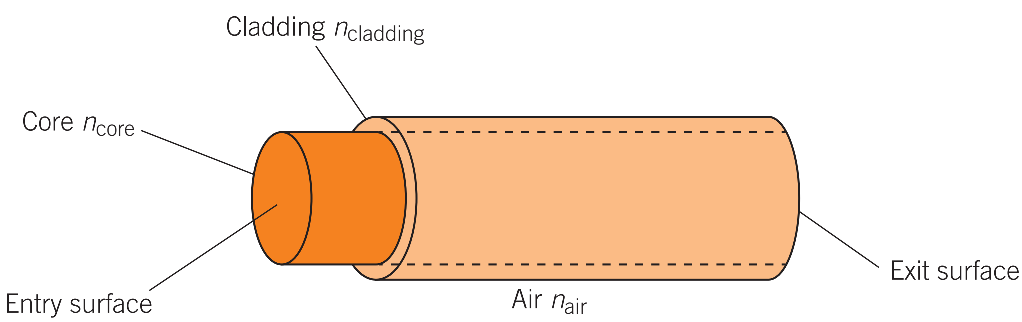
A travels from a high n medium into a low n medium.

B travels from a low n medium into a high n medium.

C travels from a high speed medium into a lower speed medium.

D is blocked from transmission, so it all reflects at the surface.

7 Which of the following combinations gives a critical angle for the core and cladding closest to 83°?



A $n_{core} = 1.31$; $n_{cladding} = 1.32$

B $n_{core} = 1.71$; $n_{cladding} = 1.73$

C $n_{cladding} = 1.71$; $n_{core} = 1.73$

D $n_{cladding} = 1.31$; $n_{core} = 1.32$

Short-answer questions

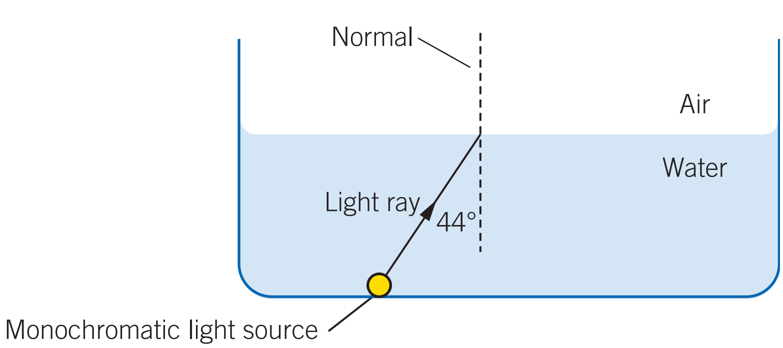
8 Using a diagram, explain how a wave description of light explains the refraction of light from a slower medium into a faster one.

9 White light is dispersed into the colours of the spectrum after passing through a triangular prism.

a Which colour, red or violet, is deviated the most in this process?

b Outline the reasons why this occurs.

10 The diagram shows a small monochromatic light source at the bottom of a water tank. It directs a ray of light towards the air–water surface as shown. For this source, take the refractive index of water as 1.33 and the refractive index of air as 1.00.



Sketch and annotate the path or paths that the light ray takes after it meets the air–water interface. Show the details of relevant calculations.

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Chapter 1 review

Summary

Create your own set of summary notes for this chapter on paper or in a digital document. A model summary is provided in the Teacher Resources, which can be used to compare with yours.

Checklist

In the Interactive Textbook, the success criteria are linked from the review questions and will be automatically ticked when answers are correct. Alternatively, print or photocopy this page and tick the boxes when you have answered the corresponding questions correctly.

	Success criteria – I am now able to:	Linked questions
1A.1	Recognise wave motion and give examples	14☐, 15☐, 18☐, 19☐, 20☐
1A.2	Understand that wave motion transfers energy without transferring matter	19☐
1A.3	Distinguish between transverse and longitudinal waves	14☐, 15☐, 18☐, 19☐
1A.4	Use amplitude (*A*), speed (*v*), frequency (*f*), period (*T*) and wavelength (λ) to describe the motion of waves	1☐, 2☐, 13☐, 20☐, 21☐
1A.5	Explain the wavelength of a wave as a result of the velocity (determined by the medium through which it travels) and the frequency (determined by the source)	6☐, 8☐
1A.6	Solve numerical problems using: $\lambda = \frac{v}{f} = vT$	21☐, 22☐, 23☐, 24☐
1B.1	Describe all electromagnetic waves as transverse vibrations of electric and magnetic fields that travel at speed, *c*, in a vacuum	4☐, 15☐, 24☐
1B.2	Describe electromagnetic radiation emitted from the Sun as mainly UV, visible and IR	3☐
1B.3	Recall approximate wavelength and frequency ranges of the radio, microwave, infrared, visible, ultraviolet, X-ray and gamma ray regions	24☐, 25☐, 26☐, 27☐, 28☐
1B.4	Give examples of the different societal uses of regions of the electromagnetic spectrum from radio through to gamma rays	24☐, 25☐, 26☐, 27☐, 28☐
1C.1	Use a ray model with wave crests to describe reflection and refraction of light	8☐, 10☐, 23☐, 29☐, 30☐, 32☐, 33☐
1C.2	Define refractive index of transparent substances	16☐, 30☐
1C.3	Use the equation: $n_1v_1 = n_2v_2$	6☐, 10☐
1C.4	Carry out practical investigations involving Snell's law	29☐, 30☐, 31☐, 34☐
1C.5	Apply Snell's law to analyse qualitative and quantitative refraction situations of visible light	7☐, 8☐, 10☐, 12☐, 17☐, 29☐, 30☐

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Success criteria – I am now able to:		Linked questions
1C.6	Qualitatively, using a ray model, explain the formation of images	31☐
1C.7	Carry out practical investigations involving total and partial internal reflection	17☐, 35☐
1C.8	Apply Snell's law to predict the critical angle at media interfaces	9☐, 17☐
1C.9	Carry out practical investigations involving dispersion of visible light	36☐
1C.10	Qualitatively analyse situations involving dispersion of visible light in prisms and lenses	5☐, 6☐
1C.11	Qualitatively explain the formation of rainbows and mirages using a ray model of light	11☐, 12☐
1C.12	Apply Snell's law to analyse qualitatively and quantitatively the operation of optical fibres for communication	9☐

Multiple-choice questions

Use the following information to answer Questions 1 and 2.

A transverse wave is travelling to the right. One particle of the wave, A, is located one-quarter of a wavelength to the left of another particle, B. The wave amplitude is 2.0 m.

1 Which one of the following statements is correct?

A A is always lower than B by 1.0 m

B A is always higher than B by 1.0 m.

C When A is at the crest of the wave motion, B will be in a trough.

D When A is located halfway between a crest and a trough, B will be either at a crest or at a trough.

2 When A is at a crest, which of the following is correct about B?

A B is travelling at maximum speed upwards.

B B is travelling at maximum speed downwards.

C B is stationary.

D B is travelling at maximum speed, but it is not possible to say whether it is travelling upwards or downwards.

3 The electromagnetic radiation from the Sun is comprises approximately

A mainly visible wavelengths.

B equal amounts of visible and IR wavelengths.

C equal parts of UV, visible and IR wavelengths.

D equal parts of UV and visible wavelengths.

4 Which one of the following is true of all electromagnetic radiation in a vacuum?

A It is a transverse wave motion.

B It travels at $3.00 \times 10^8\ \mathrm{m\,s^{-1}}$.

C It requires a medium to propagate.

D Both A and B.

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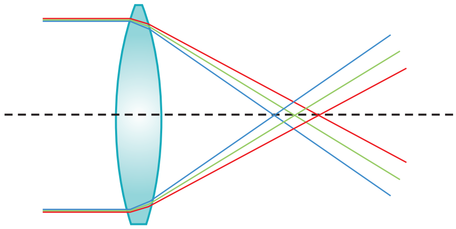
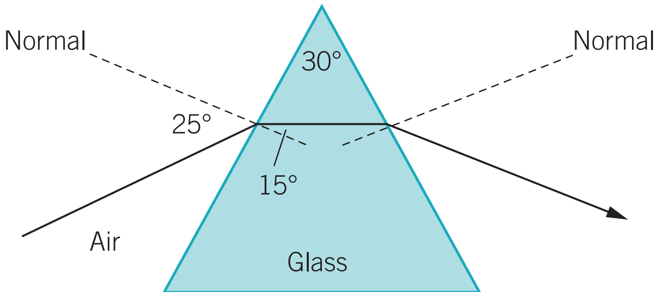
5 The diagram below is an example of which of the following options?



A a faulty lens
B coloured wave crests
C a lens adapted for colour distortion
D colour dispersion in a lens

6 Which of the following best explains why colour dispersion occurs in a glass prism?
A the equal bending of all colours of light when they travel through the prism
B the effect of differing speeds of the different colours causing different colours to leave the glass faster
C the differing wavelengths of the different colours causing different amounts of light bending in glass
D the slowing down of light in glass

7 A monochromatic ray of light passes through a glass prism as shown.



Which of the following is closest to the refractive index of the glass used in the prism?
A 1.61
B 1.63
C 1.65
D 1.67

8 When a light ray moves from a medium with n = 1.2 into a medium with n = 1.6, the
A speed, wavelength and frequency all increase.
B speed decreases, the frequency is unchanged and the wavelength decreases.
C speed is unchanged, but the wavelength and frequency decrease.
D speed and frequency are unchanged, but the wavelength increases.

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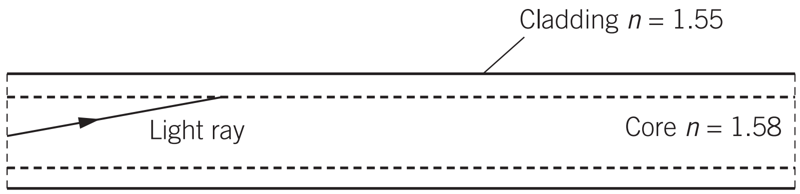
9 A ray of light in an optical fibre travels down the core (n = 1.58) of the fibre. The cladding has a refractive index of 1.55.



Which of the following is closest to the value of the critical angle for this light ray travelling from the core to the cladding?

A 1.02°
B 79°
C 88°
D 90°

10 When light waves refract at a surface between two different media, the wave crests change

A direction and wavelength but not speed.
B direction but not speed.
C frequency and wavelength.
D direction and speed.

11 The primary rainbow is best viewed

A facing the Sun so it forms a bow around the Sun.
B with your back to the Sun so that raindrops reflect light from their outer surface towards you.
C facing the Sun so that sunlight can disperse into the colours of the spectrum.
D with your back to the Sun so that sunlight can be dispersed and reflected back towards you.

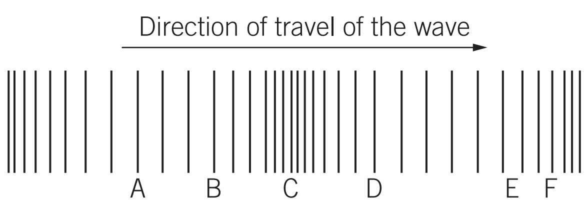
12 Mirages are formed when light rays from

A an object are refracted and reflected by layers of air to form an image.
B layers of air are refracted to create an illusion in another place.
C layers of air are reflected to create an illusion in another place.
D the sky reflect off hot surfaces to create an illusion of water.

Short-answer questions

Use $c = 3.00 \times 10^8$ m s^{-1}

13 A sketch of the wave crests of a longitudinal wave is shown below. The wave is travelling to the right.



a Which of the letters in the diagram best identifies the position of a compression (place where wave crests group up the most)? (1 mark)

b Which of the letters in the diagram best identifies the position of a rarefaction (place where wave crests spread out the most)? (1 mark)

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14 Decide if the following statements are true (T) or false (F).

a Visible light is an example of electro-acoustic wave motion. (1 mark)

b Visible light is part of the electromagnetic spectrum. (1 mark)

c Visible light is an example of a longitudinal wave. (1 mark)

d Visible light is an example of a transverse wave. (1 mark)

e Different colours of visible light correspond to different frequencies. (1 mark)

f In a vacuum, all colours of visible light travel at the same speed. (1 mark)

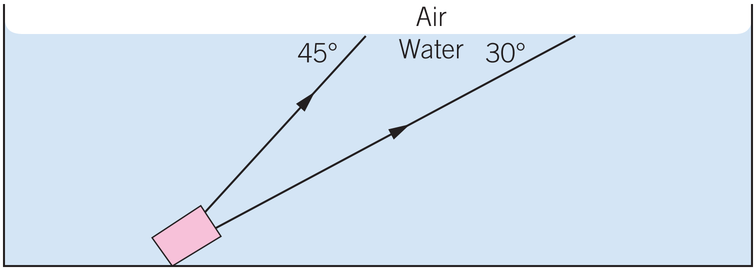
g In a glass prism, all colours of visible light travel at the same speed. (1 mark)

15 What property do the following radiations have in common, and what properties are different? (You do not need to be quantitative.)

green light, IR radiation, UV radiation (2 marks)

16 Define the refractive index, n, of a transparent medium. (1 mark)

17 A light at the bottom of a fish tank sends two beams upwards to the surface as shown. (Use $n_{air} = 1.00$; $n_{water} = 1.33$.)



Calculate the path of the rays after they strike the water–air interface. Sketch your results on the diagram, labelling relevant angles. Show your working. (4 marks)

18 Classify the following wave types as *transverse* or *longitudinal* waves.

sound waves, light waves, ‘Mexican’ waves, ripples in a pond, waves on a guitar string (1 mark)

19 Explain how the sound of a guitar reaches your ears. (2 marks)

Use the following information to answer Questions 20, 21 and 22.

A surfer sits on her board waiting for a set of waves to pass. Six waves pass her in a time of one minute, each of amplitude 1.5 m.

20 What is the total vertical distance she has moved through in this time? Her total displacement is zero. (1 mark)

21 Calculate the period of the waves. (1 mark)

22 The waves are separated by a horizontal distance of 15 m. Calculate the speed of the waves. (1 mark)

23 Water waves pass from deep water, where they have a speed of 6.0 m s^{-1} and a wavelength of 12 m, into shallow water, where their speed is 3.0 m s^{-1}. Calculate the frequency and wavelength in the shallow water. (2 marks)

24 Calculate the wavelength of the radiation emitted by the Melbourne radio station Nova (100.3 MHz). (1 mark)

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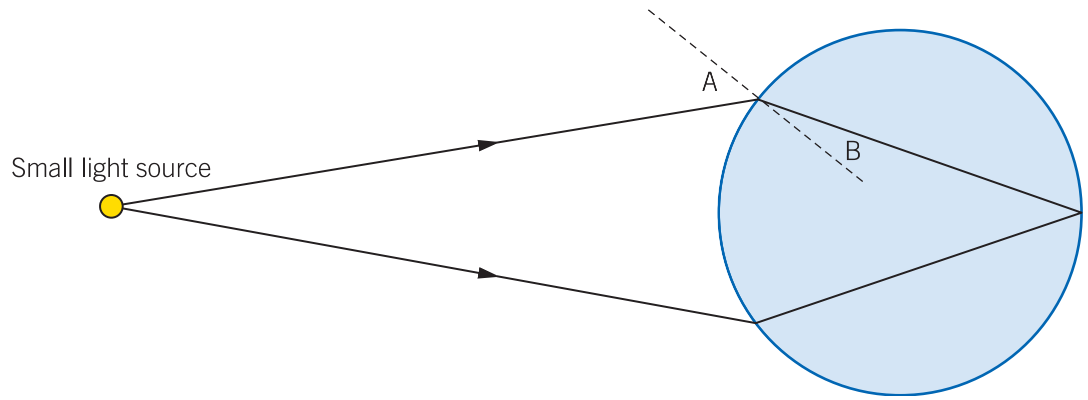
25 List two or more societal uses of electromagnetic radiation with wavelengths in the range 700 nm to 1 mm. (1 mark)

26 List two or more societal uses of electromagnetic radiation with wavelengths in the range 1 m to 1 mm. (1 mark)

27 List two or more societal uses of electromagnetic radiation with wavelengths in the range 10 nm to 400 nm. (1 mark)

28 List two or more societal uses of electromagnetic radiation with wavelengths of <10 pm. (1 mark)

29 Students send light rays through a sphere filled with liquid of refractive index n. The arrangement is shown below. The light is monochromatic. The sphere is surrounded by air (n_{air} = 1.00). The dashed line shows the normal.

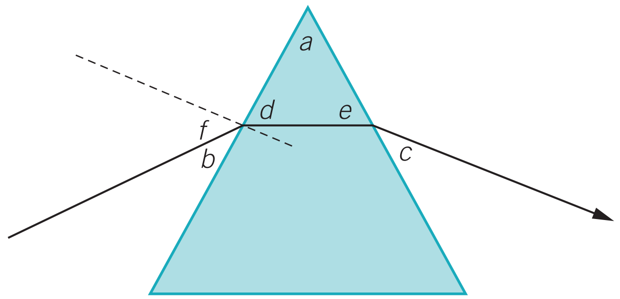


a Angle A = 55° and angle B = 25°. Calculate the value of n. (1 mark)

b The liquid is replaced by a different liquid, with a larger value of n. Students notice that the paths of the two light rays shown in the diagram are changed.

Sketch the changed paths of the light rays on the diagram. (2 marks)

30 A yellow light ray travels symmetrically through a triangular glass prism, as shown. The prism is surrounded by air (n_{air} = 1.00). Angle b = 30° and angle a = 60°.

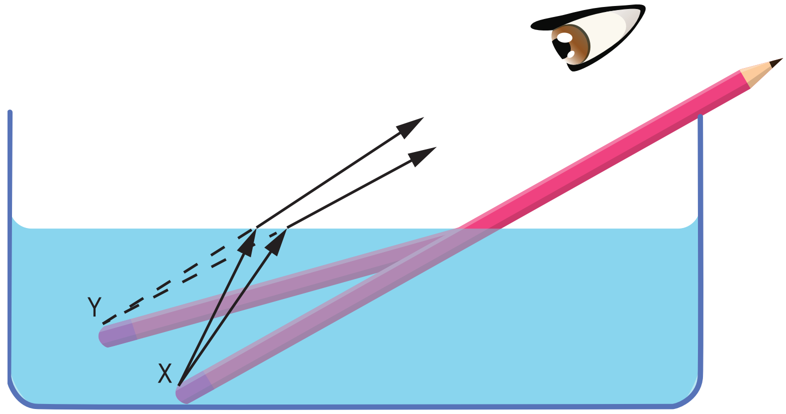


a Calculate the value of the angle c. Show your reasoning. (2 marks)

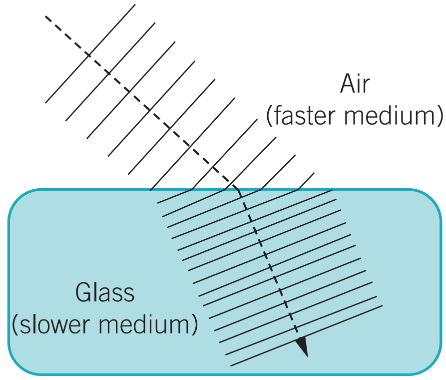
b Calculate the value of the refractive index of the glass prism. (2 marks)

c The original ray of yellow light is replaced by a ray of a mixture of yellow and blue light. It strikes the prism at the same angle as before. Draw a labelled sketch to show the effect on the new light ray. (2 marks)

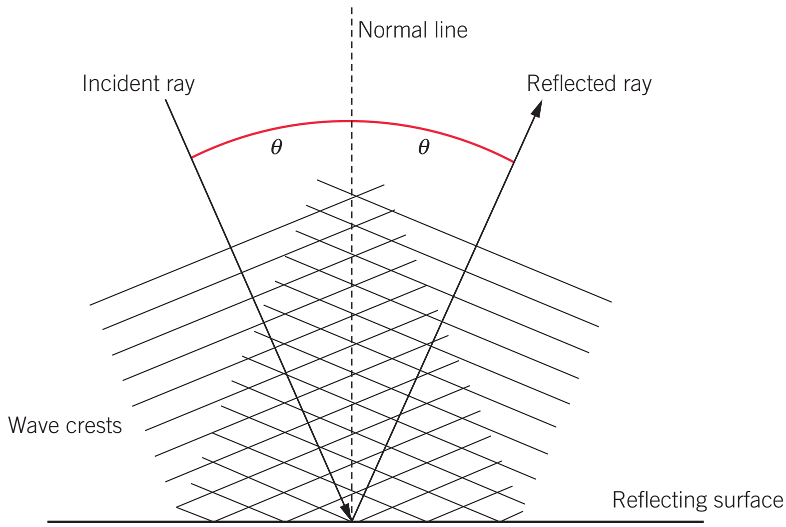
31 Use the diagram below to explain the way that the light rays form an image of the pencil at point Y. (3 marks)



32 Use the diagram below to explain how the wave crests shown predict the direction of the light rays entering the slower medium. (2 marks)



33 Use the diagram below to explain how the wave crests shown predict the phenomenon of reflection from a smooth surface. (2 marks)



34 Outline how you might practically investigate Snell's law, using a rectangular glass block, a monochromatic light ray source and a protractor. (5 marks)

35 Outline how you might practically investigate partial and total internal reflection, using a semicircular glass block, a monochromatic light ray source and a protractor. (4 marks)

36 Outline how you might practically investigate the phenomenon of colour dispersion, using a triangular glass prism, a light ray source and a protractor. (3 marks)

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UNIT 1 HOW IS ENERGY USEFUL TO SOCIETY?

CHAPTER 2 THERMAL ENERGY AND ELECTROMAGNETIC RADIATION

Introduction

The study of thermal physics helps us understand myriad aspects of life, including the reasons for sea breezes and land breezes, the reasons that lakes and the oceans seldom freeze right through even in very cold winters, why very cold surfaces can 'burn' our skin, how people can walk barefoot across hot coals of wood without burning their feet and why greenhouses can keep plants warm on sunny but freezing cold days.

Understanding thermal energy has implications for everyday matters such as keeping warm on a cold day (or cool on a hot day), minimising household energy bills, or using a heat pump that produces more thermal energy output than its electrical energy input. It enables architects to design houses that require little or no heating in winter or cooling in summer.

Thermal physics enables astrophysicists to understand how stars are formed, grow and eventually 'die'. Closer to home, it enables us to understand how the interaction between solar radiation and the thermal systems of Earth affects the climate, resulting in changes that threaten many aspects of life on our planet. It can help humanity understand how it can respond to mitigate such harmful effects.

This chapter will begin by looking at what thermal energy and temperature are before describing the different methods by which thermal energy can transfer from one place or object to another. The chapter will then look at the energy required to heat up a substance as well as the energy needed to make a substance undergo a change of state, before introducing the idea of a blackbody, Wien's law and comparing the energy emitted by objects at different temperatures. Finally, the chapter will conclude by applying all these different ideas to understanding aspects of global warming.

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Curriculum

Area of Study 1 Outcome 1
How are light and heat explained?

Study Design	Learning objectives – at the end of this chapter I will be able to:
Thermal energy • Convert between Celsius and kelvin scales • Describe how an increase in temperature corresponds to an increase in thermal energy (kinetic and potential energy of the atoms) of a system: ▸ distinguish between conduction, convection and radiation with reference to heat transfers within and between systems ▸ explain why cooling results from evaporation using a simple kinetic energy model • Investigate and analyse theoretically and practically the energy required to: ▸ raise the temperature of a substance: $Q = mc\Delta T$ ▸ change the state of a substance: $Q = mL$	**2A Thermal energy** **2A.1** Describe thermal energy as the sum of the random kinetic energy and potential energy of the atoms and molecules of an object or system **2A.2** Understand that increases and decreases of temperature are related to increases and decreases of thermal energy in a system **2A.3** Convert temperatures between Celsius and kelvin **2A.4** Analyse qualitatively thermal energy transfers in terms of conduction, convection, radiation and evaporation using a particle model **2A.5** Define specific heat capacity, c **2A.6** Define specific latent heats of vaporisation (condensation) and fusion (melting), L **2A.7** Carry out practical investigations involving changing the temperature or state of a substance **2A.8** Analyse quantitatively the thermal energy changes associated with temperature and state changes **2A.9** Use the equation $Q = mc\Delta T$ to calculate the energy needed to raise the temperature of a substance **2A.10** Use the equation $Q = mL$ to calculate the energy needed to change the state of a substance
Interaction of thermal energy and electromagnetic radiation • Calculate the peak wavelength of the re-radiated electromagnetic radiation using Wien's Law: $\lambda_{max}T$ = constant • Compare the total energy across the electromagnetic spectrum emitted by objects at different temperatures • Apply concepts of energy transfer, energy transformation, temperature change and change of state to climate change and global warming	**2B Thermal energy, electromagnetic radiation and global warming** **2B.1** Describe the general features of a blackbody object **2B.2** Use Wien's law ($\lambda_{max}T = 2.90 \times 10^{-3}$ mK) to calculate the peak emitting wavelengths of objects modelled as blackbodies **2B.3** Use graphical methods to compare total energy radiated by objects modelled as blackbodies **2B.4** Identify the way concepts of thermal energy and electromagnetic radiation can help understanding of global warming and climate change

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Glossary

Atmospheric window
Back radiation
Blackbody
Carbon dioxide (CO_2)
Celsius (°C)
Change of state
Climate
Condensation
Conduction
Convection
Evaporative cooling
Fusion
Greenhouse gas
Heat
IPPC
Kelvin (K)
Melting
Methane (CH_4)
Specific heat capacity
Specific latent heat
Thermal energy
Translational kinetic energy
Vaporisation
Wien's law

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Concept map

Energy required to change the temperature and state of a substance

Conduction, convection and radiation

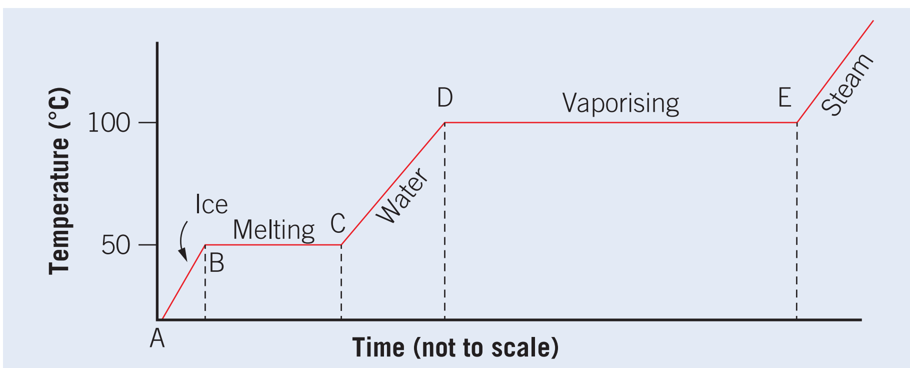
Energy transfer

Evaporation

Temperature is related to the kinetic energy of molecules

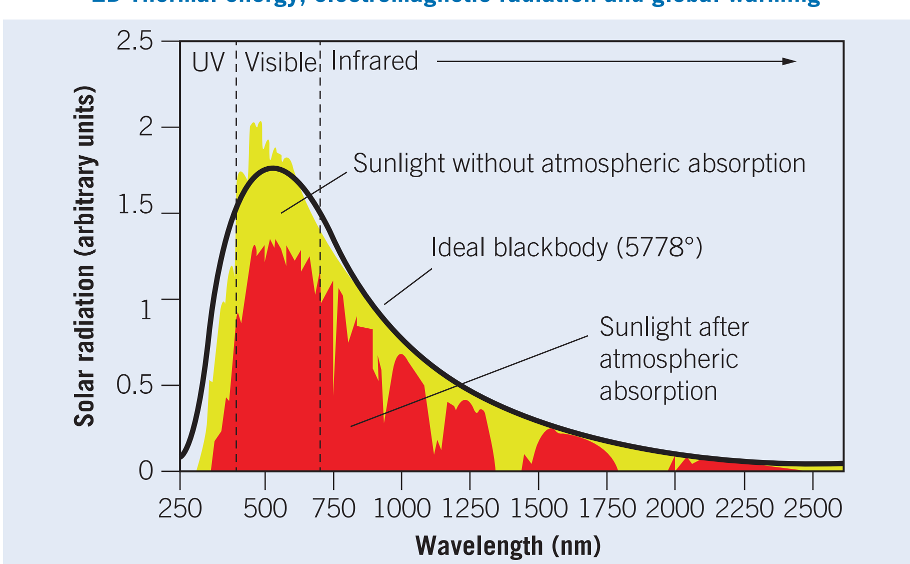
Conversion between temperature scales required for some calculations

2A Thermal energy



Radiation, Wien's law, and blackbody radiators applied to global warming and climate change

2B Thermal energy, electromagnetic radiation and global warming



See the Interactive Textbook for an interactive version of this concept map interlinked with all concept maps for the course.

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2A Thermal energy

Study Design:
- Convert between Celsius and kelvin scales
- Describe how an increase in temperature corresponds to an increase in thermal energy (kinetic and potential energy of the atoms) of a system:
  - distinguish between conduction, convection and radiation with reference to heat transfers within and between systems
  - explain why cooling results from evaporation using a simple kinetic energy model
- Investigate and analyse theoretically and practically the energy required to:
  - raise the temperature of a substance: $Q = mc\Delta T$
  - change the state of a substance: $Q = mL$

Glossary:
Celsius (°C)
Change of state
Condensation
Conduction
Convection
Evaporative cooling
Fusion
Heat
Kelvin (K)
Melting
Specific heat capacity
Specific latent heat
Thermal energy
Translational kinetic energy
Vaporisation

ENGAGE

Hot and cold 'burns'

When too much thermal energy passes into our skin, we get a burn as the cells are damaged. When too much thermal energy passes out of our skin, the cells are also damaged; this damage is sometimes called a 'cold burn' or an 'ice burn' or also commonly referred to as frostbite. Ice burns can occur from being outside in low temperatures for extended periods of time. Some other circumstances where cold burns commonly occur include being exposed to expanding gas being released from a highly compressed or liquid source (particularly from aerosol cans) for extended periods of time. Liquid nitrogen or helium spills are a cause as well as coming into contact with metal cooled by such substances. Cold burns are just as serious as hot burns and often require medical treatment in a hospital, but hot and cold 'burns' are managed very differently.

Figure 2A–1 Left: Cold burn caused by liquid nitrogen spill gas. Right: Hot burn.

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EXPLAIN

What is temperature? How is it related to thermal energy?

When we ask whether an object is hot, we reach for a thermometer. Temperature is what a thermometer measures. It is not the same as the total amount of **thermal energy** in an object. The thermal energy of an object is the sum of all the random potential and kinetic energies of its atoms and molecules. The temperature is linked to the thermal energy. When thermal energy increases, the temperature increases, and when if falls the temperature falls, but the exact relationship is complicated.

VIDEO 2A–1 THERMAL ENERGY

Thermal energy the sum of all the random potential and kinetic energies of the atoms and molecules that make up an object or a system

The tiny sparks that fly off a 'sparkler' on a birthday cake have a temperature of over 1000°C, but one or two of them landing on your skin is not going to burn you. They do not have enough thermal energy because the number of molecules involved is very small.

Figure 2A–2 Sparklers at a celebration

Thermometers, which measure temperature, have an important function because they can tell us which way thermal energy is going to transfer. If you grab an object that has a temperature that is higher than your hand, thermal energy will move into your hand – the object will feel hot. If enough energy moves, you may get burned. If the temperature is lower than your hand, thermal energy will flow out of your hand and the object will feel cold. This can also damage you if it is very cold. These effects are because the molecules in a hotter object have more random **translational kinetic energy** and potential energy than the molecules in a colder object, and as a result thermal energy moves from the hotter object to the colder one. When thermal energy is moving like this between two objects of different temperatures, we call the flow of energy **heat**.

Translational kinetic energy the energy associated with an object of mass, m, travelling with speed, v

Heat the flow of thermal energy between two bodies of different temperature

The temperature of an object is the quantity measured with a thermometer; it is related to the thermal energy of an object. When the thermal energy increases, the temperature also increases; when the thermal energy decreases, so does the temperature.

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Celsius (°C)
a unit of temperature on the Celsius temperature scale, where the boiling point of water is 100°C and the freezing point is 0°C

Kelvin (K)
a unit of temperature on the Kelvin temperature scale, where the boiling point of water is 373.15 K and the freezing point is 273.15 K. 0 K corresponds to absolute zero.

NOTE

The Kelvin scale does not have degrees, its unit is the kelvin (with lowercase k) and its symbol is uppercase K. Temperatures in kelvins do not have degree signs, just a number followed by a space and K.

Temperature scales

The two most common temperature scales are the **Celsius** and **Kelvin** scales, although Fahrenheit is also used in some countries. The scales have reference points as shown in Table 2A–1 below.

Table 2A–1 Comparing different temperature scales

Scale	Unit	Freezing point of water	Boiling point of water
Celsius	degree, symbol °C	0°C	100°C
Kelvin	kelvin, symbol K	273.15 K	373.15 K
Fahrenheit	degree, symbol °F	32°F	212°F

The size of a single degree in the Celsius scale and the size of the kelvin unit in the Kelvin scale are the same; the size of a degree in the Fahrenheit scale is smaller. The Fahrenheit scale is obsolete in Australia. To convert from degrees Celsius to kelvins you simply add 273.15 to the Celsius number. The significance of the Kelvin scale is that there are no negative temperatures. Zero kelvin is absolute zero and corresponds to the state of an object where the molecules have effectively zero kinetic energy. It is not possible to cool an object any further. Absolute zero (0 K) is the temperature of an object that has lost all its thermal energy. (The situation is complicated if quantum effects are taken into account, as quantum theory predicts the existence of zero-point energy, that is, quantum particles can never completely stop moving.)

Check-in questions – Set 1

1 Convert the boiling point of water from Celsius into kelvin.
2 Which is a lower temperature: –200°C or 63 K?
3 What does the reading on a thermometer measure?

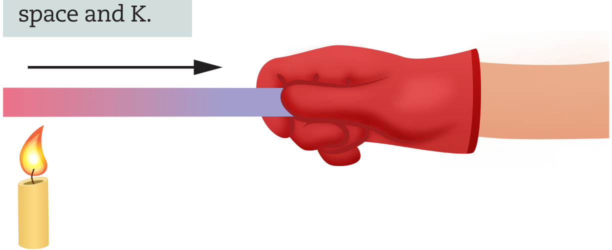

Figure 2A–3 Flow of thermal energy as heat from higher temperature to lower temperature

Transferring thermal energy by conduction

Conduction is the most significant method of thermal energy transfer in soilds. This is because the molecules of solids are closely packed together, so the vibrations caused by heating readily cause nearby particles to also vibrate by interactions. This transfers the thermal energy through the solid. Electrons can also be involved, especially in metals. In an object where one part is hotter than another part, the thermal energy moves or 'flows' as heat, as shown in Figure 2A–3.

Conduction
the process of thermal energy transfer though interactions between nearby atoms, molecules and electrons

When two objects at different temperatures are in contact, thermal energy flows as heat from the hotter object to the colder one. This is again because the kinetic and potential energies of the particles (atoms, molecules, electrons) of the hotter object are greater, on average, than those of the colder object, and interactions between the more energetic particles and the less energetic ones result in transfer of thermal energy.

The rate at which conduction of thermal energy occurs depends on the material involved. Some materials conduct better than others. Metals are generally good conductors of heat (as well as electricity). This is largely due to the ability of their free electrons to move freely throughout the metal. Non-metals do not have free electrons and are generally poor conductors but good insulators. Gases are very poor conductors (and excellent insulators) because their particles are far apart and interactions are relatively rare.

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Table 2A–2 shows a comparison of the approximate thermal conductivities of some common materials, in arbitrary units, relative to the thermal conductivity of air, which is set at 1. This means that copper (thermal conductivity of 17 000 units) has 8500 times the thermal conductivity of fibreglass (2.0 units).

It should be clear that high conductivity is very desirable for the bases of saucepans (such as copper) but low conductivity (such as fibreglass) is desirable for the handles of saucepans. (Cookware for induction stoves also requires a layer of magnetic material, but this is related to a different mechanism, where the stove induces an electric current in the pan to heat it internally).

The dimensions of materials also affect their ability to conduct or insulate. A thicker layer is better for insulation than a thinner one. Also, the greater the area of contact with the surface of a material, the better the conduction properties and the less effective the insulation.

Finally, the temperature difference across the material (the temperature gradient) affects the rate of thermal energy flow. The greater the temperature gradient, the greater the energy flow will be.

Table 2A–2 Relative thermal conductivities of different materials, in arbitrary units where air is set at 1.0

Material	Thermal conductivity (arbitrary units)
Copper	17 000
Aluminium	10 000
Household bricks	55
Window glass	40
Water	25
Concrete	20
Compacted snow	Between 25 and 5.0
Polyvinylchloride (PVC)	8.0
Ethanol	7.2
Charcoal	3.5
Fibreglass	2.0
Nitrogen gas	1
Oxygen gas	1

Figure 2A–4 Saucepan with copper base and insulated handle

Figure 2A–5 People can walk barefoot over hot coals at 500°C and not get burned feet. How is this possible? There are two main factors involved in a successful ‘firewalk’. Firstly, the low value of the thermal conductivity of charcoal means that the flow of thermal energy into the feet is slow. The low value of the specific heat of charcoal means that there is a low amount of heat that can flow into people’s feet. Lastly, a brisk walk across a 5 m long firepit means that each foot is only in contact for a few seconds.

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Convection the process of thermal energy transfer through the movement of a fluid or gas

Transferring thermal energy by convection

Convection is the main form of thermal energy transfer in liquids and gases. It occurs when there is significant flow of the liquid or gas itself, thus moving the thermal energy by the bodily movement of the material itself. It can be natural, driven by warmer fluid rising and cooler fluid falling due to density differences, or forced by fans.

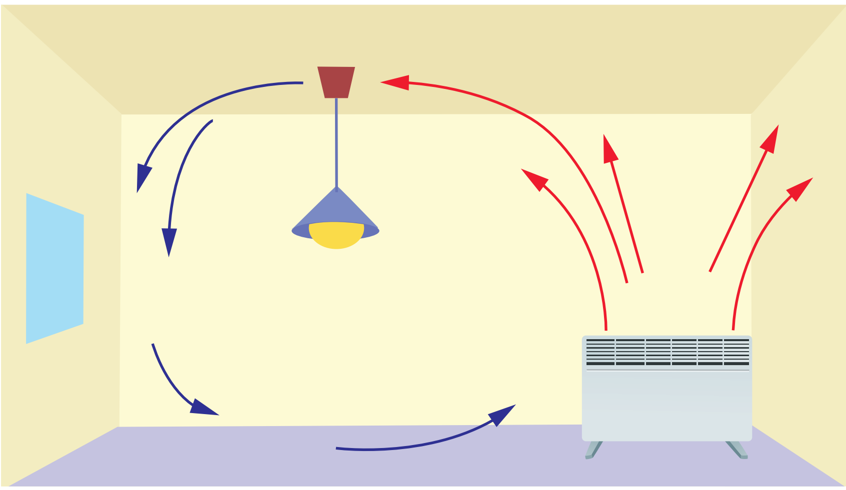

Figure 2A–6 Natural convection in a domestic setting. Air is warmed by the heater and becomes less dense so it rises to the ceiling, where it cools by conduction and radiation, becoming more dense, therefore sinking to the floor. This drives a circulating convection current.

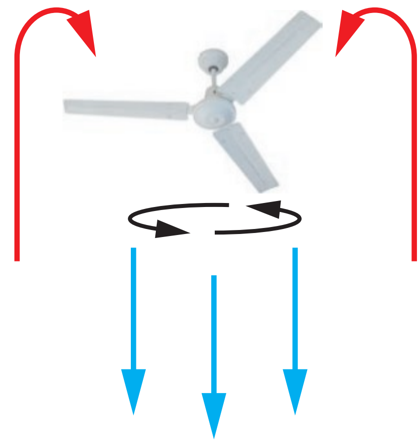

Figure 2A–7 Forced convection from a ceiling fan. Warm air that rises to the ceiling is forced down by rotation of the fan blades.

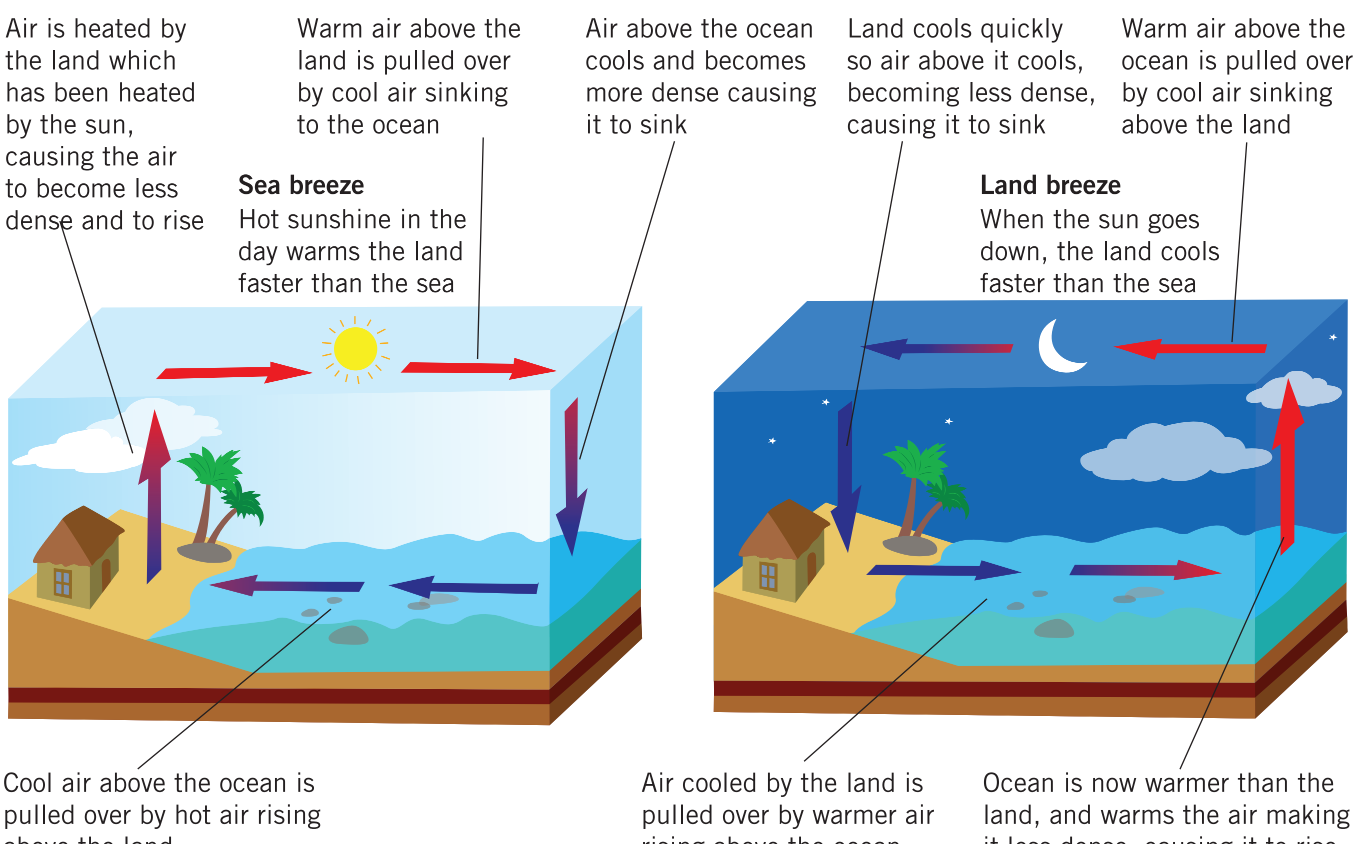

Figure 2A–8 Sea breeze and land breeze formed by natural convection, driven by the differential warming and cooling of land and sea; the land heats up faster than the ocean in the hot sun, but also cools down faster once the sun has set

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Convection is responsible for driving sea and land breezes. In the case of a sea breeze during the day, the air just above the ocean is kept cool by the water, making it a lower temperature than the air just above the land. As the air above the land heats up from the Sun its density falls and so it rises, pulling in cooler air from across the ocean. On the other hand, the ocean water cools the air above it, which causes it to sink, which in turn pulls in air from above the land. The cycle then repeats, producing a sea breeze. The movement of the air like this is an example of a convection current and it allows for the cooler ocean and warmer land to transfer heat via the breeze, shown in Figure 2A–8. A land breeze occurs at night and is just the reverse convection current caused by the land now being cooler without the Sun present. This current allows heat to transfer between the cooler land and warmer ocean water, also shown in Figure 2A–8.

Figure 2A–9 Outdoor radiant heater

Transferring thermal energy by electromagnetic radiation

Thermal energy from the Sun reaches Earth after travelling though the near perfect vacuum of space as electromagnetic radiation. The Sun's electromagnetic spectrum is 93% infrared and visible radiation and 7% ultraviolet. Some of this radiation is reflected, but most of it is absorbed and transformed to thermal energy.

LINK 1B ELECTRO-MAGNETIC WAVES

All objects with temperatures above 0 K emit electromagnetic radiation. This is thermal radiation, a result of its thermal energy. Earth re-radiates this received electromagnetic radiation, but at longer wavelengths, deep into the infrared region of the electromagnetic spectrum. The hotter an object is, the shorter the wavelength of this radiation. Once an object reaches a temperature of 700 K, the emitted thermal radiation becomes visible and the object become 'red hot'. However, even below this temperature, significant amounts of radiated energy can be felt. The nature of the radiating surfaces affects how well objects emit radiation; perfect radiators are called 'blackbody' radiators, defined in the next section. These are also perfect absorbers.

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For the warming effect of infrared radiation to occur, it has to be absorbed and then be transformed into thermal energy. The nature of the surface affects this. Shiny surfaces and white surfaces (including snow and ice) reflect much of the radiation. Black surfaces and matt surfaces are more likely to absorb most of the energy of the radiation. You will notice this when you wear matt black clothes on sunny days.

Evaporative cooling

You may have noticed, if you drink takeaway coffee (or other hot drinks), that it has become normal to fit a lid to the takeaway container to keep the drink from getting cold. Without a lid, hot drinks lose considerable thermal energy through the process of **evaporative cooling**. This process also occurs when we sweat, especially when there is a wind blowing. This process can be described by a simple kinetic energy model. Within the liquid, molecules are free to move around and interact with each other, which results in a wide range of kinetic energies for the different molecules. Because of these interactions within the liquid, some molecules have a higher kinetic energy than the average of the system. If this occurs near the liquid surface, some of these molecules will have the energy to escape the bonds of the liquid and move into air. Now in a gas state, the molecules move away from the system and are said to have evaporated from the surface of the drink. The molecules that have evaporated carry with them the extra energy they obtained from collisions within the system. This means that evaporating molecules reduce both the thermal energy and the average kinetic energy of the molecules of the liquid, lowering the temperature of the drink and resulting in a cooling effect.

Evaporative cooling the process of cooling that occurs in liquids when high-energy molecules evaporate and carry away energy from the system

Figure 2A–10 A Coolgardie safe is a box that keeps its contents cool through evaporative cooling. Water in the tank on top is allowed to drip onto the hessian sackcloth covering the safe, from where is diffuses by capillary action through the cloth and evaporates, taking away heat and so cooling the safe.

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A low-tech cooling invention, the Coolgardie safe, is a mesh box covered with damp hessian sacking. Evaporative cooling keeps the interior cool, especially if there is a breeze blowing on the sacking, which increases the rate of evaporation. It is thought that the idea may have come from the practice of some Aboriginal and Torres Strait Islander peoples carrying water in kangaroo skin bags.

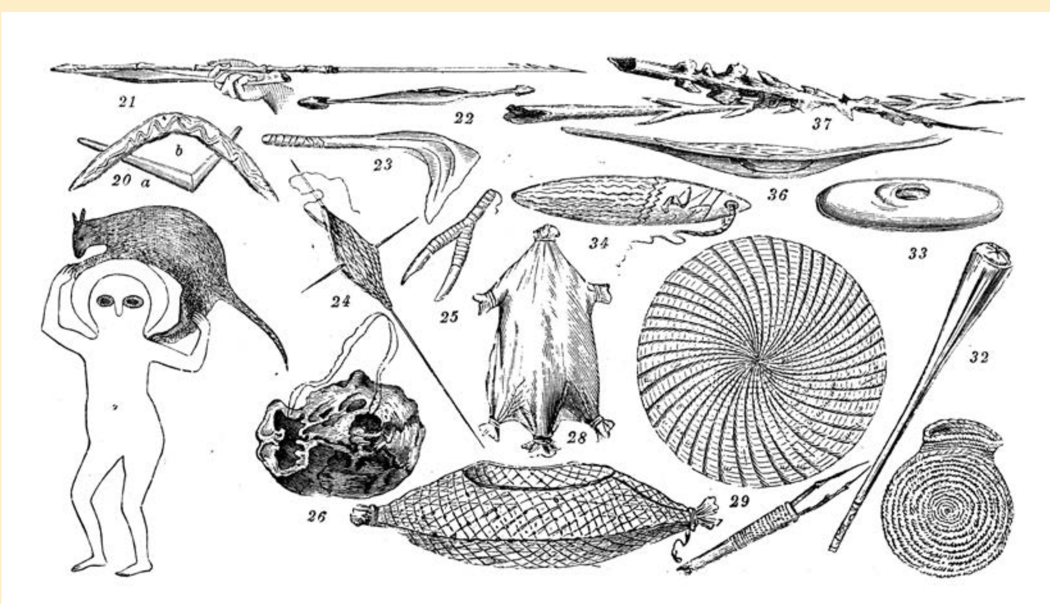
Innovation with water carriers

The kangaroo or wallaby skin water container is an important innovation developed by Aboriginal and Torres Strait Islander peoples to carry water through hot and arid environments. They can be used to transport large volumes of water as people moved from one camp to another.

The water carrier is made by removing the skin whole, taking care not to puncture it, and making a bag from it. The skin of the legs is tightly knotted or sewn up, and any excess skin is either cut off, or used to make a shoulder strap. The same is done with other openings and the tail. The skin is usually rubbed with tree resin which helps preserve it and make it waterproof. An example may be seen by visiting the Australian Museum website and searching for 'wallaby-skin water carrier.'

It uses the same principle of evaporative cooling described for the Coolgardie safe, which is thought to have inspired the design of the latter. The main difference is that that the water slowly diffuses through the skin of the water carrier and evaporates from the outside surface without making it wet. This keeps the water relatively cool.

A wallaby skin water carrier is shown in the centre of an antique drawing below made by an anthropologist studying First Nations Australians tools, artefacts and cultural items in the 19th century. A number of carved and woven items are also depicted, including hunting tools such as a woomera (spear thrower), and boomerangs at top left. A copy of a rock painting is at bottom left.



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In dry and warmer parts of Australia, evaporative air conditioning is popular and cheaper to run than compressor-based cooling. The principle is similar to the Coolgardie safe, with a fan run by electricity.

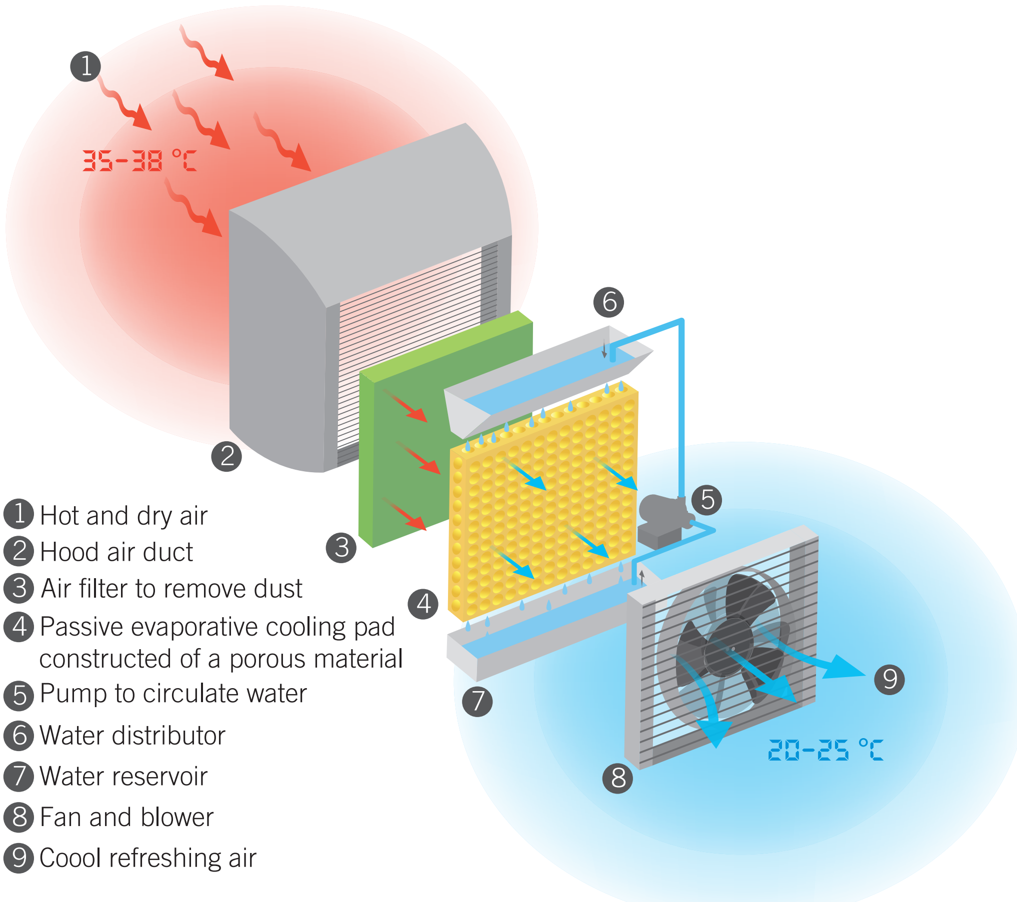

Figure 2A–11 Evaporative air conditioning drawing hot air from outside and delivering cool air inside. Circulating water drips onto and percolates through vertical pores in the yellow porous material and evaporates from it, helped by the air being forced through horizontal pores.

Check-in questions – Set 2

1 What is the dominant type of thermal energy transfer in solids?
2 What is the is the dominant type of thermal energy transfer in liquids and gases?
3 Is there a minimum temperature for an object to transfer energy by radiation?
4 What is the cooling mechanism of a Coolgardie safe?

9B ENERGY, POWER AND ENERGY EFFICIENCY LINK

Energy required to change the temperature of an object

Every time you 'boil the kettle', you have to add enough thermal energy to the water to raise its temperature by about 80°C, assuming that room temperature is 20°C. To calculate the amount of energy involved, you need to know the mass of water involved, *m*, and the **specific heat capacity** of water, *c*. The specific heat capacity of a material has units of J kg^{-1} K^{-1} and it measures the amount of energy required to raise the temperature of 1 kg of a material by 1 K. Its value depends on the material. In this example, the specific heat capacity of water is the amount of energy required to raise the temperature of 1 kg of water by 1 K.

Specific heat capacity the energy required to raise the temperature of 1 kg of a material by 1 K; units are J kg^{-1} K^{-1}. Its value depends on the material being heated. It is given the symbol *c*.

The symbol *Q* is used for the amount of thermal energy that must be added to system in the form of heat to raise the temperature of a material by the desired amount. It is calculated using the formula in the next box.

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Formula 2A–1 Thermal energy change in an object

$$Q = mc\Delta T$$

Where:

Q = Amount of thermal energy required to increase the temperature of a material by ΔT (J)

m = Mass of the material being heated (kg)

c = Specific heat capacity of the material being heated (J kg^{-1} K^{-1})

ΔT = Change in temperature before and after heating (K)

Worked example 2A–1 Thermal energy change in water

How much energy needs to be added to 2 kg of water to raise its temperature from 20°C to 100°C? Take the specific heat capacity of water, c, to be 4190 J kg^{-1} K^{-1}.

Solution

Using $Q = mc\Delta T$, where:

$m = 2$ kg

$c = 4190$ J kg^{-1} K^{-1}

$\Delta T = 80$ K

gives:

$$Q = 2 \times 4190 \times 80$$

$$= 670\,400 \text{ J}$$

$$= 670 \text{ kJ}$$

Table 2A–3 Specific heat capacity of different materials

Material	Specific heat capacity (J kg^{-1} K^{-1})
Water	4190
Wood	1300–2400
Wheat	1000–2500
Aluminium	890
Concrete	880
Household bricks	850
Window glass	800
Copper	385
Nitrogen gas	1
Oxygen gas	1

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Water has a relatively high specific heat capacity, as can be seen from Table 2A–3. This means that relatively more energy is required to heat water and water releases more energy when it cools down. Therefore, water takes a relatively long time to heat up and a relatively long time to cool down. This means that environments near lakes and oceans are protected from extremes of temperature; on very hot days a large body of water absorbs thermal energy, minimising the temperature rise. On cold days the reverse occurs; the water releasing thermal energy minimises temperature drop. This is assisted by the sea breeze and land breeze convection currents discussed earlier in this chapter.

Hot water 'bottles' have been popular bed warmers because they keep warm for a long time. In more recent times, wheat-filled bags, heated by microwaves, have become popular. They take advantage of the high specific heat capacity of wheat without the risk of water leakage and resultant scalding.

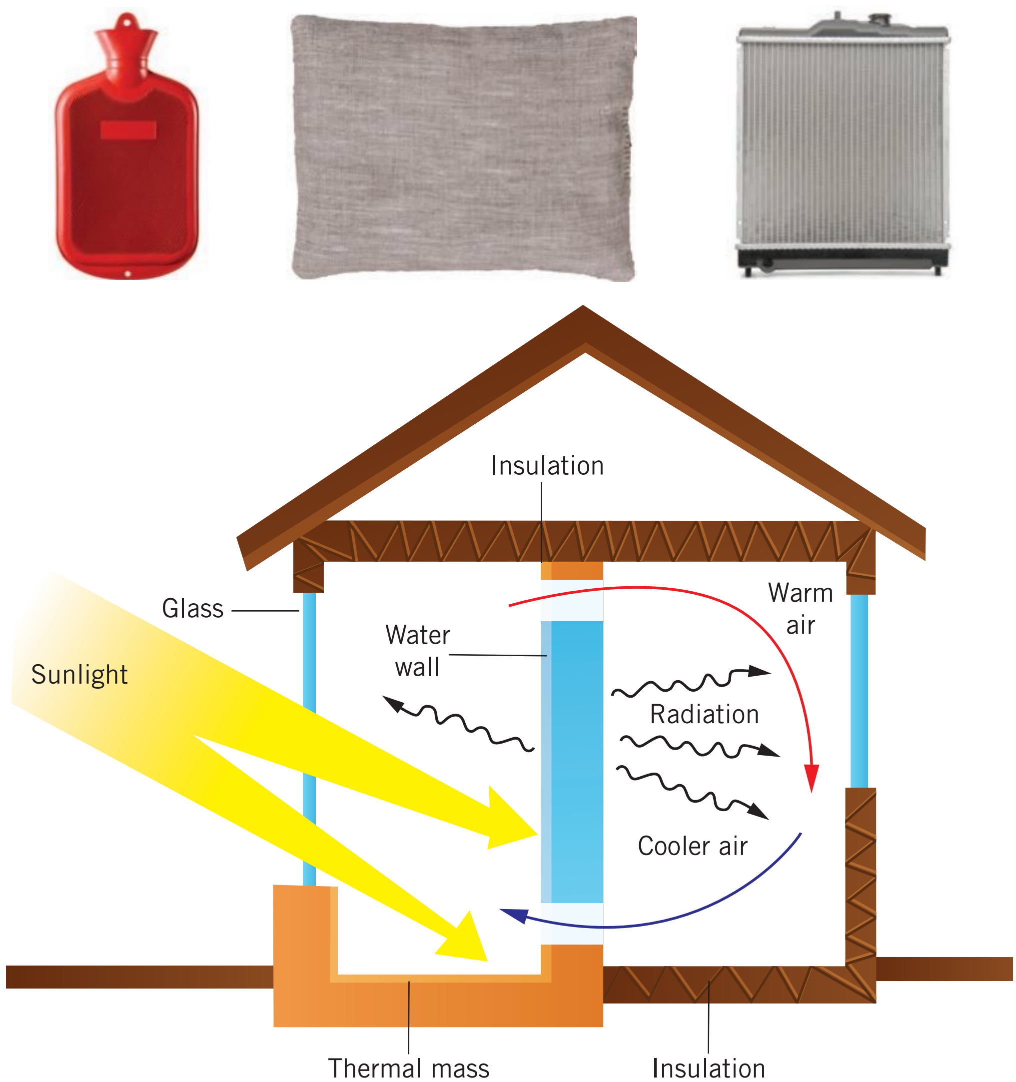

Figure 2A–12 Hot water bottle, wheat bag hot packs, car water radiator and water wall thermal energy storage

Internal combustion engines require effective cooling; water is ideal for this function because of its high specific heat capacity. Houses fitted with water-filled walls, as shown in Figure 2A–12, have high thermal energy capacity; this smooths out extremes of temperature on very hot and very cold days. Such houses can absorb thermal energy during the day and release it at night, keeping the house cooler in summer and warmer in winter.

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Energy required to change state

When ice changes into water (**melting**), water into ice (**fusion**), hot water into steam (**vaporisation**) or steam into water (**condensation**), we say that a change of state has taken place. **Changes of state** happen when energy is added or taken away from a substance, changing the interaction of the molecules with each other, either breaking bonds or allowing them to form. If a substance is to change from the solid state to the liquid state, energy is needed to break bonds; when the reverse happens, energy is released by bonds forming. If a substance is to change from the liquid state to the gas state, energy is also needed; when the reverse happens, energy is released. These additions and releases of energy do not change the temperature of the substance; they are solely involved in the change of state. The energy needed (or released) during the change of state is related to the mass, m, of the substance and the **specific latent heat** of the state change for the substance. In symbols this is shown below:

Formula 2A–2 Specific latent heat of change of state

$$Q = mL$$

Where:

Q = Amount of thermal energy required (or released) in a change of state of a substance (J)

m = Mass of the substance changing state (kg)

L = Specific latent heat of the substance (J kg^{-1})

The specific latent heat, L, has units of J kg^{-1} and is the amount of energy that is absorbed or released per kilogram of a substance that undergoes a change of state. It depends on both the substance and the state change that is occurring. For example, the specific latent heat of changing the state of water into ice (fusion) is 334 kJ kg^{-1}, but the specific latent heat of changing the state of water into steam (vaporisation) is 2256 kJ kg^{-1}. Changing water into ice releases energy while changing water into steam requires energy. If we reverse a change of state, then the specific latent heat is the same, but the energy release or absorption also reverses. From the example this means that changing ice into water still has a value of 334 kJ kg^{-1}, but now energy is required to cause the change of state instead of being released.

The idealised graph in Figure 2A–13 illustrates what happens when a sample of ice at –20°C is heated steadily, continuing after it all becomes steam. The diagram is not to scale.

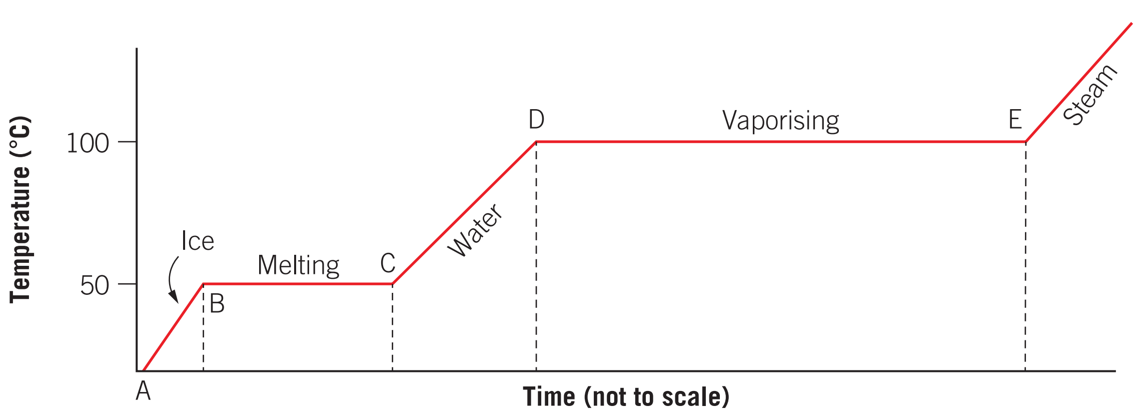

Figure 2A–13 Water change of state diagram

Melting
the change of state from solid to liquid

Fusion
the change of state from liquid to solid

Vaporisation
the change of state from liquid to gas

Condensation
the change of state from gas to liquid

Change of state
when a substance changes from one state (solid, liquid or gas) to another by absorbing or releasing energy

Specific latent heat
the energy needed to be absorbed or released per kilogram of a substance to cause a change of state, in units J kg^{-1}. It depends on both the substance and the change of state. It is given the symbol L.

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From point A to point B, the water remains in its solid state (ice) and the temperature and thermal energy are related by $Q = mc_{ice}\Delta T$. Note that c_{ice} is equal to 2093 J kg^{-1} K^{-1}, which is different from c_{water}. From point B to point C, the mixture of ice and water remains at 0°C and all the thermal energy added is being used breaking the bonds between the ice molecules. In this case the state of change that has occured is melting and the energy needed for it to occur is given by Formula 2A–2 as:

$$Q = mL_{melting}$$

where Q is the amount of thermal energy needed to melt the ice, m is the mass of the ice changing state and $L_{melting}$ is the specific latent heat of melting for water. Then from point C (when all the ice has melted) to point D, the thermal energy is related to the temperature by $Q = mc_{water}\Delta T$. At point D the water starts to boil (vaporise), and the temperature remains constant at 100°C while thermal energy is being used to break the bonds between the water molecules. This is given by Formula 2A–2 as:

$$Q = mL_{vaporisation}$$

where Q is the amount of thermal energy needed to turn water into steam, m is the amount of mass changing state and $L_{vaporisation}$ is the *specific latent heat of vaporisation of water*. One conclusion from this is that food cooked in boiling water will not cook any faster if the water is boiling rapidly, rather than just boiling. The temperature will be the same in both cases: 100°C. As discussed earlier, when the process is reversed, for example when steam condenses to liquid water, thermal energy is released to the environment. As a result, allowing steam to condense to water on your hand can result in a nasty burn.

Figure 2A–14 Steam burn. A steam burn is to the hot burn shown in Figure 2A–1, with similar treatment required.

The equation for the thermal energy released by condensation using Formula 2A–2 is:

$$Q = mL_{condensation}$$

The values for $L_{vaporisation}$ and $L_{condensation}$ are, not surprisingly, the same. The same reasoning applies to the freezing of liquids into solids; thermal energy is released as a liquid freezes. When you fill a ice cube tray with water and place it is the freezer, the thermal energy released is absorbed by the freezer compartment. The equation for the thermal energy released is:

$$Q = mL_{fusion}$$

and the values for $L_{melting}$ and L_{fusion} as discussed earlier are exactly the same. Some values for L_{fusion} and $L_{vaporisaion}$ are shown in Table 2A–4.

Table 2A–4 Specific latent heats of fusion and vaporisation for different materials

Material	Specific latent heat of fusion (kJ kg^{-1})	Specific latent heat of vaporisation (kJ kg^{-1})
Carbon dioxide	184	574
Ethanol	108	846
Lead	23	871
Sulfur	39	1510
Water	334	2256

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As you know, you can cool a drink by adding ice blocks. Thermal energy is absorbed by the ice until all the ice has melted. This cools the drink and reduces the temperature of the drink. Then the drink is further cooled as the cold water from the melted ice absorbs more energy until equilibrium is reached.

Check-in questions – Set 3

WORKSHEET 2A–1 THERMAL ENERGY

1 Which is greater: water's latent heat of melting or its latent heat of condensation?
2 How much energy is needed to melt 10 kg of ice?
3 How much energy is needed to raise the temperature of 1 kg of water by 10 K?

Worked example 2A–2 Energy in phase change of water

How much energy needs to be added to 2.0 kg of ice at 0.0°C to convert all the ice into water? Compare this to the amount of energy that needs to be added to 2.0 kg of water at 100°C to convert all the water into steam.

Solution

Use L_{fusion} for water as 334 kJ kg^{-1} and $L_{vaporisation}$ for water as 2256 kJ kg^{-1}.

To find the energy needed to convert the ice into water, use Formula 2A–2: $Q = mL$.

Where:

$m = 2$ kg

$L = 334$ kJ kg^{-1}

gives:

$Q = 2 \times 334 \times 10^3$

$= 668 \times 10^3$

$= 668$ kJ

To find the energy needed to convert the water into steam, use Formula 2A–2: $Q = mL$.

Where:

$m = 2$ kg

$L = 2256$ kJ kg^{-1}

gives:

$Q = 2 \times 2256 \times 10^3$

$= 4512 \times 10^3$

$= 4512$ kJ

Comparing the two answers, you see that it takes 3844 kJ more energy to convert 2.0 kg of water at 100°C into steam than it does to convert 2.0 kg of ice at 0.0°C into water. It takes almost seven times the energy to cause the change of state from water to steam than from ice to water.

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Worked example 2A–3 Application to cooling a drink

A container of 1.00 kg of water at 20°C is cooled by the addition of 100 g of ice at 0°C. Assume that the container is insulated. Find the final temperature of the drink when all the ice has melted and the entire container is at the same temperature.

Solution

The ice gains energy when melting, Q_1, and after it melts into water it gains more energy, Q_2, as it warms up to the final temperature, T. The drink loses energy, Q_3, as it cools to the final temperature, T. The law of conservation of energy means that $Q_1 + Q_2 = Q_3$.

Use Formula 2A–2: $Q = mL$ to find the value of Q_1.

Where:

$$m_{ice} = 0.100 \text{ kg}$$
$$L = 334 \text{ kJ kg}^{-1}$$

gives:

$$Q_1 = mL$$
$$= 0.100 \times 334\,000$$
$$= 33\,400 \text{ J}$$

Note: you need to convert temperatures in degrees Celsius to kelvins (20°C = 293 K, 0°C = 273 K).

Use Formula 2A–1: $Q = mc\Delta T$ to find the values of Q_2 and Q_3.

Where:

$$m_{water} = 0.100 \text{ kg}$$
$$c_{water} = 4190 \text{ J kg}^{-1} \text{ K}^{-1}$$
$$\Delta T = T - 273 \text{ K}$$

gives:

$$Q_2 = 0.100 \times 4190 \times (T - 273)$$
$$= 419.0 \times (\mathrm{T} - 273) \text{ J}$$

Using:

$$m_{water} = 0.100 \text{ kg}$$
$$c_{water} = 4190 \text{ J kg}^{-1} \text{ K}^{-1}$$
$$\Delta T = 293 - T \text{ K}$$

gives:

$$Q_3 = 1.000 \times 4190 \times (293 - T)$$
$$= 4190 \times (293 - T) \text{ J}$$

Putting this all together using the law of conservation of energy, $Q_1 + Q_2 = Q_3$ gives:

$$33\,400 + 419.0\,(T - 273) = 4190 \times (293 - T)$$

Solving for T gives:

$$T = \frac{33\,400 - 419 \times 273 - 4190 \times 293}{-419 - 4190}$$
$$= 283.9 \text{ K}$$

Hence, the final temperature of the water is 10.9°C.

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2A SKILLS

1 Most calculations in this section use kelvin rather than degrees Celsius. Make sure that you can convert between these scales accurately.
2 Make sure you can distinguish between thermal energy and temperature – the first is the total of all the random kinetic and potential energies of the molecules and the second is the quantity measured by a thermometer. Temperature rises and falls as the thermal energy rises and falls but the connection between them is complicated.
3 You should be able to distinguish clearly between conduction, convection, radiation and evaporation as ways in which thermal energy transfers can take place.
4 Ensure that you can use the relationship $Q = mc\Delta T$ to calculate the energy transfers involved in raising or lowering the temperature of a substance.
5 Ensure you can use the relationship $Q = mL$ to calculate the energy involved in changing the state of a substance for example, from solid to liquid (or vice versa) or liquid to gas (or vice versa).

VIDEO 2A–2
SKILLS: THERMAL ENERGY

Section 2A questions

Multiple-choice questions

1 Which of the following temperature pairs are the same, to within one degree kelvin?
 A 0 K and 273°C
 B −113°C and 160 K
 C 20°C and 253 K
 D 370 K and 90°C

2 The temperature of a block of material is
 A linked to the total thermal energy in the block.
 B proportional to the kinetic energy of the most energetic molecules in the block.
 C a measure of the amount of energy that can be extracted from the block.
 D a measure of the average potential energy of the molecules in the block.

3 When some methylated spirit at room temperature is wiped on your hand, it feels cool because
 A the methylated spirit is a good thermal conductor.
 B of convection currents in the air around your hand.
 C the most energetic molecules of methylated spirit evaporate.
 D the methylated spirit was kept at a lower temperature.

4 Energy transfers using radiation
 A occur with all objects above 0 K.
 B only occur with glowing objects.
 C cannot pass through a vacuum.
 D do not depend on the surfaces involved.

5 A block of wood at 20°C and a block of aluminium also at 20°C feel to be at different temperatures when you put your hand on them. The aluminium block feels colder. This is because
 A aluminium is a better radiator than wood.
 B aluminium is a better thermal conductor than wood.
 C wood is a better thermal conductor than aluminium.
 D your hand is not an accurate thermometer.

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Short-answer questions

6 Locations beside the sea on the edge of a dry land mass can experience a sea breeze during a sunny day and a land breeze in the night. Use the high specific heat of water and the phenomenon of convection to explain the existence and direction of these two breezes.

7 An electric kettle contains 1.5 kg of water at 20°C and has a power rating of 2000 W.

a Assume it is insulated perfectly. How long will it take to raise the entire 1.5 kg of water to boiling point?

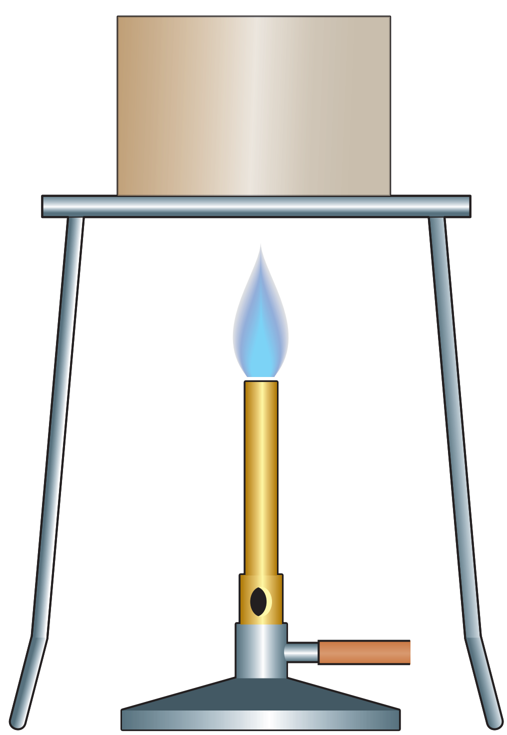
b Assuming all the water in the kettle is at 100°C, how much longer will it take it to convert all the water to steam?

8 Calculate the energy required to convert 1 kg of ice at –20°C to water at +20°C. Use the specific heat of ice, which is different from that of water, and is equal to 2108 J kg^{-1}.

9 When soups contain a large proportion of solids (e.g. vegetables, noodles, meat), compared to water, they tend to cool more quickly. Suggest physical reasons for this.

10 Suggest why people sometimes prefer mittens (left) to gloves (right) in cold weather.

11 A 1.5 kg block of a metal alloy is heated, raising its thermal energy by 4500 J. Its temperature rises by 5.0°C. Calculate the specific heat capacity of the alloy.



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2B Thermal energy, electromagnetic radiation and global warming

Study Design:
- Calculate the peak wavelength of the re-radiated electromagnetic radiation using Wien's Law: $\lambda_{max} T = \text{constant}$
- Compare the total energy across the electromagnetic spectrum emitted by objects at different temperatures
- Apply concepts of energy transfer, energy transformation, temperature change and change of state to climate change and global warming

Glossary:
Atmospheric window
Back radiation
Blackbody
Carbon dioxide (CO_2)
Climate
Greenhouse gas
IPPC
Methane (CH_4)
Wien's law

ENGAGE
Horticultural greenhouses

A traditional gardener's greenhouse is a small garden shed made mainly of glass or clear plastic. It can keep plants warm on sunny days even if it is very cold.

The glass of the greenhouse allows light of visible and near infrared wavelengths to pass through. The energy of this light is converted into thermal energy, warming the interior. The re-radiation from the warmed contents of the greenhouse gives rise to re-radiated long-wavelength infrared, which cannot pass easily through the glass (or plastic) and is trapped, causing further warming. Energy losses by convection can be minimised by keeping the windows closed and conduction through the glass can also be reduced by double glazing.

In very cold areas when temperatures might dip below freezing at night, a heater can be left on to prevent frost damage to plants.

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EXPLAIN

Solar radiation and the temperature of Earth

The surface of Earth is almost entirely warmed by electromagnetic energy from the Sun. A total of 1.73×10^{17} watts (W) shines on our planet all the time; this is more than 10 000 times the power needs of its inhabitants. (Remember that power is a measure of energy per second.) To understand how this solar energy affects our planet, we need to understand what makes up the spectrum of solar radiation. A simplified diagram of this spectrum is shown in Figure 2B–1.

1B ELECTROMAGNETIC WAVES LINK

VIDEO 2B–1 THERMAL ENERGY, ELECTROMAGNETIC RADIATION AND GLOBAL WARMING

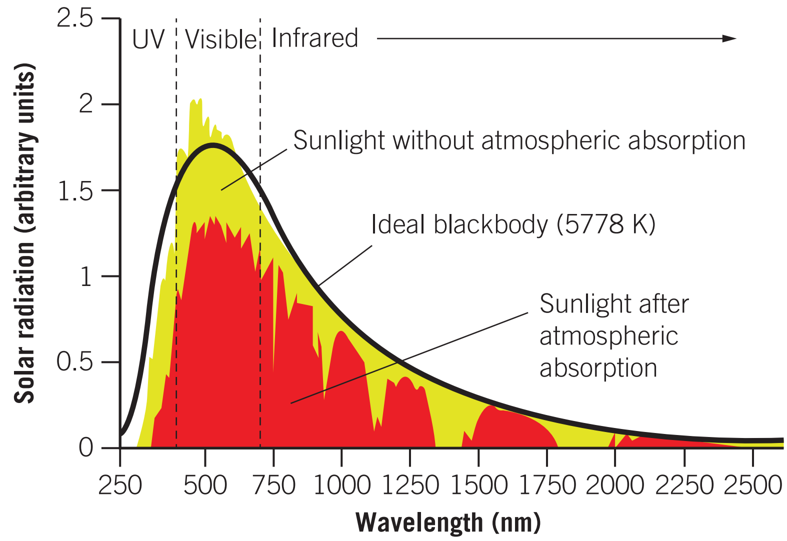

Figure 2B–1 Solar radiation spectrum, showing how much power is radiated at different wavelengths. The red and yellow regions together are the the power reaching the top of the atmosphere, while the red regions represent the power at ground level. The black curve is the power emitted at different wavelengths calculated for a theoretical ideal black body at a temperature of 5778 K, this is the same kind of curve as in Figure 2B–2.

One feature that can be seen from the graph is that the Sun's surface can be modelled as a nearly *ideal blackbody radiator*.

Blackbody radiators, blackbody radiation

All objects above 0 K will emit electromagnetic radiation. The energy comes from the internal thermal energy of the object. However, some bodies (e.g. ones with matt black surfaces) emit radiation more efficiently than others (such as one with a shiny white or metallic surface). When an object emits all of the frequencies produced in it by its thermal energy with maximum efficiency, it is described as a **blackbody**, and the radiation it produces is called *blackbody radiation*. Note that blackbodies also absorb all frequencies of radiation that fall on it. The blackbody radiation emission curves for objects at different temperatures are shown in Figure 2B–2.

Blackbody a theoretical object that perfectly absorbs all radiation falling on it

Wien's law an equation that relates the peak wavelength emitted and the temperature of an ideal blackbody

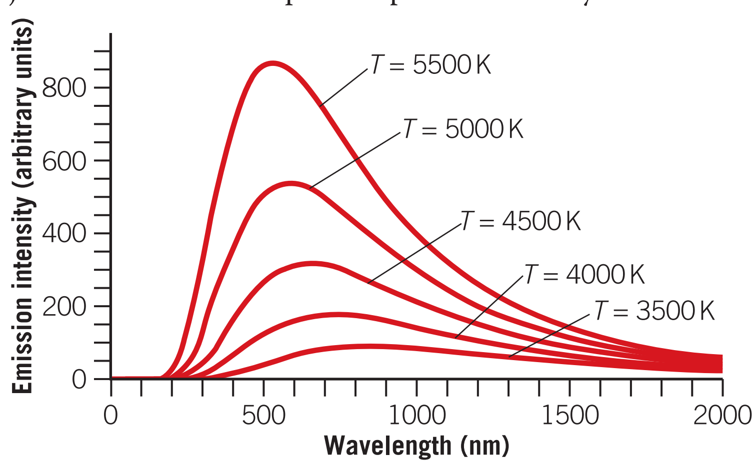

Figure 2B–2 Blackbody radiation curves of radiation emission intensity by wavelength for different temperatures in kelvin

The shape of these curves varies with temperature, and two blackbodies at the same temperature will have the same shaped curve, even if they are made of different materials.The total emitted power by a blackbody is the total area under the emission intensity vs wavelength curve. As we can see in Figure 2B–2, the total power across the electromagnetic spectrum emitted by an object increases with temperature of the object. Also, since the shape of any curve doesn't depend on the material, we can estimate the object's temperature from its shape. The peak wavelength is related to the temperature by **Wien's law**, outlined in the next box.

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Formula 2B–1 Wien's law

$$\lambda_{max} T = b$$

Where:

λ_{max} = Peak wavelength emitted by the blackbody (m)

T = Temperature of the blackbody (K)

b = A constant, 2.898×10^{-3} m K (0.002898 m K)

This means that you can also estimate the temperature (or total emitted energy) of distant objects (modelled as blackbodies) by observing their peak wavelength. Using this modelling for the surface of the Sun, which approximates closely to a blackbody and has a peak wavelength 524.7 nm, gives a surface temperature of the Sun as 5778 K or 5505°C. Wien's law is routinely used to estimate the effective temperature of visible stars, and in other applications such as scanning thermometers to measure human forehead temperatures.

Figure 2B–3 Measuring forehead temperature by measuring the intensity of infra-red radiation emission and converting using Wien's law.

Worked example 2B–1 Peak wavelength of a human

The human body can be modelled as a blackbody with a temperature of 310 K. What region of the electromagnetic spectrum would the peak wavelength of its emitted radiation be located in?

Solution

Using Wien's law:

$$\lambda_{max} = \frac{b}{T}$$

$$= \frac{0.002\,898}{310}$$

$$= 9.35 \times 10^{-6}\,\text{m}$$

This is in the infrared region of the electromagnetic spectrum.

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As well as receiving radiation from the Sun, Earth radiates energy into space, as it is an object with a temperature greater than 0 K. Modelling Earth as a blackbody with a temperature of 15°C gives the radiation intensity curve against wavelength as shown in Figure 2B–4, along with the corresponding data for the Sun, scaled down by a factor of 10^6.

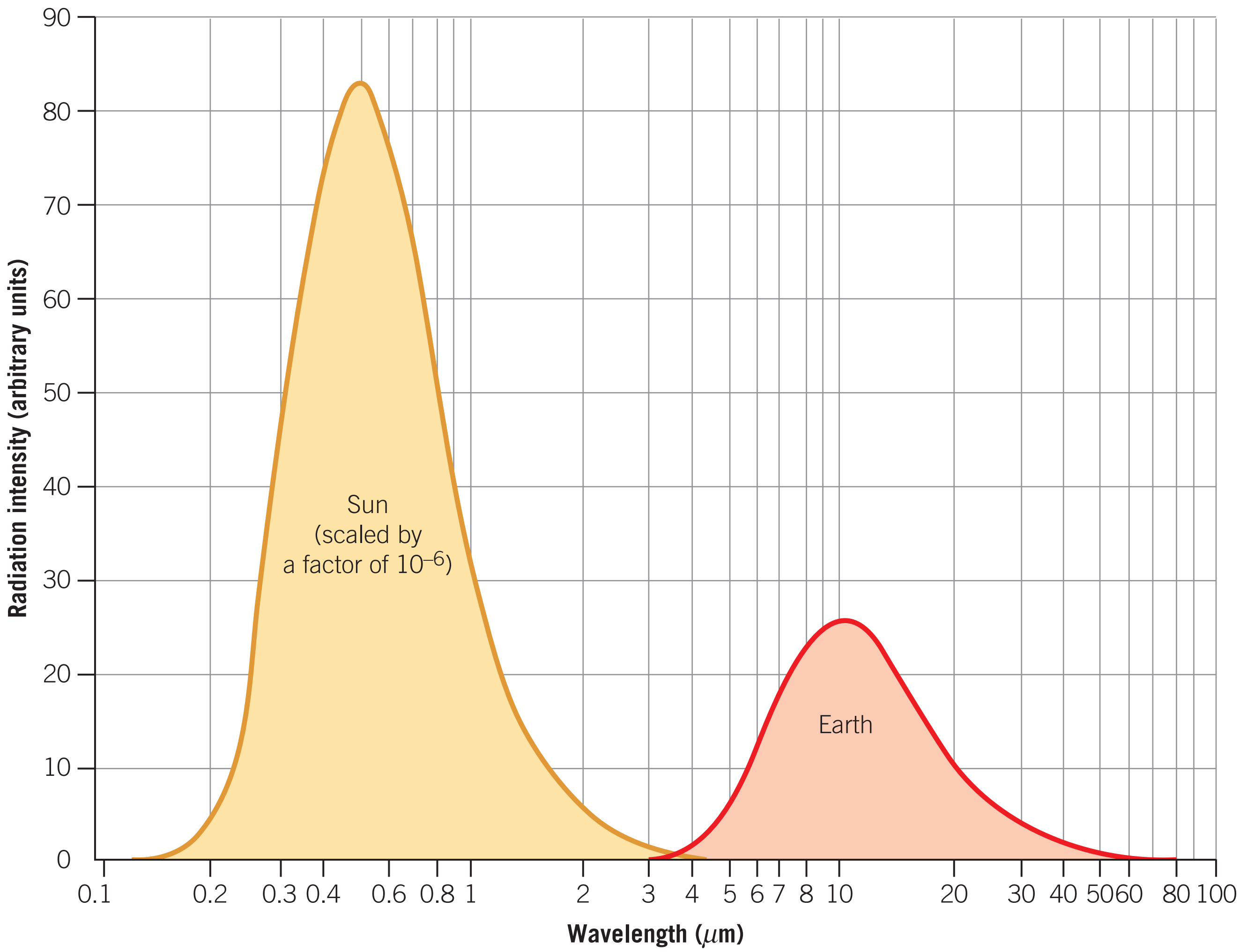

Figure 2B–4 Blackbody emission of the Sun and Earth, with the Sun's radiation intensity scaled down to a millionth of its actual value relative to Earth.

Looking at the curves in Figure 2B–4, you can see that it is clear the total radiated power (given by the area under the curve) increases sharply as the temperature increases and the wavelength shortens. From the graph, Earth clearly emits much less radiation energy than the Sun and the wavelengths of Earth's emissions are all much longer, located in the infrared region of the electromagnetic spectrum. This is an example of how blackbody models can be useful, as it allows for comparisons of temperature, energy emitted and peak wavelength to be easily made between different bodies.

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Worked example 2B–2 Peak wavelength emitted by Earth

What is the peak wavelength emitted by Earth modelled as a 15°C blackbody?

Solution

Converting Celsius (15°C) to kelvin gives you 288 K. Now, using Wien's law:

$$\lambda_{max} = \frac{b}{T}$$

$$= \frac{0.002\,898}{288}$$

$$= 1.01 \times 10^{-5}\ \text{m}$$

Check-in questions – Set 1

1 What is the relationship between the peak wavelength of a blackbody radiator and its temperature in kelvin?

2 What two changes happen to the spectrum of a blackbody as its temperature increases?

Understanding global warming and climate change

Our lives on Earth depend on an equilibrium between the energy received from the Sun and the energy that Earth reflects and radiates back into space. If this equilibrium is disturbed, the planet either warms or cools. At present the planet is undergoing global warming, as shown in Figure 2B–5; the data used in the graph is from NASA (National Aeronautics and Space Administration).

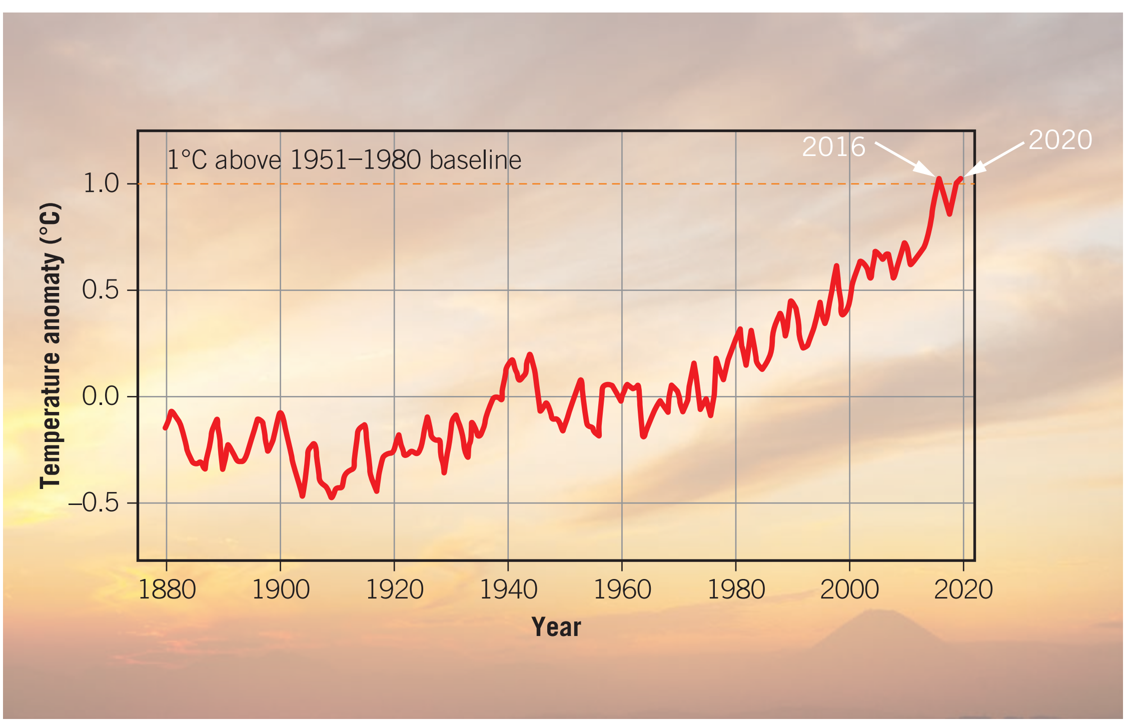

Figure 2B–5 Mean global temperature anomaly from 1880 to 2020. The anomaly (deviation from what is considered normal) is measured as the difference in mean global temperature for each year compared to the calculated 1951–1980 mean global temperature, which is selected as the baseline, labelled 0.0 on the graph. Up to1940 global temperatures were fractionally below the baseline, and from about 1970 they have been rising and in 2016 and 2020 were 1°C higher than the baseline.

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Climate the long-term weather patterns or average weather in an area, typically over a period of 30 years

Such global warming, even of only one or two degrees, causes significant changes in the **climate** – the local, regional and global average weather patterns over Earth's surface. These changes can include land, sea and air temperature increases, higher sea levels, loss of ice from glaciers and Arctic and, Antarctic ice caps, and more frequent extreme weather events like cyclones, heatwaves, bushfires, droughts and floods. Patterns of rainfall can also shift, making land less suitable (or more suitable) for agriculture and animal habitats. Sea level rises would make some lower lying parts of the planet uninhabitable; for example islands like the Maldives and delta communities such as the Nile and in Bangladesh.

WORKSHEET 2B–1 THERMAL ENERGY, ELECTROMAGNETIC RADIATION AND GLOBAL WARMING

Earth's energy budget

'Budget' is used here in the sense of a reckoning of inputs (incoming energy) and outputs (outgoing energy). Almost all the energy in Earth's climate system comes from solar radiation (a tiny amount comes from Earth's interior). Figure 2B–6, published by NASA in 2009 and based on 10 years of data, outlines what happens to the incoming solar radiation and the radiation emitted and reflected by Earth.

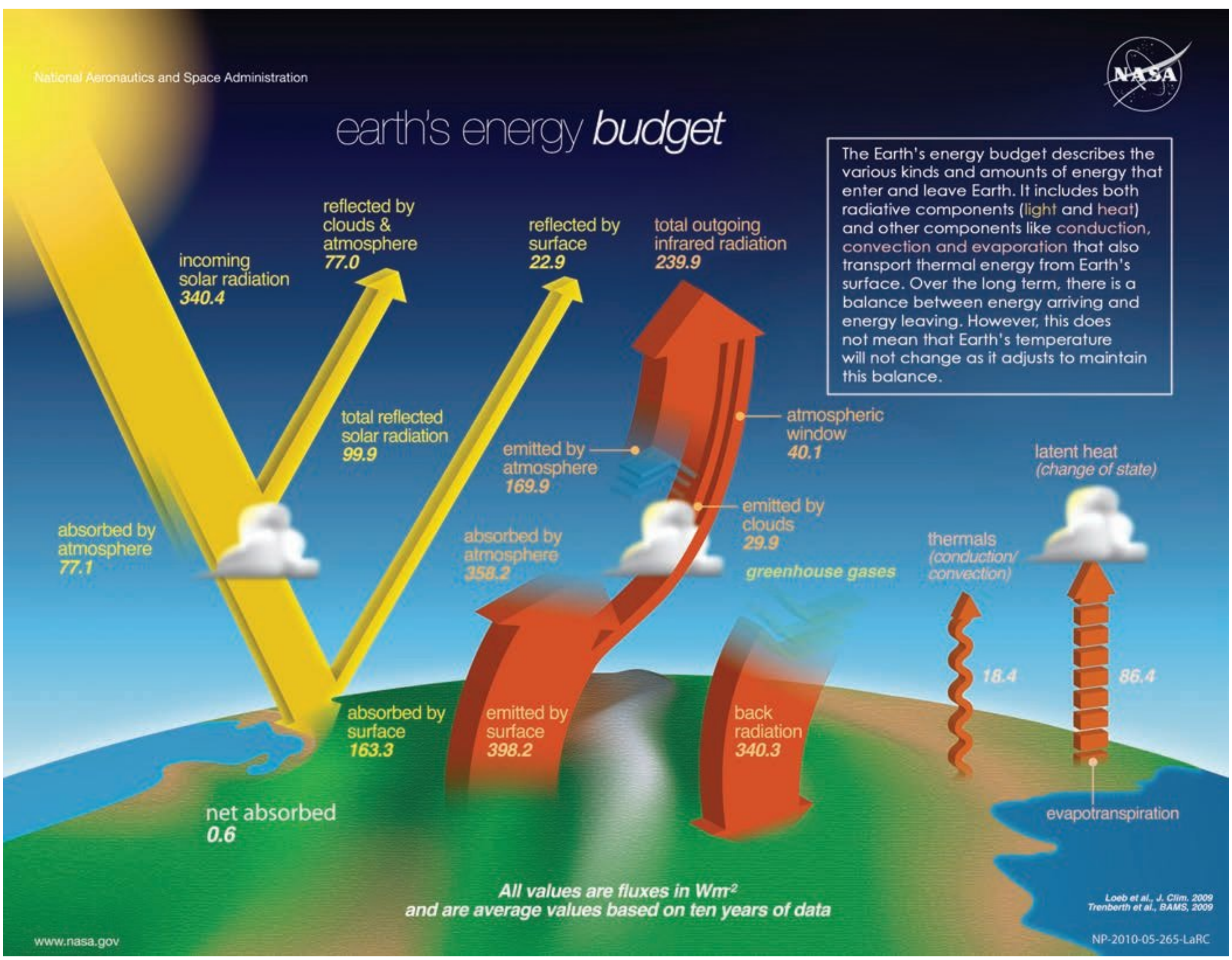

Figure 2B–6 Earth's energy budget, calculated by NASA in 2009, based on the means of 10 years of data. The units are watts per square metre of the Earth's surface, i.e. power per square metre, or energy per second per square metre.

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On average, Earth receives energy at a rate of 340 W m^{-2} from the Sun. Of this, about 100 W m^{-2} is reflected straight back into space by clouds, dust, aerosols and Earth's surface (particularly ice, snow and desert areas). The rest (about 240 W m^{-2}) is absorbed directly by the atmosphere and the surface, where it is converted to thermal energy. As well as receiving this radiation energy directly, the atmosphere also receives energy by convection, evaporation and infrared radiation from Earth's surface.

Earth radiates an almost equal amount of infrared radiation back into space, but a small residual amount – about 0.8 W m^{-2} according to a recent **IPCC** report – contributes to global warming. Most of this is stored as increased thermal energy in the oceans. This residual has been growing, according to research done by NASA. Because the Earth–atmosphere system is out of balance like this, Earth's temperature will increase so as to restore the balance, since an increased temperature will increase heat loss though all the processes available.

Earth's infrared emissions are quite complex. The surface radiates about 400 W m^{-2}, of which about 40 W m^{-2} lie in the **atmospheric window** and escapes to space. However, most of it is absorbed by the atmosphere, particularly by the 'greenhouse' gases like water vapour (H_2O), **methane (CH_4)** and **carbon dioxide (CO_2)**. These gases then re-radiate energy, resulting in the large back radiation shown. As the percentage of **greenhouse gases** in the atmosphere increases, this **back radiation** will also increase. This will further increase the residual energy and consequently increase global warming.

Check-in questions – Set 2

1 How many W m^{-2} of Earth's surface infrared radiation finds its way into space without being absorbed by the atmosphere?
2 According to the IPCC, what is the approximate residual amount of energy currently contributing to global warming?
3 What role do the gases CO_2, CH_4 and H_2O play in Earth's infrared radiation?

2B SKILLS

1 Make sure that you can use Wien's law ($\lambda_{max}T = 0.00289$) with either T or λ_{max} as the subject, applied to blackbodies (or objects modelled as blackbodies).
2 Ensure that you can use blackbody spectra to compare the total electromagnetic energy emitted by various objects, from the area under their electromagnetic spectrum graphs.
3 Be able to identify the contributions of various energy transfer mechanisms (e.g. conduction, convection, radiation, evaporation) to the temperature changes in Earth's global energy budget.
4 Be able to explain the various factors affecting global temperature changes.

IPCC
Intergovernmental Panel on Climate Change

Atmospheric window
the range of wavelengths of the electromagnetic spectrum that experience little to no absorption by atmospheric gases

Methane (CH_4)
a gas that occurs in relatively small quantities in the atmosphere that contributes a large amount to back radiation; it is the main component of natural gas and commonly produced by cattle

Carbon dioxide (CO_2)
a common gas in the atmosphere that contributes to back radiation; it is produced by many chemical processes especially combustion and is absorbed by photosynthetic plants and microorganisms

Greenhouse gas
a term used to classify gases that absorb and emit radiation in the infrared range

VIDEO 2B–2
SKILLS: WIEN'S AND ENERGY TRANSFERS

Back radiation
the amount of radiation emitted from the atmosphere back towards Earth's surface

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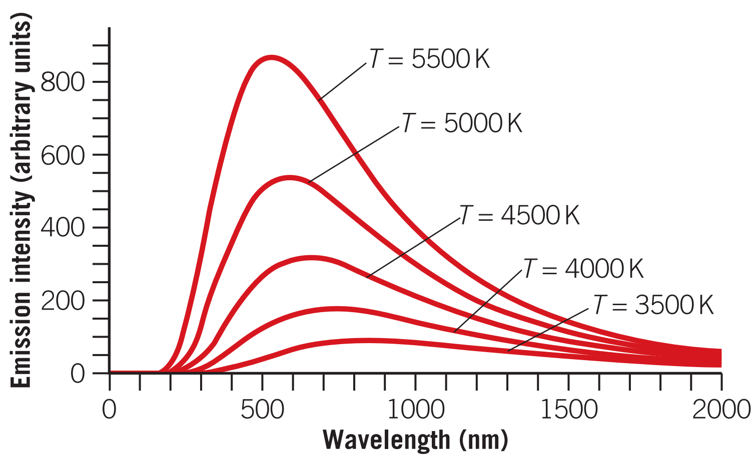
Section 2B questions

Multiple-choice questions

1 A key characteristic of a blackbody is that
- **A** it has a dark-coloured surface.
- **B** it absorbs all radiation frequencies falling on it.
- **C** it has a temperature above 0 K.
- **D** its peak radiation increases with its temperature.

2 Wien's law states that
- **A** the peak wavelength of a blackbody is inversely proportional to its Celsius temperature.
- **B** the peak wavelength of a blackbody is directly proportional to its kelvin temperature.
- **C** the peak wavelength of a blackbody is directly proportional to its Celsius temperature.
- **D** the peak wavelength of a blackbody is inversely proportional to its kelvin temperature.

Use the following blackbody radiation curves to answer Questions 3 and 4.



3 Which temperature curve has the highest peak frequency value?
- **A** T = 5500 K
- **B** T = 5000 K
- **C** T = 4000 K
- **D** T = 3500 K

4 Which of the five graphs has the greatest total energy emission?
- **A** T = 5500 K
- **B** T = 5000 K
- **C** T = 4000 K
- **D** T = 3500 K

Short-answer questions

5 Earth can be modelled as a blackbody with a temperature of 20°C.
- **a** Use Wien's law to estimate the peak wavelength emitted from Earth.
- **b** Identify the region of the electromagnetic spectrum of this peak wavelength.

6 Outline the role that 'greenhouse' gases (such as H_2O, CH_4 and CO_2) play in Earth's infrared emissions.

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Chapter 2 review

Summary

Create your own set of summary notes for this chapter on paper or in a digital document. A model summary is provided in the Teacher Resources, which can be used to compare with yours.

Checklist

In the Interactive Textbook, the success criteria are linked from the review questions and will be automatically ticked when answers are correct. Alternatively, print or photocopy this page and tick the boxes when you have answered the corresponding questions correctly.

Success criteria – I am now able to:		Linked questions
2A.1	Describe thermal energy as the sum of the random kinetic energy and potential energy of the atoms and molecules of an object or system	2☐
2A.2	Understand that increases and decreases of temperature are related to increases and decreases of thermal energy in a system	3☐
2A.3	Convert temperatures between Celsius and kelvin	1☐
2A.4	Analyse qualitatively thermal energy transfers in terms of conduction, convection, radiation and evaporation using a particle model	4☐, 5☐, 13☐, 14☐, 15☐, 16☐, 20☐
2A.5	Define specific heat capacity, c	6☐
2A.6	Define specific latent heats of vaporisation (condensation) and fusion (melting), L	7☐, 8☐
2A.7	Carry out practical investigations involving changing the temperature or state of a substance	22☐, 23☐
2A.8	Analyse quantitatively the thermal energy changes associated with temperature and state changes	9☐, 17☐, 18☐
2A.9	Use the equation $Q = mc\Delta T$ to calculate the energy needed to raise the temperature of a substance	17☐
2A.10	Use the equation $Q = mL$ to calculate the energy needed to change the state of a substance	18☐
2B.1	Describe the general features of a blackbody object	10☐, 11☐
2B.2	Use Wien's law ($\lambda_{max}T = 2.90 \times 10^{-3}$ m K) to calculate the peak emitting wavelengths of objects modelled as blackbodies	12☐, 19☐
2B.3	Use graphical methods to compare total energy radiated by objects modelled as blackbodies	19☐
2B.4	Identify the way concepts of thermal energy and electromagnetic radiation can help understanding of global warming and climate change	21☐

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Multiple-choice questions

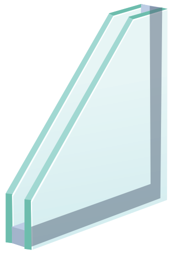
1 Which of the following are correct (to within one degree)?
  A 100 Celsius degrees are equal to 273 kelvin
  B −273 K is equal to 100°C
  C −273 K is equal to 0°C
  D 100 K is equal to −173°

2 Which of the following statements about thermal energy is correct?
  A The thermal energy of an object can be increased by increasing its thermal conductivity.
  B Increasing the total potential energy of an object's molecules increases its thermal energy.
  C Increasing the heat capacity of an object will increase its thermal energy.
  D Changing the temperature of an object is unlikely to change its thermal energy.

3 Which of the following changes will increase the temperature of an object?
  A increasing its heat capacity
  B increasing the random kinetic energy of its molecules
  C decreasing its thermal conductivity
  D converting the potential energy of some of its molecules to random kinetic energy

4 A Coolgardie safe is a mesh box covered with damp hessian sacking. The interior of the mesh box keeps food cool because
  A evaporation of water from the damp hessian sacking removes thermal energy from the box.
  B the water in the hessian sacking conducts thermal energy away from the box.
  C a convection cell is set up in the mesh box, keeping it cool.
  D the evaporating water from the sacking raises thermal energy away from the safe.

5 Many modern houses, particularly in cooler climates, use double-glazed windows to reduce thermal energy losses through them. A basic type comprises two panes of glass that are separated by a thin layer of air.



  Glass is a poor insulator, but these windows are used because
  A two thicknesses of glass give double the insulation of one layer.
  B air and inert gases are good insulators provided convection can be minimised.
  C evaporation losses are minimised by using air in the space between the glass panes.
  D they are good sound insulators when noise pollution is a problem.

6 Which of the following is the best definition of the specific heat capacity of an object?
  A the energy required to raise the temperature of a body by 1 K
  B the energy required to raise the temperature of a body by 1 K in 1 s
  C the energy per kg required to raise the temperature of a body by 1 K in 1 s
  D the energy per kg required to raise the temperature of a body by 1 K

7 Which of the following is the best definition of the specific latent heat of vaporisation?
  A the energy required to vaporise 1 kg of the material involved
  B the energy required to vaporise 1 kg of the material involved in 1 s
  C the energy required to raise the temperature enough to vaporise 1 kg of the material involved
  D the energy required to raise the temperature enough to vaporise 1 kg of the material involved in 1 s

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8 Which of the following is the best definition of the specific latent heat of fusion?

- **A** the energy required to melt 1 kg of the material involved in 1 s
- **B** the energy required to melt 1 kg of the material involved
- **C** the energy required to raise the temperature enough to melt 1 kg of the material involved
- **D** the energy required to raise the temperature enough to melt 1 kg of the material involved in 1 s

9 A 250 W immersion heater is used to bring 0.50 kg of water at 20°C to the boil. The specific heat capacity of water is 4190 J kg^{-1} K^{-1}. Ignoring thermal energy losses, and the energy to heat the heater itself, the time that this would take is closest to

- **A** 11 minutes.
- **B** 14 minutes.
- **C** 22 minutes.
- **D** 28 minutes.

10 A blackbody can be identified by the

- **A** longest wavelength that it emits.
- **B** shape of the emission intensity vs wavelength curve.
- **C** material it is made of.
- **D** shape of the material it is made of.

11 A blackbody is an object that

- **A** is painted with black paint.
- **B** is only visible when black light shines on it
- **C** does not reflect any frequencies of electromagnetic radiation
- **D** only emits certain electromagnetic radiation frequencies

12 A temperature sensor measures the forehead of a person's temperature to be 36.6°C.

Use Wien's law to estimate which of the following wavelengths is closest to the peak wavelength.

- **A** 9.4 μm
- **B** 9.7 μm
- **C** 11 μm
- **D** 79 μm

13 The surface of Earth radiates about 400 W m^{-2} of infrared radiation. Which of the following best describes what happens to this radiation?

- **A** About 10% of this radiation is absorbed by greenhouse gases; the rest escapes into space.
- **B** About 10% of this radiation escapes into space; the rest is converted into visible wavelengths.
- **C** About 10% of this radiation escapes into space; the rest is absorbed by the atmosphere.
- **D** Almost all of this radiation is reflected back to the surface.

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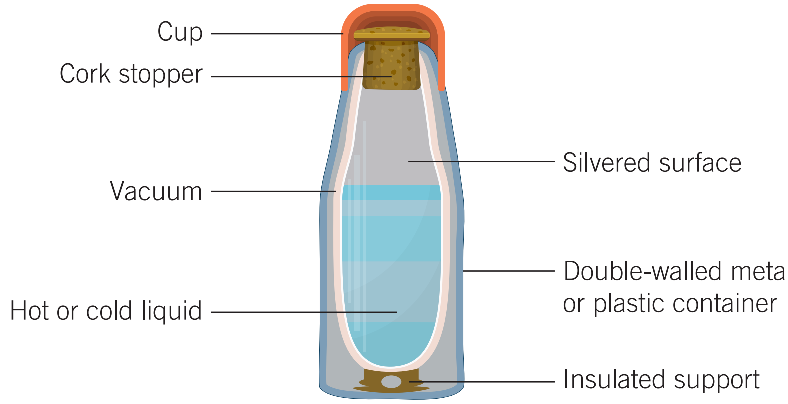
Short-answer questions

14 A vacuum flask can be used to keep drinks hot or cold. Explain the ways in which these flasks reduce heat transfer by convection, conduction, radiation and evaporation. (8 marks)



15 A cup of freshly brewed coffee sits on a table. Describe the various ways in which heat transfers occur from the hot coffee to the environment. (4 marks)

16 A silver spoon is placed in a hot cup of tea. After a short time, the handle of the spoon becomes much warmer. Describe the mechanism by which thermal energy is transferred along the spoon. (2 marks)

17 Students measure the specific heat capacity of an unknown alloy by immersing 500 g of the alloy at room temperature (20°C) in an insulated container with 500 g of water at 80°C and waiting until the water and the alloy are at the same temperature. They measure the final temperature as 70°C. Ignoring thermal losses to the environment, calculate the specific heat capacity of the alloy. (3 marks)

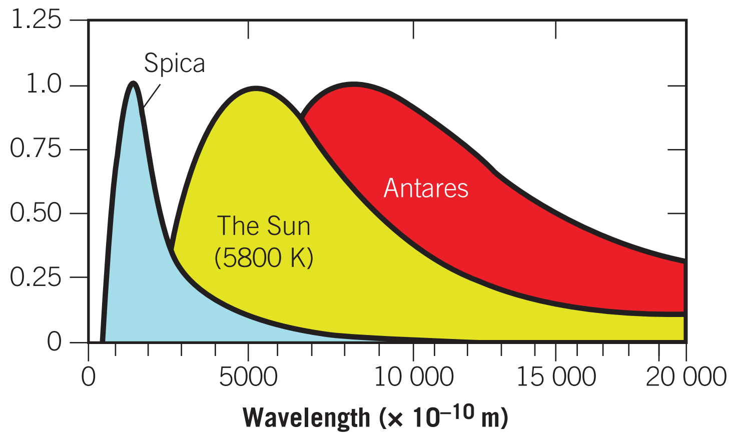
18 Students observe a dish of ice melting in the sunlight. There is 250 g of ice; it is initially at 0°C. They stop the observation when all the ice has turned to water at 15°C.

a How much energy in kJ is required to convert the ice at 0°C to water at 0°C? (2 marks)

b How much energy is required to raise the 250 g of water at 0°C to 15°C? (2 marks)

c The students use their results to estimate the average solar radiation power falling on the dish. Neglecting thermal energy losses, calculate their result in W if the time taken is 10 min. (2 marks)

19 The idealised spectra of three stars, Spica, the Sun and Antares are shown below. The units on the *y*-axis are relative emission intensities. The three stars can be modelled as blackbodies.



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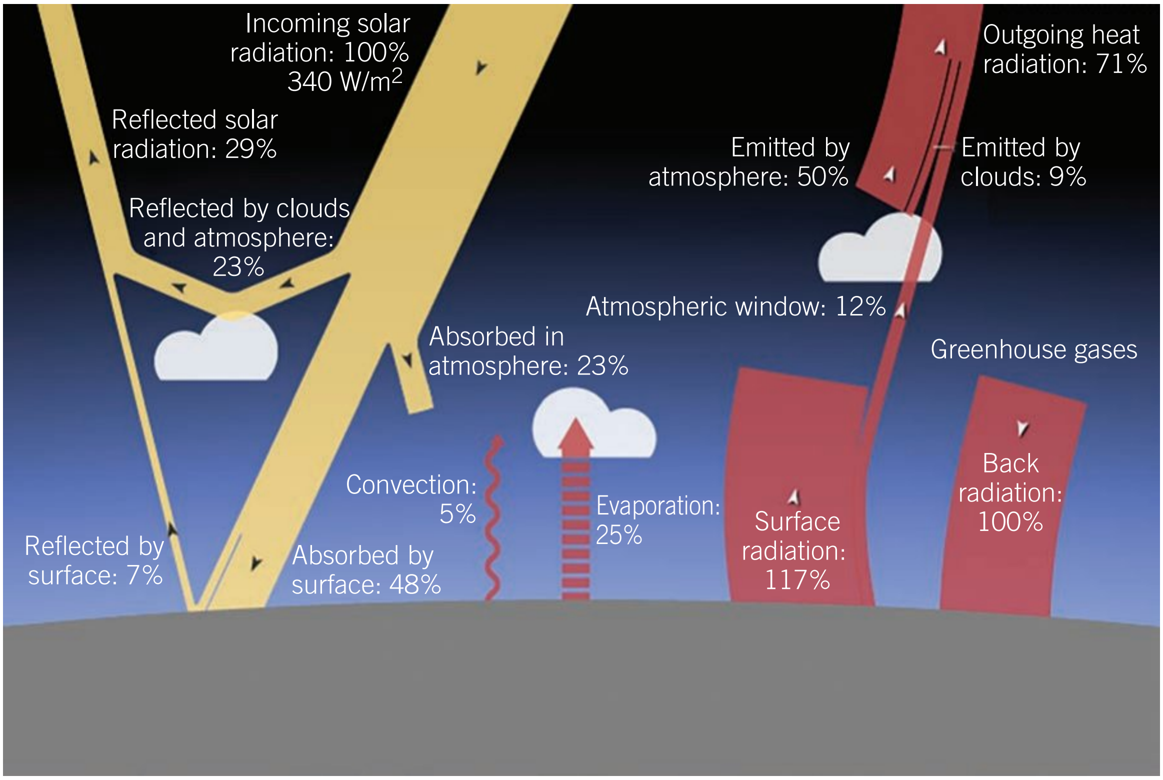
a Estimate from the graph the peak wavelengths of Spica and Antares. (1 mark)
b Use Wien's law and the data for the Sun to estimate the constant in Wien's law. (2 marks)
c Estimate the temperature of Spica and Antares. (4 marks)
d Rank the three stars in order of increasing total energy emission. (1 mark)

20 Summarise briefly why the inside of a car warms up on a cool but sunny day if the windows are up. (3 marks)

21 The diagram below shows some approximate data on Earth's global energy flows in 2009.



Identify on the diagram where the following physical processes occur.

a reflection of electromagnetic radiation (1 mark)
b release of latent heat of evaporation (1 mark)
c convection currents involving thermals (1 mark)
d IR radiation from Earth's surface (1 mark)
e IR radiation from gases in the atmosphere (1 mark)

22 Describe a practical investigation using simple laboratory equipment that could estimate the specific heat capacity of aluminium. (5 marks)

23 Describe a practical investigation using simple laboratory equipment that could estimate the specific latent heat of ice. (5 marks)

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UNIT 1 HOW IS ENERGY USEFUL TO SOCIETY?

CHAPTER 3 RADIATION FROM THE NUCLEUS

Introduction

Physicists believe that ever since Earth was formed 4500 million years ago, there have been two major mechanisms at work that continually produce the natural radiation that is within Earth's biosphere: radiation from Earth (terrestrial radiation) and radiation from space (cosmic radiation).

Because soils (and rocks) contain radioactive substances, it is logical that food grown in soils and water that runs off soils also contain radioactive substances. The air we breathe contains traces of radioactive gases (mainly radon). As a natural consequence of living, breathing, eating and drinking, humans accumulate various radioactive substances in their bodies. Natural terrestrial radiation is responsible for 70% of our average annual radiation dose.

Earth's upper atmosphere is continually being bombarded with high-energy particles and gamma rays that originate from the Sun, from outside of our solar system in our own galaxy and from distant galaxies. These produce cosmic radiation 'showers' that 'rain' on Earth and they are responsible for 12% of our average annual radiation dose.

Artificial sources constitute 18% of our average radiation dose and are mainly associated with medical diagnostic and therapeutical uses. There are also small amounts of nuclear radiation doses received from nuclear weapons testing (e.g. Maralinga in South Australia) and nuclear power stations accidents (e.g. Chernobyl).

This chapter explains the concept of nuclear stability and radioactivity and examines the properties of alpha (α), beta (β) and gamma (γ) radiation from the nucleus. You will explore the strength and half-life of radioisotopes, the effect of nuclear radiation on humans and how understanding the physics of nuclear radiation allows for effective use of radioisotopes in medical diagnosis and therapy.

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Curriculum

Area of Study 2 Outcome 2
How is energy from the nucleus utilised?

Study Design	Learning objectives – at the end of this chapter I will be able to:
Radiation from the nucleus • Explain nuclear stability with reference to the forces in the nucleus including electrostatic forces, the strong nuclear force and the weak nuclear force • Explain, using a binding energy curve, why both fusion and fission are reactions that release energy	**3A Nuclear stability: forces in the nucleus** **3A.1** Know that nuclear stability depends on proton to neutron ratios **3A.2** Understand the roles of the electrostatic force, the strong nuclear force and the weak nuclear force **3A.3** Know that electrostatic forces on protons in the nucleus are extremely large repulsive forces **3A.4** Know that the nucleus contains a short-range strong nuclear force that can overcome electrostatic repulsion forces **3A.5** Know that the weak force explains the transformation of protons into neutrons and vice versa **3A.6** Interpret the binding energy curve
• Describe the properties of α, β^-, β^+ and γ radiation • Explain nuclear transformations using decay equations involving α, β^-, β^+ and γ radiation	**3B Alpha, beta and gamma radiation** **3B.1** Know the properties of α-, β^--, β^+- and γ-radiation **3B.2** Explain nuclear transformations using decay equations involving α-, β^--, β^+- and γ-radiation
• Model radioactive decay as random decay with a particular half-life, including mathematical modelling with reference to whole half-lives	**3C Modelling radioactive decay** **3C.1** Understand the concept of half-life for radioactive sources **3C.2** Determine the strength (activity) of radioactive sources after a whole number of half-lives have elapsed
• Analyse decay series diagrams with reference to type of decay and stability of isotopes	**3D Analysing decay series diagrams** **3D.1** Analyse radioactive isotope decay chains (e.g. U-238) and understand that a decay series is a sequence of stages a radioisotope passes through before eventually reaching a stable isotope

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Study Design	Learning objectives – at the end of this chapter I will be able to:
• Explain the effects of α, β and γ radiation on humans, including: ▸ different capacities to cause cell damage ▸ short- and long-term effects of low and high doses ▸ ionising impacts of radioactive sources outside and inside the body ▸ calculations of absorbed dose (gray), equivalent dose (sievert) and effective dose (sievert) • Evaluate the use of medical radioisotopes in therapy including the effects on healthy and damaged tissues and cells	**3E The effect of radiation on humans** **3E.1** Explain effects of α-, β^--, β^+- and γ-radiation on humans **3E.2** Understand the different capacity of α-, β^--, β^+- and γ-radiation to cause cell damage **3E.3** Understand the short- and long-term effects of low and high doses of radiation **3E.4** Understand the ionising impacts of external and internal radiation sources **3E.5** Be able to calculate absorbed dose (gray), equivalent dose (sievert) and effective dose (sievert) **3E.6** Evaluate the use of medical radioisotopes in therapy, including the effects on healthy and damaged tissues and cells

Glossary

Absorbed dose
Activity
Alpha (α) particle
Atomic number
Belt of stability
Beta (β) particle
Binding energy
Binding energy curve
Daughter nucleus
Decay chain
Decay curve
Dose equivalent
Dose–risk relationship
Dosimeter
Effective dose
Electrostatic force
Element
External radiation
Gamma (γ) ray
Geiger counter
Genetic effects
Gray (Gy)
Half-life
Internal radiation
Ionise
Isotope
Mass number
Neutrino
Neutron
Nuclear decay
Nuclear transformation
Nucleon
Nucleus
Parent nucleus
Periodic table
Photon
Positron
Proton
Radiation weighting factor
Radiocarbon dating
Radioactive
Radioactive decay series
Radioactive isotope
Radiotherapy
Sievert (Sv)
Strong nuclear force
Transmutation
Transuranic
Weak nuclear force

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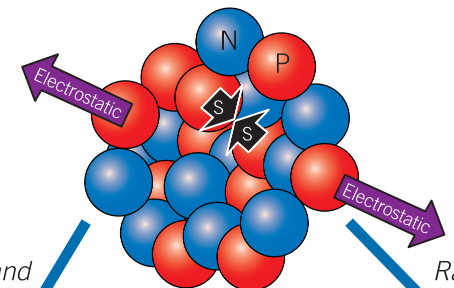
Concept map

A stable nucleus is an ensemble of neutrons and protons in which attraction between particles exceeds repulsion

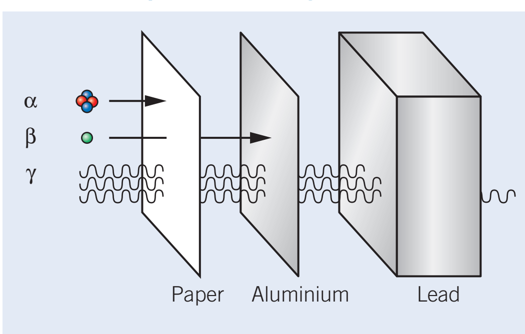
3A Nuclear stability: forces in the nucleus



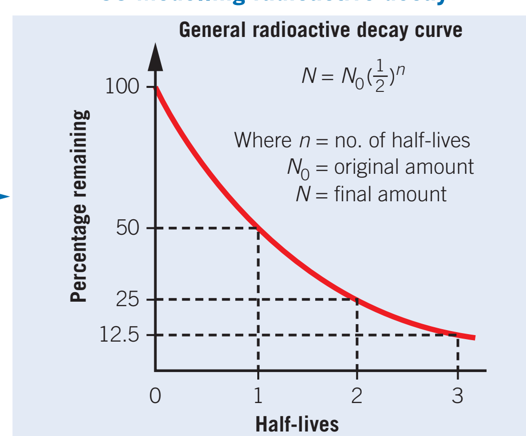
Unstable nuclei release alpha, beta and gamma radiation, transforming the nucleus as shown by decay equations

Random decay of nuclei with a particular half-life, and modelling using whole numbers of half-lives

3B Alpha, beta and gamma radiation



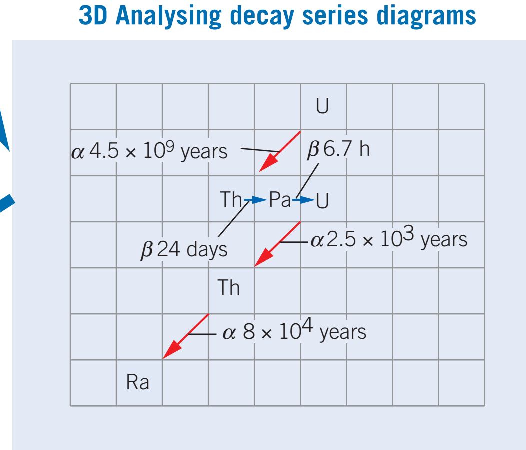
3C Modelling radioactive decay



Different capacities to cause damage, short- and long-term effects of low and high doses, including cell damage and medical uses of radiation

Type of decay and stability of isotopes

3D Analysing decay series diagrams



3E The effect of radiation on humans

See the Interactive Textbook for an interactive version of this concept map interlinked with all concept maps for the course.

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3A Nuclear stability: forces in the nucleus

Study Design:

- Explain nuclear stability with reference to the forces in the nucleus including electrostatic forces, the strong nuclear force and the weak nuclear force
- Explain, using a binding energy curve, why both fusion and fission are reactions that release energy

Glossary:

Atomic number
Belt of stability
Binding energy
Binding energy curve
Electrostatic force
Element
Isotope
Mass number
Neutrino
Neutron
Nuclear decay
Nucleon
Nucleus
Periodic table
Positron
Proton
Radioactive
Radioactive isotope
Strong nuclear force
Transuranic
Weak nuclear force

ENGAGE

Why is understanding nuclear stability important?

Most of the natural elements in the world are stable; that is, they do not spontaneously change into other elements. For example, an expensive gold ring you buy from a jewellery shop does not change into an almost worthless lead or iron ring overnight! (Figure 3A–1).

Figure 3A–1 Imagine a gold ring changing into an iron or lead ring overnight!

However, sometimes elements can transform into other elements. For example, a rare form of manufactured gold (gold-194) transforms into platinum (platinum-194). After 38 hours have elapsed, a ring made of gold-194 would be half gold-194 and half platinum-194!

Understanding nuclear stability gives important insights into how stable and unstable nuclei behave in the real world.

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EXPLAIN

Protons and neutrons

To understand radiation physics we need to understand a little more about the structure of matter. A useful model of the atom is the simple 'billiard ball' type shown in Figure 3A–2. The central nucleus consists of protons and neutrons (collectively called **nucleons**), while the electrons orbit the **nucleus**.

Nucleon
a proton or a neutron in a nucleus

Nucleus
the solid centre of an atom where most of the mass of an atom is concentrated

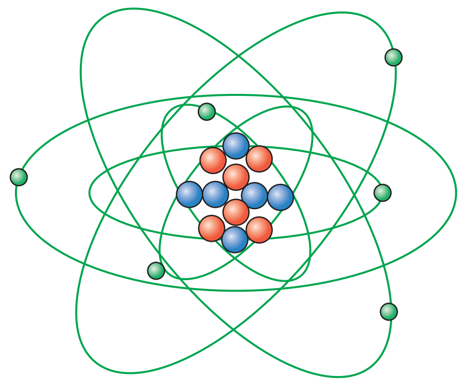

Figure 3A–2 A useful model of the atom showing a nucleus with protons (red), neutrons (blue), and orbiting electrons (green)

The simplest atom, hydrogen, normally consists of only one **proton** and one orbiting electron (Figure 3A–3 left). The next simplest **element**, helium, normally consists of two protons, two **neutrons** and two orbiting electrons (Figure 3A–3 right).

Proton
a positively charged particle in the nucleus of an atom

Element
a pure substance consisting only of atoms that all have the same numbers of protons in their nuclei

Neutron
an uncharged particle in the nucleus of an atom

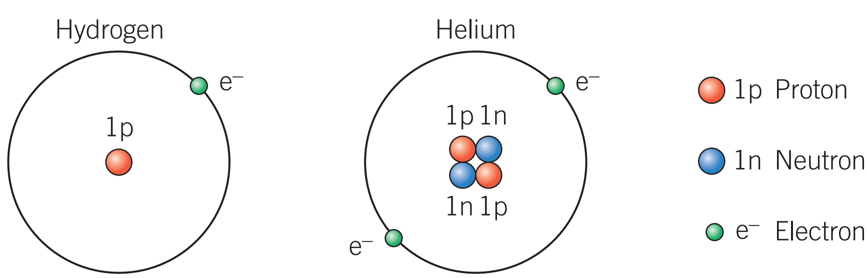

Figure 3A–3 A two-dimensional diagram representing a hydrogen and helium atom. These two elements make up 99.9% of the known Universe (in a ratio of 10:1 H:He). Note that this two-dimensional style of diagram, rather than the model in Figure 3A–2, should be used to show the number of protons, neutrons and electrons in an atom or nucleus.

The number of protons in the nucleus determines the chemical properties of the atom and so uniquely defines each element. For example, all atoms with one central proton are hydrogen atoms, all atoms with two protons are helium atoms and all atoms with six protons are carbon atoms. This continues up to element 92, the heaviest naturally occurring element, where all atoms with 92 protons are uranium atoms.

A number of elements with more protons in the nucleus have been artificially produced in recent years. They are all unstable and are usually only made in special circumstances – in high-energy particle accelerators in physics laboratories, in nuclear power stations and in nuclear explosions. A full list of the known elements is presented in Figure 3A–4: the **periodic table**. Note the number above the element is the **atomic number**, which represents the number of protons in the nucleus – this is what determines which element an atom or nucleus belongs to.

Periodic table
a table of the elements arranged in order of atomic number

Atomic number
the number of protons in the nucleus; given by the symbol Z

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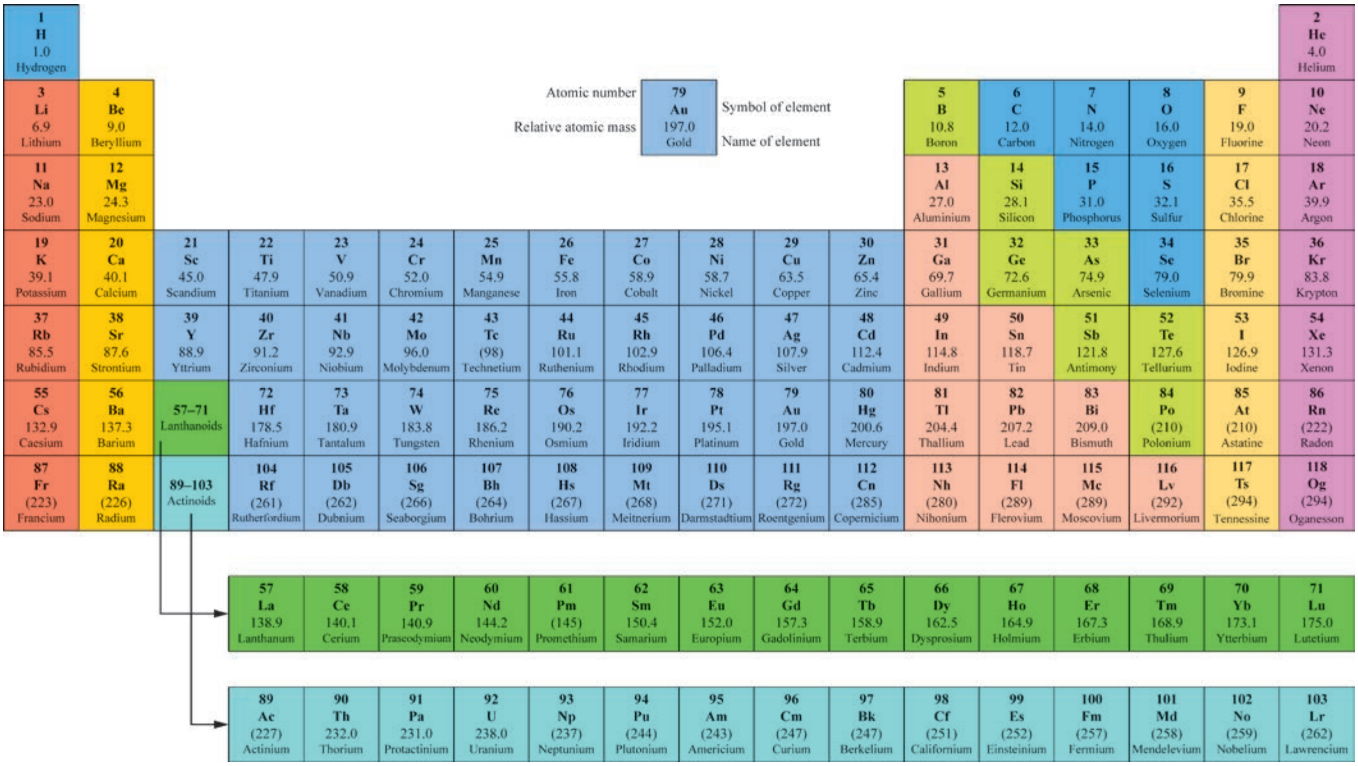

Figure 3A–4 On the periodic table, the number of protons in an element increases across a row, while the columns relate to the number of electrons in the outermost orbital shell, which determine chemical reactions. The table is a useful tool for understanding the nature of our atomic universe. To see the table in more detail, see page 551 of Appendix 2 or go to the Interactive Textbook and zoom in on the table.

The periodic table and isotopes

The periodic table (Figure 3A–4) shows a large number of important features concerning the nature of various elements.

- The number of protons in an atom is called the atomic number, and is represented by the symbol Z. $Z = 1$ for hydrogen, $Z = 2$ for helium, $Z = 3$ for lithium, $Z = 6$ for carbon, $Z = 92$ for uranium, $Z = 93$ for neptunium, $Z = 94$ for plutonium, etc. The atomic number of an element appears in the periodic table together with the symbol for that element (H for hydrogen, He for helium and so on).
- The mass of an atom is determined by the number of protons and neutrons in its nucleus. The very small mass of the electrons is ignored for this calculation. The sum of the number of protons and neutrons in the nucleus (collectively called the number of nucleons) is called the **mass number** and is represented by the symbol A. $A = 1$ (one proton) for the hydrogen atom shown in Figure 3A–3 (left), $A = 4$ (two protons plus two neutrons) for the helium atom shown in Figure 3A–3 (right).

Mass number the sum of the number of protons and neutrons in the nucleus; given the symbol *A*

Isotope a form of the same element with the same numbers of protons but different numbers of neutrons in their nuclei

In general, for any particular element X, the atomic number (Z) and the mass number (A) are written in the following internationally accepted format $^{A}_{Z}X$.

Using this format, we can write hydrogen as $^{1}_{1}H$, helium as $^{4}_{2}He$ and uranium as $^{238}_{92}U$.

Although all the atoms of a particular element contain the same number of protons in the nucleus, they may have different numbers of neutrons. These different forms of an element are known as **isotopes**.

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NOTE

In a neutrally charged atom, the number of electrons equals the number of protons. In an electrically charged ion, the number of electrons is lower or higher than the number of protons. The electrons in the outermost shell of an atom or ion determine its chemical properties, so the different isotopes of an element have the same chemical properties but different physical ones. Being concerned with the nucleus and nuclear reactions, this chapter does not discuss electrons except in passing.

Hydrogen has three naturally occurring isotopes: ${}^{1}_{1}H$, ${}^{2}_{1}H$, ${}^{3}_{1}H$ (Figure 3A–5). With hydrogen the isotopes have been given different names so that ${}^{1}_{1}H$ is called hydrogen-1 (protium), ${}^{2}_{1}H$ is deuterium and can also be written as ${}^{2}_{1}D$, while ${}^{3}_{1}H$ is tritium and can also be written ${}^{3}_{1}T$. Tritium is a rare and unstable **radioactive isotope** of hydrogen.

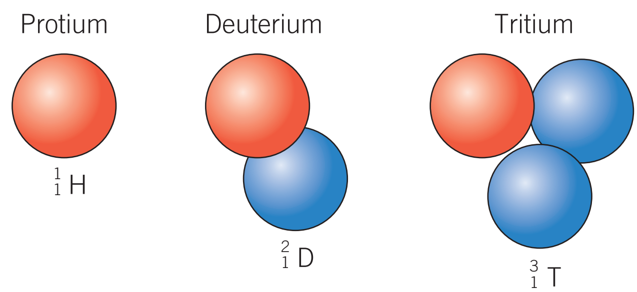

Figure 3A–5 The three naturally occurring isotopes of hydrogen: protium, deuterium and tritium (${}^{1}_{1}H$, ${}^{2}_{1}H$, ${}^{3}_{1}H$)

Radioactive isotope
any isotope of an element whose nuclei are unstable and dissipate energy by spontaneously emitting radiation

Helium has two naturally occurring isotopes and these are referred to as helium-3 and helium-4 (Figure 3A–6). This is a more common method of labelling isotopes. Two important isotopes of uranium that are used both in nuclear power stations and nuclear bombs, uranium-235 and uranium-238, are also labelled this way.

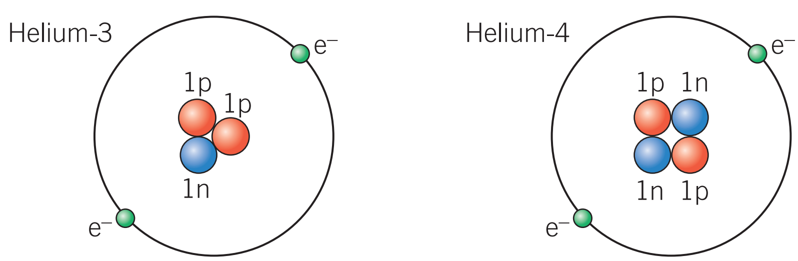

Figure 3A–6 The two naturally occurring isotopes of helium: helium-3 and helium-4 (${}^{3}_{2}He$, ${}^{4}_{2}He$). Natural helium consists almost entirely of ${}^{4}He$ and only contains just over 0.0001% of ${}^{3}He$.

Check-in questions – Set 1

1 How many protons are there in the nucleus of the atom shown in Figure 3A–2? What element does this correspond to?

2 Copy and complete the following using the periodic table (Figure 3A–4 or see page 551 of Appendix 2).

Number of protons in the nucleus	Name of the element
3	
	Iron
29	
	Gold
86	

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Proton to neutron ratio and nuclear stability

The stability of any nucleus depends on the number of protons and neutrons in the nucleus. For small nuclei to be stable, the number of protons must roughly equal the number of neutrons. However, as the number of protons increases, more neutrons are needed to maintain stability.

Belt of stability nuclei that have a neutron/proton ratio between 1:1 and 1.5:1

The graph shown in Figure 3A–7 is a plot of the number of neutrons versus the number of protons in various stable isotopes up to the element mercury – $^{200}_{80}Hg$.

The stable nuclei are in the blue band, which is known as the **belt of stability** (also known as the valley of stability).

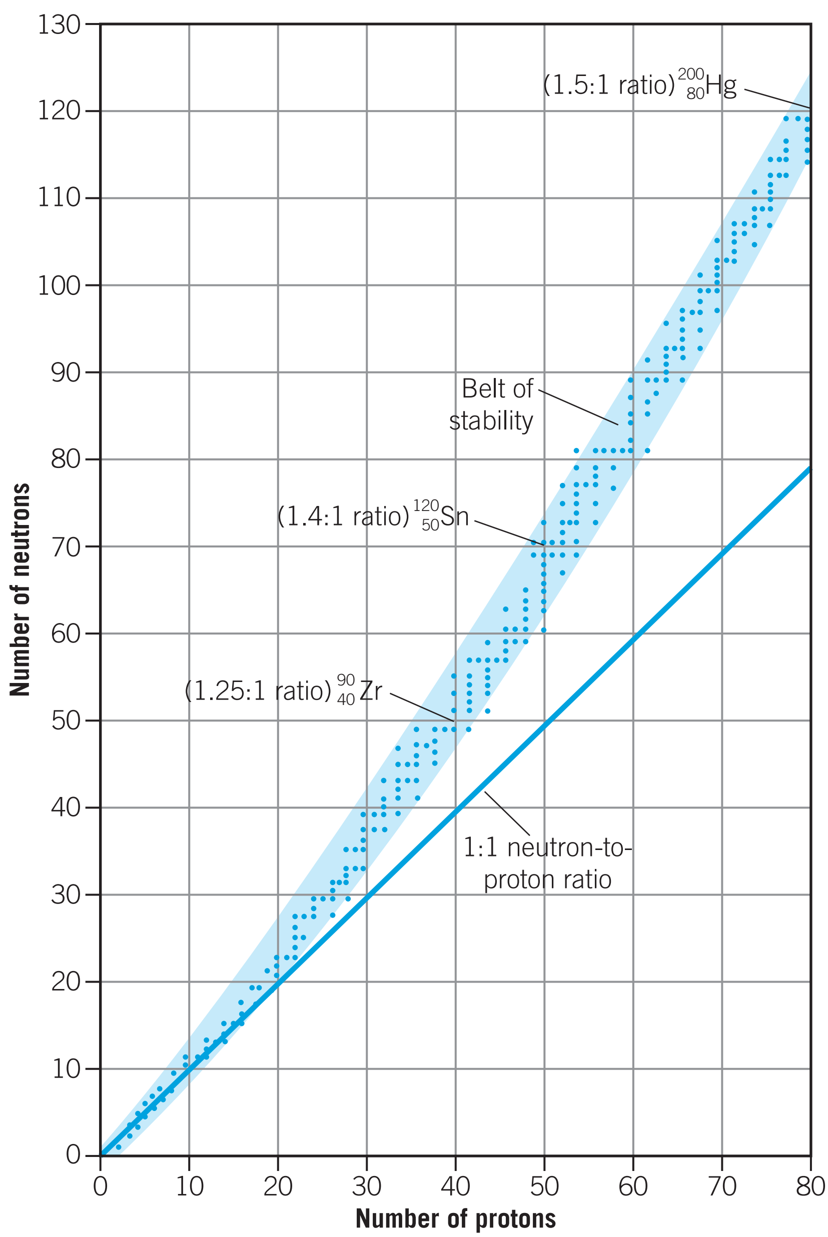

Figure 3A–7 The belt of stability showing all of the stable isotopes of elements up to mercury – $^{200}_{80}Hg$. The ratios are for numbers of neutrons to protons.

The reason that more neutrons are needed in the nucleus to maintain nuclear stability as the number of protons increases is the competing electrostatic forces and the strong nuclear forces inside the nucleus. This is explained in more detail below.

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Radioactive isotopes

Isotopes of elements outside of the belt of stability are all **radioactive** and all undergo **nuclear decay**.

Although there are 254 stable isotopes, more than 3000 radioactive isotopes are known, of which only about 84 are seen in nature. The rest are produced artificially as the direct products of nuclear reactions or the indirect radioactive descendants of these products.

Radioactive isotopes have many useful applications. For example, cobalt-60 has 27 protons and 33 neutrons and a proton to neutron ratio of 1:22. It decays by emitting an electron (beta particle) from the nucleus and high-energy electromagnetic radiation (gamma rays). It is an extremely useful radioactive isotope that is used in radiation treatment of cancerous tumours (discussed in Section 3E). It does not exist in nature but can be produced as an artificial radioactive isotope in nuclear reactors.

Figure 3A–8 International symbol for radioactive sources

Radioactive any substance that spontaneously emits ionising radiation

Nuclear decay when the nucleus of an atom is unstable and spontaneously emits energy in the form of nuclear radiation

LINK 3E THE EFFECT OF RADIATION ON HUMANS

Check-in questions – Set 2

1 What is an isotope of an element?
2 What is a radioactive isotope of an element?

Four fundamental forces

There are only four fundamental forces at work in the Universe: the gravitational force, the weak nuclear force, the electromagnetic force and the strong nuclear force.

Both gravitational and electromagnetic forces were discovered long before the discovery of the strong and weak nuclear forces. The gravitational force was accurately described by Isaac Newton in 1687 and acts between all objects having mass.

The electric force (also called the electrostatic force) acting between charged bodies was published by Coulomb in 1785, while Oersted in 1820 discovered that an electric current creates an associated magnetic field. With the publication of *A Dynamical Theory of the Electromagnetic Field* in 1865, James Clerk Maxwell (Figure 3A–9 left) gave physicists a tremendously powerful theory of electromagnetism that is often seen succinctly summarised on physics student's and teacher's T-shirts (Figure 3A–9 right).

Then Maxwell said

$$\oint \vec{E} \cdot d\vec{A} = \frac{Q}{\varepsilon_0}$$
$$\oint \vec{B} \cdot d\vec{A} = 0$$
$$\oint \vec{B} \cdot d\vec{l} = \mu_0 i_C + \mu_0 \varepsilon_0 \frac{d\Phi_E}{dt}$$
$$\oint \vec{E} \cdot d\vec{l} = -\frac{d\Phi_B}{dt}$$

And then there was light

Figure 3A–9 Left: James Clerk Maxwell (1831–1879) was one of the greatest scientists who have ever lived. To him we owe the most significant discovery of our age – the theory of electromagnetism. He is rightly acclaimed as the father of modern physics. Right: Maxwell's equations (not needed for this course) as part of a saying popular with physicists

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The strong and weak forces were discovered by physicists in the 20th century when they started to probe into the nucleus of the atom.

The strong force was initially proposed by Hideki Yukawa in 1935. He reasoned that the residual effects of the strong force would bind the protons and neutrons of the atomic nucleus together in spite of the intense repulsion of the positively charged protons for each other.

Neutrino a neutral subatomic particle with a mass close to zero that rarely reacts with normal matter

The weak force (or weak interaction) was initially proposed by Enrico Fermi in 1933 to try and explain radioactive beta decay. In the process Fermi 'discovered' a new particle, the **neutrino** initially proposed by Wolfgang Pauli in 1930.

The four fundamental forces work over vastly different ranges (from one-thousandth of the diameter of a proton to infinity) and have vastly different strengths, as shown in Table 3A–1.

Table 3A–1 The relative sizes of the gravitational, weak, electromagnetic and strong forces and their ranges based on relative strength to the strong nuclear force (being 1)

Force	Relative strength	Range
Strong nuclear	1	10^{-15} m (diameter of a nucleus)
Electromagnetic	10^{-2}	Infinite
Weak nuclear	10^{-6}	10^{-18} m (1/1000th of proton diameter)
Gravitational	10^{-38}	Infinite

To understand the physics of the nucleus and radioactivity physicists, ignore the gravitational attraction between nucleons (as this force is so extremely small) and concentrate instead on the roles the other three fundamental forces play.

Neutrinos galore

When the nucleus of a radioactive atom disintegrates, physicists observed that the nucleus was losing more energy than the detectors were picking up. To account for that extra energy, the physicist Wolfgang Pauli conceived an extra, invisible particle emitted by the nucleus (which Fermi later named the neutrino, though at the time it was still theoretical). 'I have done something very bad today by proposing a particle that cannot be detected,' Pauli wrote in his journal. "It is something no theorist should ever do."

The Universe turns out to be awash with neutrinos. They're among the lightest of the known subatomic particles and they come from all directions: the Big Bang that began the Universe, exploding stars and, most of all for us on Earth, the Sun. They come straight through Earth at nearly the speed of light, all the time, day and night, in enormous numbers. About 100 trillion neutrinos pass through our bodies every second.

The problem for physicists is that neutrinos are impossible to see and difficult to detect. Hoping to detect neutrinos in larger numbers, scientists in Japan led an experiment 1100 metres underground in a zinc mine. Super-Kamiokande, or Super-K as it is known, began operating in 1996. The detector consists of 50 000 tonnes of water in a domed tank whose walls are covered with 13 000 light sensors (Figure 3A–10).

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The physicists working at Super-K discovered that neutrinos can change into different types. This contradicts the long-held notion that they have no mass. For neutrinos to oscillate they must have different, and thus non-zero, masses. The discovery contradicted the reigning theory of particle physics, the Standard Model, which has no explanation at present for how neutrinos could have obtained their mass.

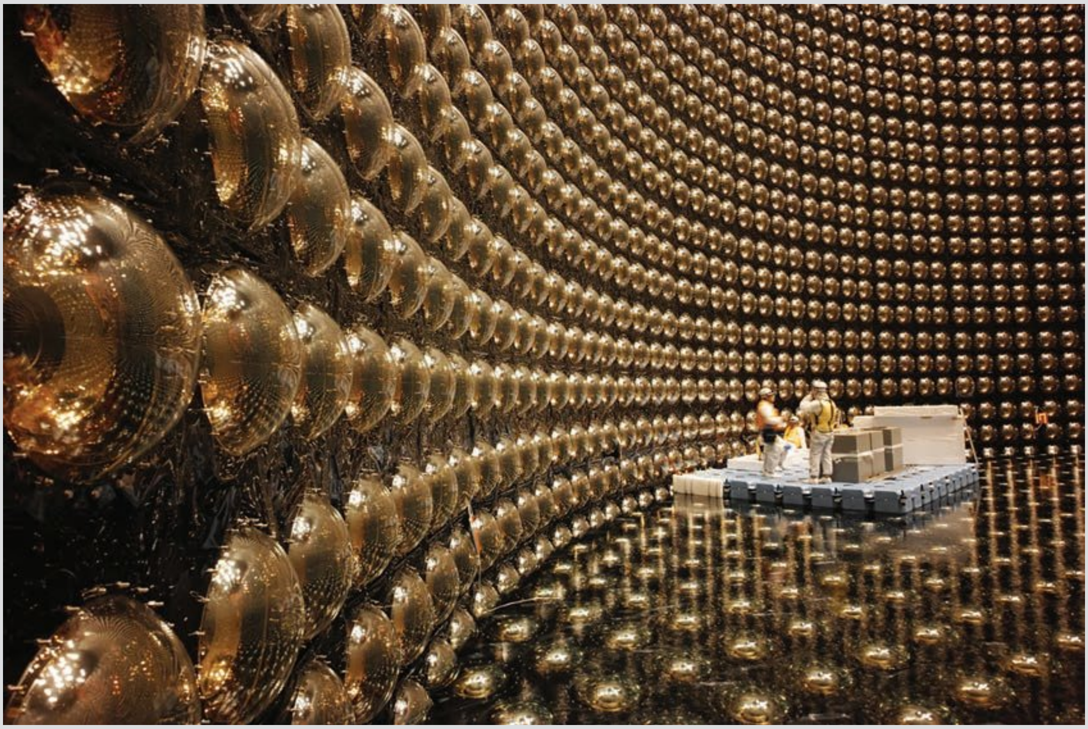


Figure 3A–10 The cavernous Super-Kamiokande detector in Japan is lined with 13 000 sensors to pinpoint signs of neutrinos.

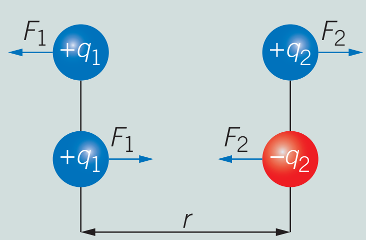
Electrostatic forces in the nucleus

Electrostatic attraction exists between unlike charges, and electrostatic repulsion exists between like charges. The closer together the charges are, the stronger the **electrostatic force**.

Electrostatic force
a force that exists between charged particles, e.g. two positively charged protons

NOTE

Electrostatic forces exist between charged objects. Like charges repel each other (e.g. positive–positive or negative–negative) and unlike charges attract each other (e.g. positive–negative). The French physicist Charles-Augustin de Coulomb in 1785 published that the magnitude of the electrostatic force depends directly on the amount of charge present on each charge and inversely as the square of the distance between the charges. This relationship is known as Coulomb's law, expressed by the formula below, which is not needed in Unit 1 of this course.



$$|F_1| = |F_2| = k_e \frac{|q_1 q_2|}{r^2}$$

Formula

$$F = k\frac{q_1 q_2}{r^2}$$

F = Electric force
k = Coulomb constant
q_1, q_2 = Charges
r = Distance of separation

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Positive charges inside a nucleus are extremely close together. For example, a helium nucleus that contains two protons and two neutrons is ~10^{-15} m in size (Figure 3A–11). Therefore, it is a surprise that the very large electrostatic force of repulsion doesn't split the nucleus apart.

The fact that two protons in such close proximity have such extremely strong electrostatic repulsion forces acting on them made physicists realise that the force of electrostatic repulsion must be overcome by an even stronger force. The force that stops the nucleus from splitting apart due to electrostatic repulsion is known as the strong nuclear force.

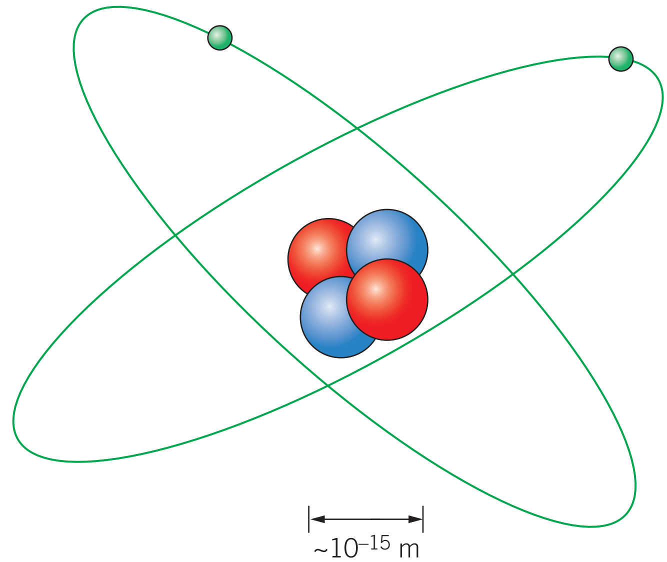

Figure 3A–11 The electrostatic force of repulsion between the two protons in the helium nucleus should blow it apart – but this does not happen.

Strong nuclear force

Strong nuclear force the force that holds the nucleons together in a nucleus of an atom. It acts only over very short distances (10^{-15} m).

While the **strong nuclear force** is, as its name suggests, a very strong force, it is only able to act over incredibly small distances (Figure 3A–12). The strong nuclear force acts on all of the nucleons (protons and neutrons). Inside a stable nucleus, the nucleons are sufficiently close that the pull of the strong nuclear force is much greater than the push of the protons electrostatically repelling each other, and therefore the nucleus remains intact.

Nuclear force and electrostatic force

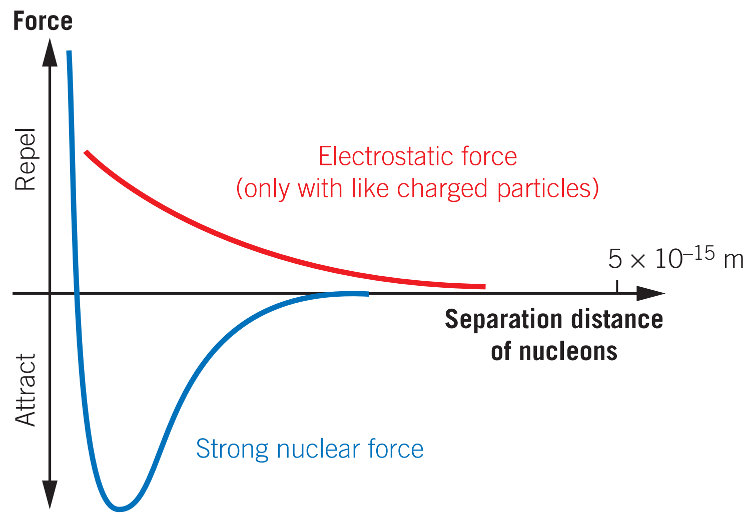

Figure 3A–12 The strength and direction of the strong nuclear force and the electrostatic force plotted against the separation distance of the protons and neutrons.

The electrostatic force has more influence as atoms get bigger because protons on opposite sides will now be further apart and begin to repel each other although they are still bound to their immediate neighbours (protons and neutrons) by the strong force (S) (Figure 3A–13).

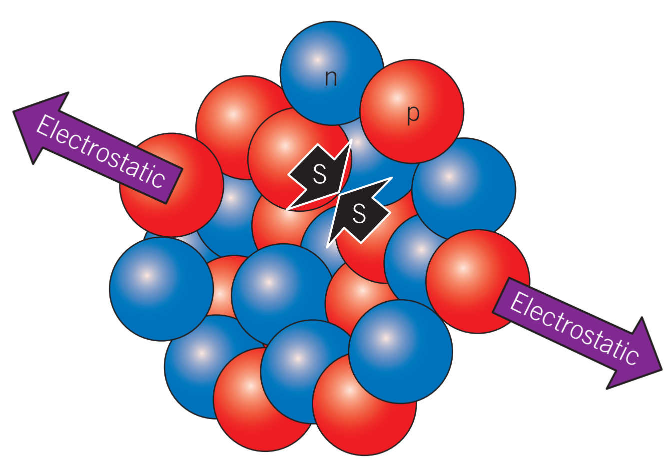

Figure 3A–13 As nuclei get larger, protons on opposite sides will now be further apart and begin to repel each other.

For natural elements with more than 82 protons (the element lead, Pb, has 82 protons), the nuclei are no longer stable and these elements are radioactive.

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The so-called **transuranic** elements, those with more than 92 protons, are so unstable they don't exist naturally. As with many such statements in science, improved measuring techniques find exceptions to rules, and trace amounts (1 part in 10^{11}) of the transuranic element plutonium have been found to occur naturally in uranium ore.

Transuranic
an element with more than 92 protons

Note that the strong nuclear forces that hold the nucleus together are much stronger than the electrostatic forces that hold the 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. Chemical changes in a 2-kg lump of coal, about the size of a baseball, (Figure 3A–14 left) can produce about the same energy as 480 g of TNT (the explosive used in dynamite), which would make a ball about two-thirds that size. However, nuclear changes in a baseball-sized lump of uranium-235 (with a mass of about 28 kg) can release a similar amount of energy to the chemical changes of 20 000 tonnes of TNT exploding (Figure 3A–14 right).

Figure 3A–14 Left: Chemical changes occur in a lump of burning coal, releasing small amounts of energy. Right: Nuclear energy is millions of times more powerful than chemical energy for the same mass of fuel.

Weak nuclear force

The **weak nuclear force** is the fundamental force used to explain radioactive beta decay. Specifically, it explains the transformation of neutrons into protons and vice versa.

Inside a nucleus a neutron can spontaneously decay into a proton, emitting a beta minus (β^-) particle (or an electron) from the nucleus. This is normal beta radiation. Also, inside a nucleus a proton can spontaneously decay into a neutron, emitting a beta plus (β^+) particle (or a **positron**) from the nucleus. These processes are explained in more detail in Section 3B.

Weak nuclear force
the force responsible for radioactive beta decay

Positron
a positively charged subatomic particle having the same mass and magnitude of charge as the electron

LINK 3B ALPHA, BETA AND GAMMA RADIATION

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3B ALPHA, BETA AND GAMMA RADIATION LINK

Check-in questions – Set 3

1 a Which one of the four fundamental forces is the least important in understanding the forces acting in the nucleus?
  b Explain your answer.
2 Explain how nucleons are held together in the nucleus.

Binding energy the amount of energy required to split a nucleus into its individual nucleons

Binding energy curve a graph of the average binding energy per nucleon versus mass number

Binding energy

The amount of energy needed to overcome the strong nuclear force and pull a nucleus apart is known as the **binding energy**. This is the amount of energy required to split a nucleus into its individual nucleons; that is, to reverse the original binding process. For example, it would take 2.23 MeV of energy to split the $^{2}_{1}H$ nucleus (the deuterium isotope of hydrogen) into a separate proton and neutron.

Conversely, when a neutron and proton combine to form a hydrogen-2 nucleus, 2.23 MeV of energy is liberated. The total mass of the bound particles is less than the sum of the masses of the separate particles by an amount equivalent to the binding energy (using Einstein's $E = mc^2$ equation).

CHAPTER 4 LINK

Chapter 4 explains, using a **binding energy curve**, why both fusion and fission are reactions that release energy (except as noted below in the case of the fusion of iron nuclei and those of higher mass number). The concept is introduced here in this chapter to explain how much energy is required to overcome the strong force inside a nucleus and pull the nucleus apart.

Each isotope of each element has its own specific binding energy. Nuclei with high binding energies are very stable because it takes a lot of energy to split them. Nuclei with lower binding energies are easier to split.

To compare the binding energies of various nuclei, and therefore their stability, it is useful to look at the average binding energy per nucleon. The average binding energy per nucleon is the total binding energy of a nucleus divided by the number of nucleons in the nucleus.

Worked example 3A–1 Binding energy in oxygen

Oxygen-16 (O-16) has a total binding energy of 127 MeV.

Calculate the average binding energy per nucleon of O-16.

Solution

Oxygen has 16 nucleons. The total binding energy for oxygen is 127 MeV.

Therefore, the binding energy per nucleon of O-16 is $\frac{127}{16} = 7.94$ MeV.

It can be seen from the binding energy curve for stable or long-lived nuclei (Figure 3A–16) that iron (Fe-56) has the highest binding energy per nucleon (8.8 MeV). This means it is the most stable of all nuclei.

The build-up of heavier elements in the nuclear fusion processes in stars is limited to elements below iron on the periodic table, since the fusion of iron would subtract energy rather than provide it. This means that elements heavier than iron are produced in cosmic events that release far more energy than fusion in a star, such as a supernova explosion (Figure 3A–15).

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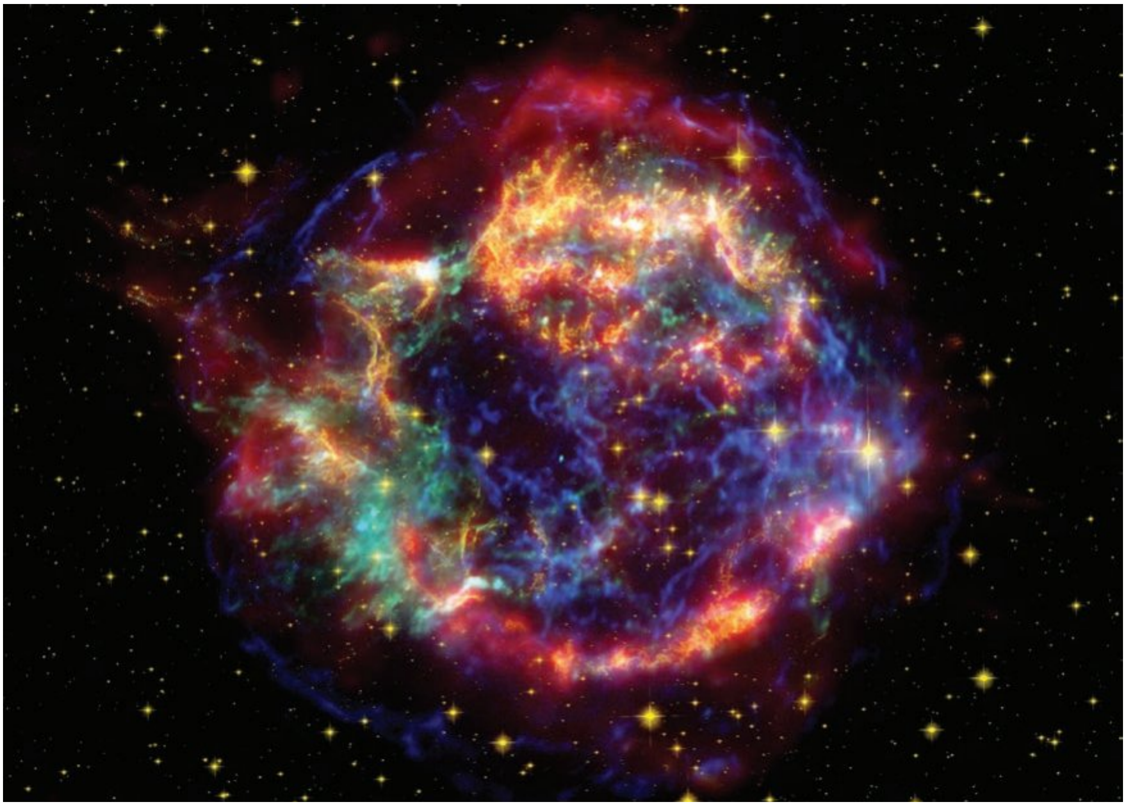

Figure 3A–15 The binding energy curve means that all elements heavier than iron are produced in a supernova like the Crab Nebula supernova remnant shown here.

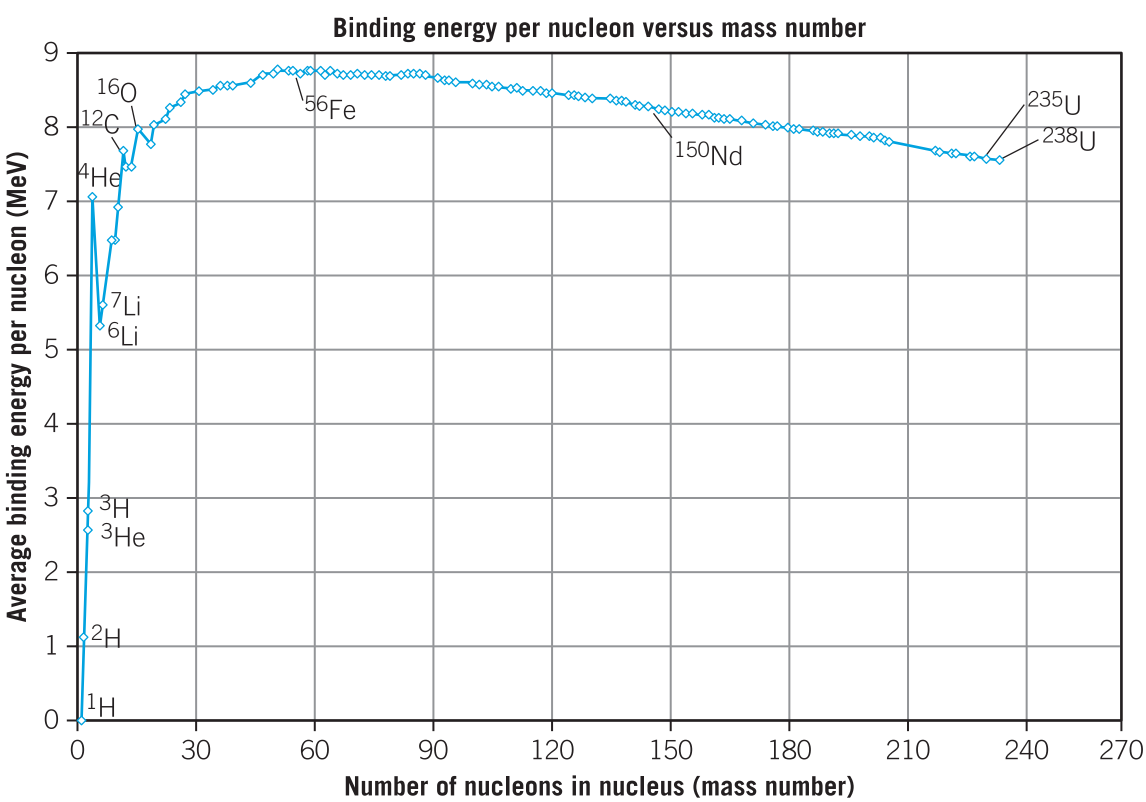

Figure 3A–16 The binding energy per nucleon versus mass number is a measure of stability as atoms get bigger, since the higher the binding energy, the more energy it takes to split the atom apart. The graph shows that the element iron (^{56}Fe) has the most stable nucleus.

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WORKSHEET 3A–1 NUCLEAR STABILITY: FORCES IN THE NUCLEUS

Check-in questions – Set 4

1 What is binding energy in relation to the nucleus?
2 Explain what the average binding energy per nucleon is.
3 The element iron-56 has the highest binding energy per nucleon. What is the implication of this for the stability of iron-56?

VIDEO 3A–1 SKILLS: CONVERTING UNITS OF ENERGY

3A SKILLS

Converting units of energy
In nuclear physics you sometimes use different units of energy from what you would use in, for example, mechanics. It is an important skill to know how to convert from one unit to another.

The main unit of energy used in this textbook is the joule (J). The joule is a very convenient unit when dealing with the amounts of energy involved in things and processes we can see. For the very small amounts of energy of individual atoms and subatomic particles it is more convenient to use units known as electronvolts.

An electronvolt is the energy that an electron would gain if it was accelerated by a voltage of 1 volt. The conversion factor is $1.0 \text{ eV} = 1.6 \times 10^{-19}$ J, so the electronvolt is unimaginably small.

Energies involved with emissions of nuclear radiation are usually in the range 0.1 – 10 MeV. The 'M' is the SI unit prefix 'mega-', meaning 10^6, i.e. a million.

$1.0 \text{ MeV} = 1.0 \times 10^6$ eV (one million electronvolts)

Building a glossary
In studying physics, you are required to remember, apply and explain many terms.

Before you start applying new terms, you need to understand them. A strategy to achieve this is to create a glossary of your own. A glossary will sharpen your skills in defining and understanding the meaning of terms.

This area of study 'Radiation from the nucleus' introduces to you many terms that you probably either haven't met before (e.g. activity (becquerel), radiation weighting factors, strong nuclear force) or have never had a precise definition for (e.g. nucleons, half-life, radioactive decay chain).

To *define* is to state the precise meaning of the terms. For example, if you were asked to define 'activity (becquerel)', then the following definition in your notes may help.

Definition: The 'strength' of any given radioactive source is determined by its activity.

The activity is defined as the number of nuclei that decay each second; that is, the number of disintegrations per second. The unit of activity is the becquerel (Bq), where 1 becquerel is defined as 1 disintegration per second (1 Bq = 1 disintegration s^{-1}).

To start creating your own glossary, you can use the highlighted glossary terms in this textbook. However the best way to learn and remember the terms is to rewrite the definitions in your own words and then write out an example of the use of the term. The Interactive Textbook includes a 'scorcher' quiz based on the terms and definitions, and it is a good idea to self-assess your understanding and to return to this quiz from time to time.

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Section 3A questions

Multiple-choice questions

1 Uranium-235 has 92 protons in the nucleus. The number of neutrons in the nucleus is
- A 92
- B 143
- C 235
- D 327

2 Isotopes of an element have the same number of
- A nucleons.
- B neutrons.
- C neutrons but a different number of protons.
- D protons but a different number of neutrons.

3 Elements outside of the belt of stability are all
- A α-emitters.
- B β-emitters.
- C γ-emitters.
- D radioactive.

4 Inside a nucleus, the electrostatic force acts on the
- A electrons.
- B protons.
- C neutrons.
- D nucleons.

5 Inside a nucleus, the strong force acts on the
- A electrons.
- B protons.
- C neutrons.
- D nucleons.

Short-answer questions

6 Use the internationally accepted format $^{A}_{Z}X$ to write down the elements containing the following nucleons:
- a 2 neutrons and 1 proton
- b 12 protons and 25 nucleons
- c 94 protons and 143 neutrons

7 Explain why it is possible to have two different elements with the same number of nucleons.

8 What is the neutron/proton ratio range for an element to be in the belt of stability?

9 What are two important characteristics of isotopes of elements that lie outside the belt of stability?

10 Explain why the electrostatic force has more influence as nuclei get bigger and contain more protons and neutrons.

11 a Which force is used to explain radioactive beta decay?
- b Explain what happens when a neutron inside the nucleus turns into a proton.
- c Explain what happens when a proton inside the nucleus turns into a neutron.

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3B Alpha, beta and gamma radiation

Study Design:
- Describe the properties of α, β^-, β^+ and γ radiation
- Explain nuclear transformations using decay equations involving α, β^-, β^+ and γ radiation

Glossary:
Alpha (α) particle
Beta (β) particle
Gamma (γ) ray
Ionise
Nuclear transformation
Photon
Transmutation

ENGAGE

Lead into gold

3D ANALYSING DECAY SERIES DIAGRAMS LINK

A common aim of alchemy was to turn 'base metals' (common and cheap lead and iron, for instance) into 'noble metals' (rare and valuable metals such as gold and silver). Alchemists failed to turn lead into gold but they did discover much of chemistry along the way. An element cannot be converted into another by chemical means but the spontaneous emission of alpha (α) radiation and beta (β) radiation automatically generates other elements. (See also radioactive decay chains in Section 3D.)

Figure 3B–1 *Heating the Pot* by David Teniers the Younger (1610–1690), one of a number of paintings he made depicting alchemy

Particle accelerators can be used to create gold but at a much higher cost than digging it up from the ground. Gold was created by neutron bombardment of the element mercury in 1941, but all of the isotopes of gold produced were radioactive.

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EXPLAIN

Different types of radiation

Following the 1896 discovery of radioactivity by Henri Becquerel, Ernest Rutherford (Figure 3B–2 left) in 1899 studied the absorption of radioactivity by thin sheets of metal foil and found two components: alpha (represented by the symbol α) radiation, which is absorbed by a few thousandths of a centimetre of metal foil or a sheet of paper, and beta (represented by the symbol β) radiation, which can pass through 100 times as much foil before it was absorbed. Shortly afterwards, a third form of radiation, named gamma (represented by the symbol γ) rays, were discovered that can penetrate as much as several centimetres of lead (Figure 3B–2 right).

VIDEO 3B–1
RADIATION FROM THE NUCLEUS

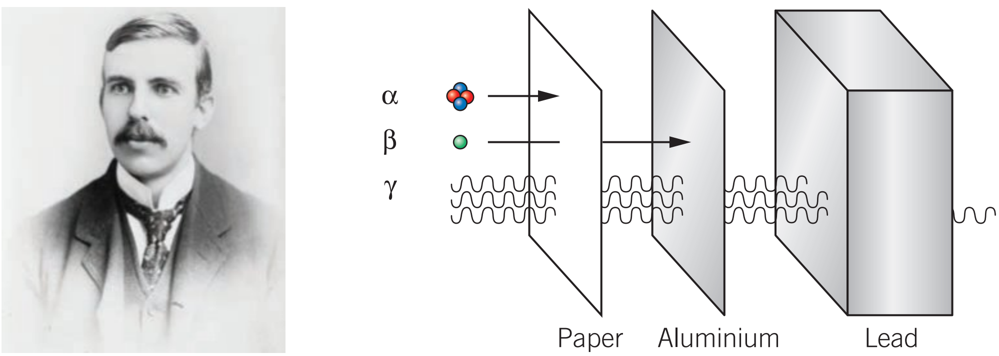

Figure 3B–2 Only three years after the discovery of radioactivity, the physicist Ernest Rutherford (left) found that three different kinds of radiation are emitted in the decay of radioactive substances; these he called alpha, beta and gamma rays in sequence based on how far they could penetrate matter (right).

Unstable isotopes emit various types of radiation as they transform to stable isotopes. There are three naturally occurring forms of nuclear radiation: α-, β- and γ-radiation (Figure 3B–3).

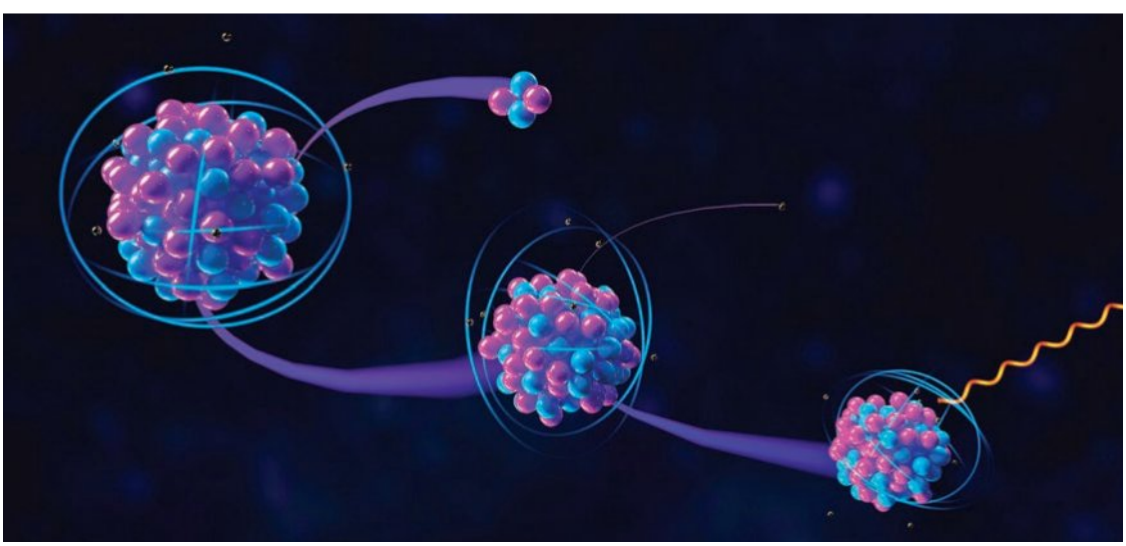

Figure 3B–3 A radioactive nucleus spontaneously emitting (from left to right) an alpha (α) particle, a beta (β) particle and a gamma (γ) ray

When these different types of radiation were first discovered, Ernest Rutherford did not know exactly what they were. So each type of radiation was given a different Greek letter (in this case the first three letters of the Greek alphabet) from least penetrating (α) to most penetrating (γ) radiation.

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Photon
a quantum of light or other electromagnetic radiation

Ionise
the removal or addition of electrons from a neutral atom

Later it was discovered that alpha particles were actually helium nuclei, beta particles came in both negative and positive forms and were actually electrons (–) and positrons (+) emitted from the nucleus, and gamma rays were very high-energy **photons**.

These three nuclear radiations are energetic enough to **ionise** atoms. Figure 3B–4 shows a gamma ray ionising a helium atom to create a He^+ ion.

NOTE

- Atoms with an overall positive or negative charge are referred to as ions.
- Positive ions form when electrons are removed from a neutral atom.
- Negative ions form when electrons are gained by a neutral atom.
- α-, β- and γ-radiation all have the ability to ionise atoms that they come into contact with.

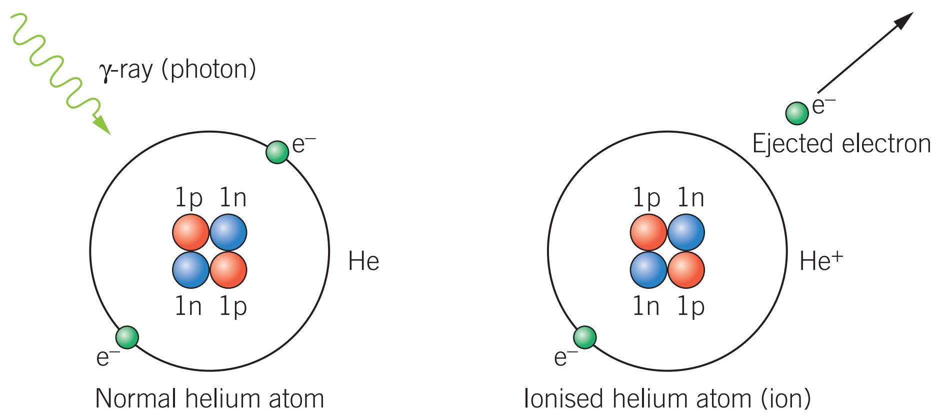

Figure 3B–4 A γ-ray ionising a helium atom, by ejecting an electron, to create a He^+ ion

These three nuclear radiations differ in many important properties; for example, their charge, mass, energy, capacity to penetrate substances, capacity to ionise materials and their behaviour in electric and magnetic fields.

Check-in questions – Set 1

1 a What were the names given by Ernest Rutherford for the three different radiations he discovered?
  b Give the order of the three different radiations from least penetrating to most penetrating.
2 How can nuclear radiation ionise a neutral atom to create a positive ion?

Alpha particle radiation (α)

Alpha (α) particle
a radioactive decay product comprising two protons and two neutrons; the same as a He nucleus

Alpha particle radiation consists of two neutrons and two protons (that is the same as a helium nucleus) ejected as a package from the nucleus of a radioactive atom. The package carries two positive charges. Their charged nature means that they are affected by both electric and magnetic fields. The speed of the **alpha (α) particles** depends very much on the nature of the radioactive source, but typically their maximum speed (~30 000 km s^{-1}) is about 10% of the speed of light (Figure 3B–5).

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The capacity of α-particle radiation to penetrate materials is not very great: it usually penetrates no more than a few centimetres in air and is absorbed even by a relatively small thickness of paper or human skin. However, because they are travelling so fast, and are relatively massive (compared, say, with β-particles), α-particles can ionise a large number of atoms over their very short range of penetration as they dissipate their kinetic energy. This makes α-particle radiation relatively harmless for most external sources that are about a metre or more away from us, as the radiation will be easily absorbed by the intervening air. But if radiation sources are close to or within sensitive organs α-particle radiation is extremely dangerous.

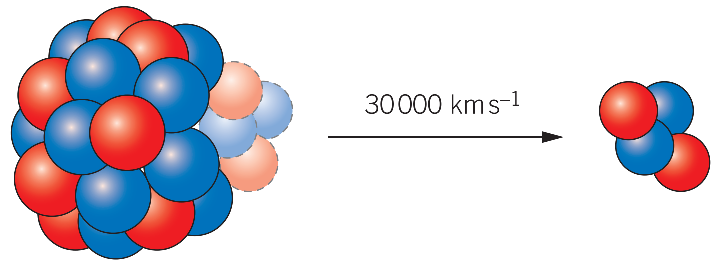

Figure 3B–5 A radioactive nucleus is shown ejecting two protons and two neutrons bound together as a helium nucleus, reducing its mass and becoming a different element. The ejected helium nucleus is called an α-particle, which carries a positive charge. α-particles cannot penetrate a piece of paper or skin but are very dangerous when substances emitting them are ingested or inhaled.

Alpha particle radiation results in **transmutation** of elements. The decaying radioactive nucleus is called the parent nucleus and the produced radionuclide is called the daughter nucleus. For example, when uranium-238 decays by emitting an α-particle, the original (parent) nucleus is left with four less nucleons (2 protons and 2 neutrons). The daughter nucleus now has 90 protons, which is the element thorium-234.

Transmutation a change in the structure of atomic nuclei that converts one element into another element

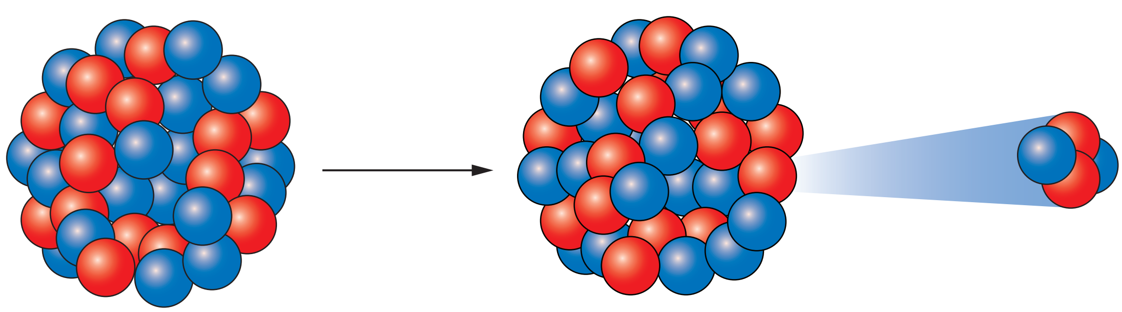

Figure 3B–6 The transmutation of uranium-238 (parent nucleus) to thorium-234 (daughter nucleus) as a result of the emission of an alpha particle

This can be written as follows:

$$^{238}_{92}\text{U} \rightarrow {}^{234}_{90}\text{Th} + {}^{4}_{2}\text{He} + \text{energy}$$

Alpha particles are emitted with specific energies that are unique to the properties of the parent nucleus. In the case of the uranium-238 nucleus, the α-particle emitted has an energy of 4.3 MeV.

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Worked example 3B–1 Energy of an α-particle

An α-particle emitted from a radioactive element has an energy of 2.99×10^{-12} J.

How much energy does this represent in electronvolts (eV)?

Solution

The conversion factor between eV and joule is:

$$1 \text{ eV} = 1.6 \times 10^{-19} \text{ J}$$

Therefore, the energy of the α-particle can be written as:

$$\frac{2.99 \times 10^{-12}}{1.6 \times 10^{-19}} = 1.87 \times 10^{7} \text{ eV}$$

$$= 18.7 \text{ MeV}$$

Useful applications of alpha radiation

Although α-particles have low penetrating power, they still provide a range of useful applications:

- smoke detectors – americium-241 is commonly used in ionising smoke detectors. Smoke that enters the detector reduces the amount of α-particles that are detected and triggers the alarm
- static eliminators typically use α-particles from polonium-210 to remove static electric charges from equipment
- α-emitters are used in radiotherapy to treat cancers
- radioisotope thermoelectric generators use α-particle decay from plutonium-238 to generate heat that is converted to electricity; they are commonly used in space probes and robotic planetary explorers (Figure 3B–7).

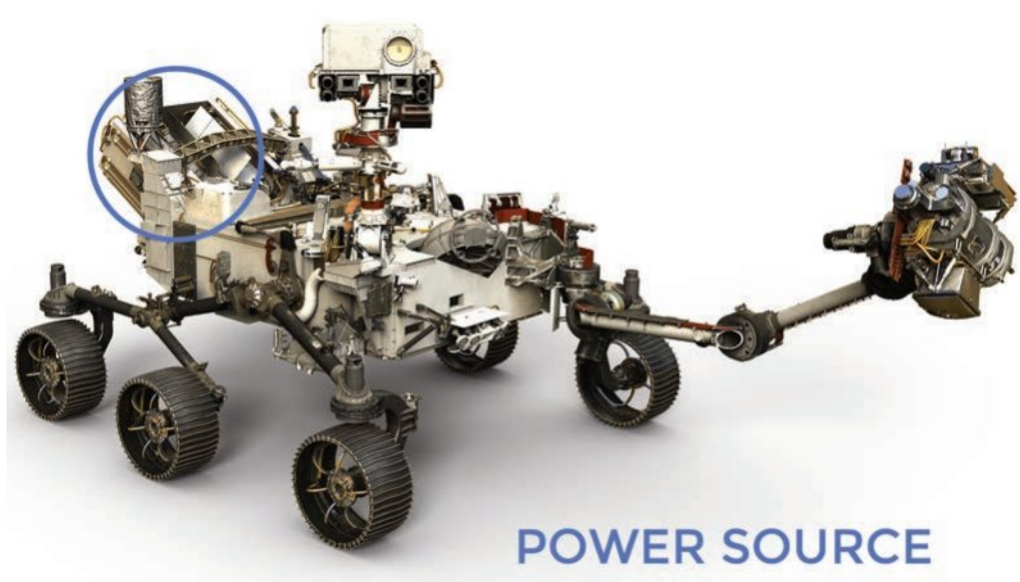

Figure 3B–7 The Mars Perseverance Rover uses a plutonium-238 radioisotope thermoelectric generator (circled) to generate 110 W of electrical energy. This power system produces a dependable flow of electricity using the heat of the plutonium's radioactive α-decay as its 'fuel'.

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Check-in questions – Set 2

1 a What is another name for an alpha (α) particle?
  b What charge does an α-particle carry?

2 a Write the complete equation for the transmutation of uranium-238 to thorium-234.
  b In this transmutation, which element is the parent nucleus and which is the daughter nucleus?

3 An α-particle has a kinetic energy of 2.00×10^{-12} J. Calculate the energy of the α-particle in MeV.

Beta radiation (β)

Beta particle radiation usually consists of very fast-moving electrons or positrons. Every **beta (β) particle** carries either one negative or one positive electronic charge (i.e. $\pm 1.6 \times 10^{-19}$ coulomb: electron $-e$, positron $+e$). Their charged nature means that they are affected by both electric and magnetic fields (as α-particles are), and this property was also important for their original discovery. The velocity of β-particles also varies over a wide range, depending on the nature of the radioactive source, but it is usually never more than 90% of the speed of light, c ($0.9c$ or 270 000 km s^{-1}).

Beta (β) particle a high-energy, high-speed electron (β^-) or positron (β^+) that is ejected from the nucleus by some radionuclides during a form of radioactive decay

Beta particles can penetrate up to 1 metre of air. They can be absorbed by aluminium a few millimetres thick. Their ionising capacity is considerably less than that of α-radiation. However, they penetrate further through materials so they can be dangerous if the source is closer than a metre externally, or very dangerous if the source is ingested internally, for much the same sort of reasons as for α-particle radiation.

In β^--decay an electron is emitted from inside the nucleus. However, since a nucleus does not contain any electrons, how is this possible? The electrons emitted do not come from the electron shell surrounding the nucleus.

Some very interesting changes take place inside a radioactive nucleus when it emits an electron. A neutron turns into a proton and emits an electron (β^-). This can be written as:

$$^{1}_{0}n \rightarrow {}^{1}_{1}p + {}^{0}_{-1}e + \text{energy or } {}^{1}_{0}n \rightarrow {}^{1}_{1}p + {}^{0}_{-1}\beta + \text{energy}$$

In a similar manner, a proton can also turn into a neutron, emitting a positron or beta-plus particle (β^+).

$$^{1}_{1}p \rightarrow {}^{1}_{0}n + {}^{0}_{+1}e + \text{energy} \text{ or } {}^{1}_{1}p \rightarrow {}^{1}_{0}n + {}^{0}_{+1}\beta + \text{energy}$$

These β^-- and β^+-emissions are shown in Figure 3B–8.

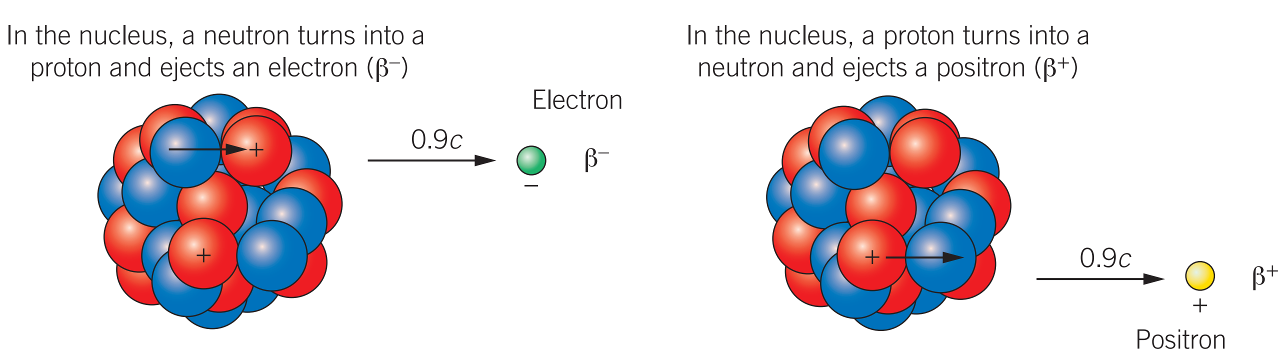

Figure 3B–8 Diagram of β^--radiation (electrons, left) and β^+-radiation (positrons, right). The electrons and positrons can move at 90% of the speed of light, c, hence '$0.9c$'. They can penetrate paper or several millimetres of skin. Like α-particles they are harmful when emitted inside the human body.

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As noted previously, α-particles are emitted with specific energies that are unique to the parent nucleus. Beta particles are emitted with any energy up to a maximum value, but not all of the initial energy can be accounted for in the products.

Does this mean that energy is not conserved in this β-decay nuclear process?

3A NUCLEAR STABILITY: FORCES IN THE NUCLEUS LINK

As introduced in Section 3A, Wolfgang Pauli (a theoretical physicist) in 1930 suggested that another particle, as yet undetected, was emitted. This particle would 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'. It was first experimentally detected in 1956.

The complete β^--decay process is:

$$^{1}_{0}\text{n} \rightarrow {}^{1}_{1}\text{p} + {}^{0}_{-1}\beta + \text{neutrino}$$

where the neutrino is the carrier of the 'missing' energy.

The complete β^+-decay process is:

$$^{1}_{1}\text{p} \rightarrow {}^{1}_{0}\text{n} + {}^{0}_{+1}\beta + \text{neutrino}$$

where again the neutrino is the carrier of the 'missing' energy.

Useful applications of beta radiation

The medium penetrating power of β-particles provides a range of useful applications that include:

- thickness detectors for the quality control of thin materials, i.e. paper
- treatment of eye and bone cancers; strontium-89 is commonly used
- fluorine-18 as a tracer for positron emission tomography (PET).

Check-in questions – Set 3

1 a What are other names for beta (β) particles?
  b What charges do β-particles carry?
2 a Write the equation for when a neutron in the nucleus changes into a proton.
  b Write the equation for when a proton in the nucleus changes into a neutron.

Gamma radiation (γ)

Gamma radiation does not consist of charged particles. It is a form of very short wavelength electromagnetic energy similar to X-ray radiation.

Gamma (γ) ray a high-energy photon released when a nucleus remains unstable after alpha or beta decay. Gamma rays travel at the speed of light and carry no charge.

These forms of electromagnetic radiation can be considered as small discrete packages of energy called photons. The speed of γ-radiation is the speed of light (300 000 km s^{-1} or *c*).

Gamma radiation is very difficult to stop: even lead that is several centimetres thick does not absorb all of the radiation. Although the ionising capacity of **gamma (γ) rays** is considerably smaller than that of β-radiation, their high penetration ability means that they are dangerous even at a distance as they can penetrate our bodies and hit sensitive organs. This makes γ-radiation extremely dangerous to us, both as an external source and if internally ingested or inhaled.

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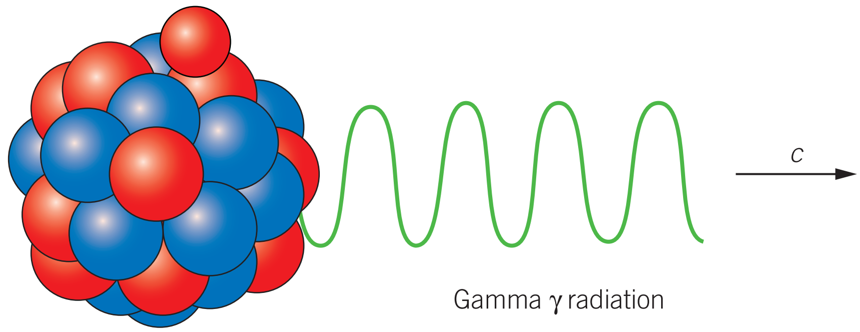

Figure 3B–9 An unstable nucleus can sometimes remain excited even after emitting alpha or beta particles. It usually rids itself of excess energy by emitting a gamma ray – a photon of high frequency. With very high energy and no electrical charge, gamma rays have great penetrating power. Not even a thick piece of lead or concrete will stop all of them and they pass easily into the human body, possibly damaging tissue in the process.

NOTE

Both γ-rays and X-rays are part of the electromagnetic spectrum and as seen in Figure 3B–10 these two regions of the electromagnetic spectrum overlap. X-rays and γ-rays have the same basic properties but originate from different parts of the atom. X-rays are emitted from processes outside the nucleus, but γ-rays originate inside the nucleus. X-rays are also generally lower in energy and therefore less penetrating than γ-rays but both have enough energy to ionise atoms.

LINK CHAPTER 1

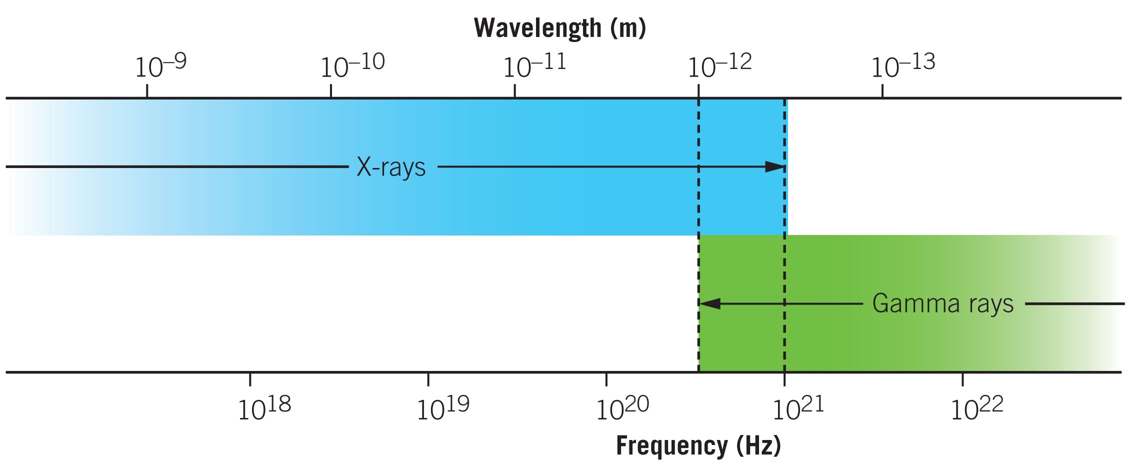

Figure 3B–10 X-rays and gamma rays overlap in the electromagnetic spectrum.

Useful applications of gamma radiation

Gamma-emitting radioisotopes are the most widely used radiation sources. The strong penetrating power of gamma rays has many applications. The three radioisotopes that are by far the most useful gamma ray emitters are caesium-137, technetium-99m and cobalt-60.

Some uses of cobalt-60

Sterilisation of medical equipment in hospitals; pasteurisation, via irradiation, of certain foodstuffs; levelling or thickness gauges (i.e. food packaging, steel mills); industrial radiography; and medical radiation treatment of cancerous tumours using a gamma 'knife' (see Figure 3B–11).

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3A NUCLEAR STABILITY: FORCES IN THE NUCLEUS LINK

Some uses of caesium-137

Measurement and control of the flow of liquids in industrial processes; investigation of subterranean strata (i.e. oil, coal, gas and other mineralisation); measurement of soil moisture-density at construction sites; and medical radiation treatment of cancerous tumours.

Some uses of technetium-99m

Tc-99m is the most widely used radioactive isotope for medical diagnostic studies in different chemical forms for brain, bone, liver, spleen and kidney imaging. It is also used for blood flow studies.

Cobalt-60 decays by emitting a low-energy electron (beta particle) from the nucleus and high-energy electromagnetic radiation (gamma rays). It is an extremely useful radioactive isotope that is used in radiation treatment of cancerous tumours. It does not exist in nature but can be produced as an artificial radioactive isotope in nuclear reactors.

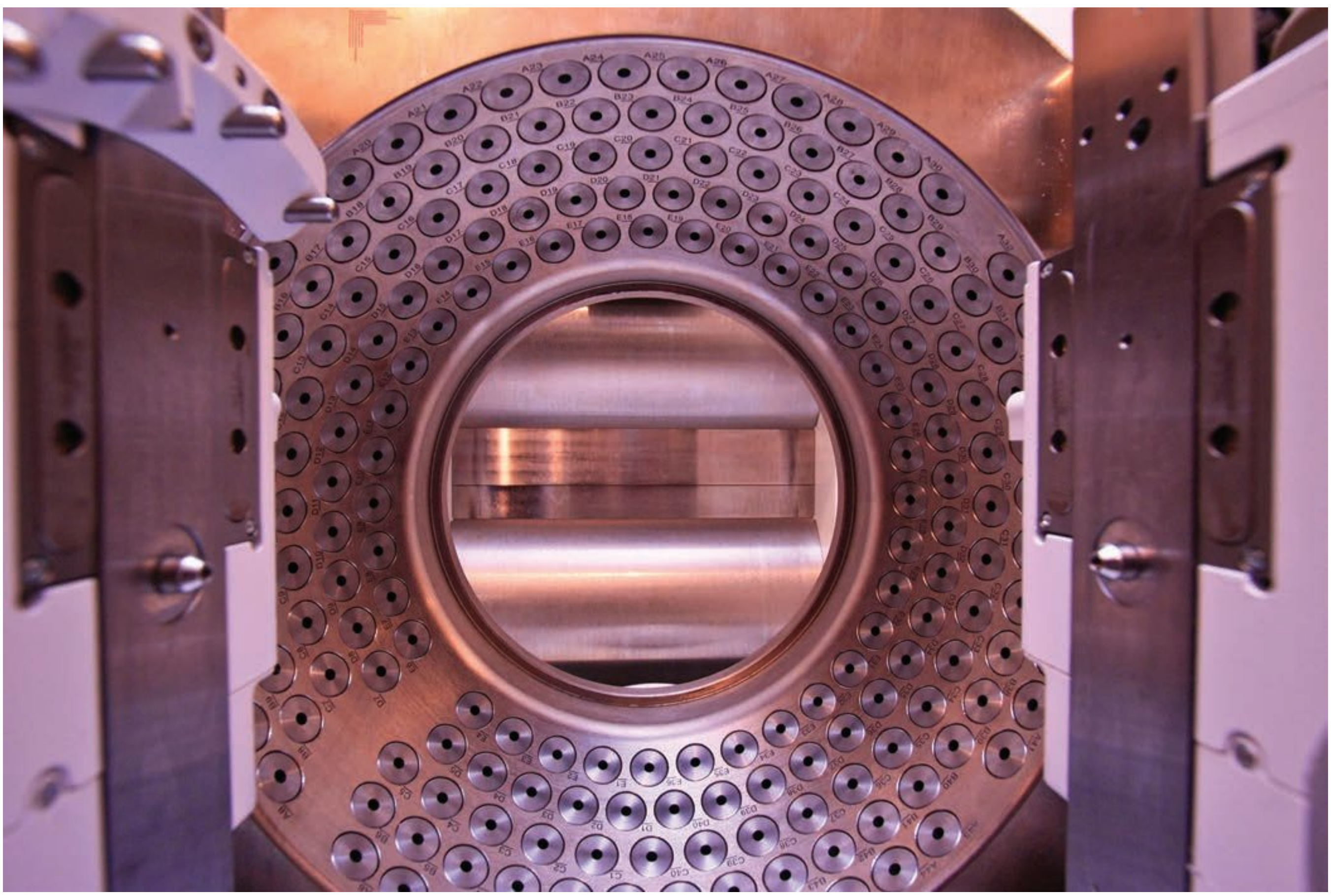

Figure 3B–11 A medical gamma ray 'knife' containing 192 cobalt-60 radioactive sources used to treat cancerous brain tumours

Check-in questions – Set 4

1 What charge does a gamma (γ) ray carry?
2 At what speed does γ-radiation travel?
3 Why do γ-rays have lower ionising power?

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Nuclear transformations

A **nuclear transformation** is the conversion of one nuclide into another. It can occur by the natural radioactive decay of a nucleus.

Nuclear transformation the conversion of one nuclide into another nuclide

For example, carbon-14, a naturally occurring radioactive isotope of carbon, decays via β^--decay into nitrogen-14 during which one of the neutrons in the carbon atom becomes a proton. This increases the number of protons in the atom by one, creating a nitrogen atom rather than a carbon atom:

$$^{14}_{6}C \rightarrow {}^{14}_{7}N + {}^{0}_{-1}\beta$$

α-, β- and γ-radiation all change the nucleus in different ways. Because both α-radiation and β-radiation are accompanied by changes in the number of protons and neutrons in the nucleus, they give rise to the formation of a different element.

Other nuclear transformations can be induced by bombarding elements with other nuclear particles – protons, neutrons, α-particles and so on.

The first artificial nucleus produced by this technique was in Ernest Rutherford's laboratory in 1917. Rutherford bombarded nitrogen atoms with high-speed α-particles from a natural radioactive isotope of radium, and observed both protons and an isotope of oxygen resulting from the reaction:

$$^{14}_{7}N + {}^{4}_{2}He \rightarrow {}^{17}_{8}O + {}^{1}_{1}H$$

Both the $^{17}_{8}O$ and $^{1}_{1}H$ nuclei that are produced are stable.

The advent of particle accelerators in the early 1930s enabled charged particles such as protons to be fired at atoms. The advantage of using a particle accelerator is that the energy of the bombarding particle can be accurately controlled. The limitation of using positively charged particles, however, is that they have to be travelling at very high speed to overcome the electrostatic repulsion of the positively charged nucleus.

In 1932, the physicist James Chadwick bombarded beryllium with α-particles. The resulting radiation went through a lead shield, but it was completely unaffected by electric or magnetic fields. Chadwick had discovered the neutron – a neutral particle with almost the same mass as a proton.

After the neutron was discovered, physicists realised that it would make a good probe for exploring the atomic nucleus as there would be no electrostatic repulsion acting on the neutron.

Nuclear physicists can also use neutrons in breeder nuclear reactors to 'breed' fissile plutonium-239 from non-fissile uranium-238. This will be important when we look at nuclear reactors and nuclear weapons in Chapter 4.

LINK CHAPTER 4

Alpha particle radiation involves the ejection of two neutrons and two protons (helium nucleus or α-particle) from the nucleus of the radioactive element. For example, the isotope uranium-238 has 92 protons and 146 neutrons. In order to achieve greater stability, the nucleus may emit an α-particle, so reducing its number of protons to 90 and its number of neutrons to 144. However, it is no longer a uranium nucleus. Checking the periodic table for $Z = 90$ indicates it is now an isotope of the element thorium (Th) with atomic number 90 and mass number 234 (90 + 144). In fact, it is thorium-234. The decay process can be represented as follows:

$$^{238}_{92}U \rightarrow {}^{234}_{90}Th + {}^{4}_{2}He$$

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The overall effect of α-particle emission is to produce neutron-rich nuclei; that is, nuclei that have too many neutrons to be stable. The nucleus does not simply eject a neutron (or neutrons) to correct this instability. Instead, one of the neutrons in the nucleus changes into a proton by emitting a β^--particle; that is, a high-speed electron:

$$^{1}_{0}\text{n} \rightarrow {}^{1}_{1}\text{p} + {}^{0}_{-1}\text{e}$$

3A NUCLEAR STABILITY: FORCES IN THE NUCLEUS LINK

This phenomenon is known as β^--emission and is an example of the weak nuclear force in action (see Section 3A). For instance, in the case of thorium-234 (which was formed by the α-particle decay of uranium-238) the nucleus further decays by β^--emission to protactinium-234 (Pa):

$$^{234}_{90}\text{Th} \rightarrow {}^{234}_{91}\text{Pa} + {}^{0}_{-1}\text{e}$$

In most cases after the emission of an α-particle or a β^--particle, the nucleus rearranges slightly to minimise its internal energy state. This rearrangement of the nucleus releases energy in the form of a γ-ray. Since γ-ray emission is the emission of energy rather than a particle, it causes no change in either the mass number (A) or the atomic number (Z). This process occurs almost instantaneously after the α-particle or β^--particle emission, so γ-rays are emitted along with either an α-particle or a β^--particle. For example, sodium-24 decays by emitting a β^--particle and a γ-ray as follows:

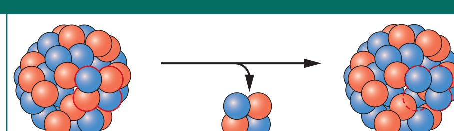
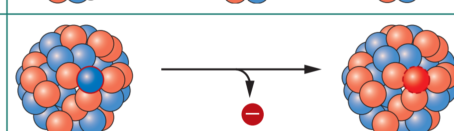
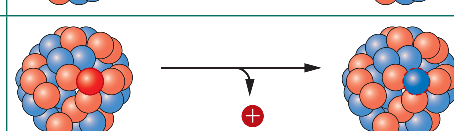
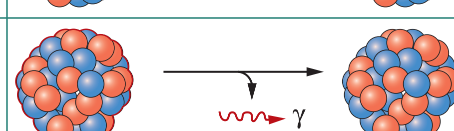
$$^{24}_{11}\text{Na} \rightarrow {}^{24}_{12}\text{Mg}^* + {}^{0}_{-1}\text{e}$$

$$^{24}_{12}\text{Mg}^* \rightarrow {}^{24}_{12}\text{Mg} + {}^{0}_{0}\gamma$$

The asterisk (*) signifies that the nucleus is excited (i.e. unstable) and has excessive internal energy. Eventually sodium-24 decays to stable magnesium-24.

Table 3B–1 summarises the nuclear transformation equations involved in α-, β^--, β^+- and γ-radioactive decay.

Table 3B–1 Nuclear transformation equations involved in α-, β^--, β^+- and γ-radioactive decay

Type	Nuclear equation	Representation	Change in mass/ atomic numbers
Alpha decay	$^{A}_{Z}\text{X} \rightarrow {}^{4}_{2}\text{He} + {}^{A-4}_{Z-2}\text{Y}$		A: decrease by 4 Z: decrease by 2
Beta decay	$^{A}_{Z}\text{X} \rightarrow {}^{0}_{-1}\text{e} + {}^{A}_{Z+1}\text{Y}$		A: unchanged Z: increase by 1
Positron emission	$^{A}_{Z}\text{X} \rightarrow {}^{0}_{+1}\text{e} + {}^{A}_{Y+1}\text{Y}$		A: unchanged Z: decrease by 1
Gamma decay	$^{A}_{Z}\text{X}^* \rightarrow {}^{0}_{0}\gamma + {}^{A}_{Z}\text{X}$		A: unchanged Z: unchanged

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Check-in questions – Set 5

WORKSHEET 3B–1 ALPHA, BETA AND GAMMA RADIATION

1 a Complete the following radioactive decay equation:

$${}^{234}_{92}\text{Au} \rightarrow {}^{230}_{90}\text{Th} + ?$$

b What type of radioactive decay does this represent?

2 a Complete the following radioactive decay equation:

$${}^{210}_{82}\text{Pb} \rightarrow {}^{210}_{83}\text{Bi} + ?$$

b What type of radioactive decay does this represent?

3 a Complete the following radioactive decay equation:

$${}^{210}_{83}\text{Bi}^{*} \rightarrow {}^{210}_{83}\text{Bi} + ?$$

b What type of radioactive decay does this represent?

3B SKILLS

VIDEO 3B–2 SKILLS: WRITING NUCLEAR TRANSFORMATION EQUATIONS

Writing nuclear transformation equations

Equations can be written to show how a nucleus changes during a nuclear decay process. With these nuclear equations we track both the atomic number and the mass number.

For any particular element X, the atomic number (Z) and the mass number (A) are written in the following accepted format:

$${}^{A}_{Z}\text{X}$$

In writing nuclear equations it is important to correctly write each of the symbols for each of the particles involved. A nuclear equation is written for an alpha decay and a beta decay below. Notice that the sum of the atomic numbers is equal on both sides of the arrow. The sum of the mass numbers is also equal on both sides:

$${}^{238}_{92}\text{U} \rightarrow {}^{234}_{90}\text{Th} + {}^{4}_{2}\text{He}$$

For uranium-238 alpha decay:

atomic numbers (Z) LHS = 92

RHS = 90 + 2 = 92

mass numbers (A) LHS = 238

RHS = 234 + 4 = 238

$${}^{14}_{6}\text{C} \rightarrow {}^{14}_{7}\text{N} + {}^{0}_{-1}\beta$$

For carbon-14 beta decay:

atomic numbers (Z) LHS = 6

RHS = 7 −1 = 6

mass numbers (A) LHS = 14

RHS = 14 + 0 = 14

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Section 3B questions

Multiple-choice questions

1 Which one of the following correctly identifies β^--particles and β^+-particles?

	β^--particles	β^+-particles
A	Electrons	Photons
B	Electrons	Protons
C	Negative photons	Positive photons
D	Electrons	Positrons

2 Which one of the following best explains the ionising properties of nuclear radiations and their penetration power?

A α-particles are not very ionising so they are easily stopped by a thin sheet of paper.

B α-particles are very ionising so they only travel a few centimetres in air.

C γ-radiation can easily penetrate a sheet of card because it is very ionising.

D γ-radiation is not very penetrating because it is very ionising.

3 An α-particle has an energy of 1.0×10^{-12} J. The energy of the α-particle in MeV is closest to:

A 1.0 MeV

B 6.2 MeV

C 9.4 MeV

D 18.7 MeV

4 A radioactive source is placed 2 cm from a detector. The count rate decreases slightly if a sheet of paper is inserted between the source and the detector. It is reduced to background radiation level if the sheet of paper is replaced by a 1 cm thick sheet of aluminium.

The radiation emitted by the radioactive source is most likely to be

A α only.

B α and β.

C β and γ.

D γ only.

Short-answer questions

5 From which part of an atom are α- and β-particles and γ-rays emitted from?

6 a Complete the nuclear transformation equation of thorium-230 to radium-226:

$$^{230}_{90}\text{Th} \rightarrow \, ^{226}_{88}\text{Ra} + ?$$

b Which element is the parent nucleus and which element is the daughter nucleus?

c What is the name of the particle emitted?

7 a What particle was proposed by Wolfgang Pauli in 1930 to ensure that the law of conservation of energy held in radioactive beta decay?

b What were the properties of this hypothetical particle?

8 a Complete the nuclear transformation equation of thorium-234 to protactinium-234:

$$^{234}_{90}\text{Th} \rightarrow \, ^{234}_{91}\text{Pa} + ?$$

b What is the name of the particle emitted?

9 a Complete the nuclear transformation equation of magnesium-24:

$$^{24}_{12}\text{Mg}^* \rightarrow ? + ?$$

b What is the name of the emission?

c What does the asterisk (*) stand for?

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3C Modelling radioactive decay

Study Design:
Model radioactive decay as random decay with a particular half-life, including mathematical modelling with reference to whole half-lives

Glossary:
Activity
Decay curve
Half-life
Radiocarbon dating

ENGAGE

Using radioactive carbon-14 to date the settlement of Aboriginal peoples

Dr Vladimir Levchenko of the Australian Nuclear Science and Technology Organisation (ANSTO) and his team, using **radiocarbon dating** techniques, have discovered evidence that now suggests Aboriginal peoples settled in the Flinders Ranges of South Australia some 49 000 years ago. The scientists used radiocarbon dating techniques that are reliable to 55 000–60 000 years.

The Warratyi site (Figure 3C–1) preserves reliably dated, stratified evidence of extinct Australian megafauna, the earliest-known use of ochre in Australia and Southeast Asia, gypsum pigment and bone tools. The evidence clearly shows that Aboriginal peoples not only settled in the arid interior within a few millennia of entering the continent, but also developed key technologies much earlier than previously recorded.

Radiocarbon dating
a method for determining the age of an object containing organic material by using the decay of radioactive carbon-14

Figure 3C–1 Evidence from the Warratyi rock shelter in the Flinders Ranges shows that Aboriginal peoples occupied arid Southern Australia about 49 000 years ago.

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EXPLAIN

Random decay

Radioactive decay is a completely random process, which means that it is impossible to predict when a particular radioactive nucleus will decay regardless of how long the atom has existed. However, with large numbers of nuclei it is possibly to statistically predict the behaviour of the entire group. For example, one gram of radioactive uranium-238 contains 2.6×10^{21} radioactive atoms. The overall decay rate of such a significant number of radioactive nuclei can be expressed using the concept of the half-life of that radioactive element – the length of time for half the radioactive nuclei to decay.

Simulating random radioactive decay using dice

It is possible to simulate random radioactive decay using dice. Typically, 120 dice are rolled and all dice showing, say, the number 6 face up are removed (they have decayed). Note it is impossible beforehand to predict which of the thrown dice will roll with number 6 face up (i.e. the random nature of decay) – but approximately one-sixth of all the dice thrown each time will show with the number 6 face up.

If this is repeated a number of times, a table similar to Table 3C–1 might be generated.

Table 3C–1 Example of rolling 120 dice

Roll	0	1	2	3	4	5	6	7	8	9
Dice remaining	120	101	84	71	59	50	42	36	30	25

Note that it takes approximately four rolls of the dice to have approximately half of the original number of dice left 'active'. This is the half-life of a number 6 die face. If it takes 5 minutes to roll and count the dice, then the half-life for this configuration is 20 minutes.

If the experiment is repeated with all the odd numbered dice being removed each time, then the half-life would be very close to one roll or 5 minutes.

Half-life

Half-life
the time taken for half of a group of unstable nuclei to decay

The element technetium-99m, a useful medical radioisotope, decays so that after a period of 6.0 hours exactly half of the original technetium-99m nuclei have decayed. Such a period of time is called a **half-life**, $t_{\frac{1}{2}}$. The half-life is a measure of the rate of radioactive decay. Every radioactive isotope can be characterised by its half-life.

Different radioisotopes emit radiation at different rates. There are those that decay very quickly and have a very short half-life (e.g. for francium-218, $t_{\frac{1}{2}}$ = 1.0 millisecond), while others decay extremely slowly and have a very long half-life (e.g. for uranium-238, $t_{\frac{1}{2}}$ = 4500 million years). Table 3C–2 shows some natural and artificial radioisotopes, their emissions, their half-lives and common applications.

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Table 3C–2 Some natural and artificial radioisotopes, their emissions, their half-lives and common applications

Isotope	Emission	Half-life	Application
Natural			
Lead-210	β^-	22.2 years	Lead dating of sand and soil
Radium-88	α	1600 years	See Radium girls (Section 3E)
Carbon-14	β^-	5730 years	Carbon dating
Uranium-238	α	4500 million years	Nuclear fuel, geological dating age of Earth
Artificial			
Fluorine–18	β^+	110 minutes	PET scans
Technetium–99m	β^-	6.0 hours	Medical tracer
Iodine-131	β^-	8 days	Medical tracer, radiation therapy
Iodine-125	γ	60 days	Internal radiation therapy
Cobalt-60	γ	5.3 years	External radiation therapy
Americium-241	α	460 years	Smoke detectors
Plutonium-239	α	24 100 years	Nuclear reactor fuel, geological dating

LINK 3E THE EFFECT OF RADIATION ON HUMANS

Technetium-99m has a half-life of 6.0 h; after another 6.0 h (a total of 12.0 h), only one-quarter of the original mass of technetium-99m will remain. This process continues so that at any given instant, the rate of decay is proportional to the amount of radioactive material that is left. This can be plotted graphically as a radioactive **decay curve**. All radioactive elements have the same shaped decay curve as shown in Figure 3C–2. The only significant differences relate to the scale values placed on each axes. This type of curve often appears in physics. It is called an exponential decay curve. The decay curve for carbon-14 is shown in Figure 3C–3.

Decay curve a graph of the number of radioactive nuclei remaining in a substance versus time elapsed

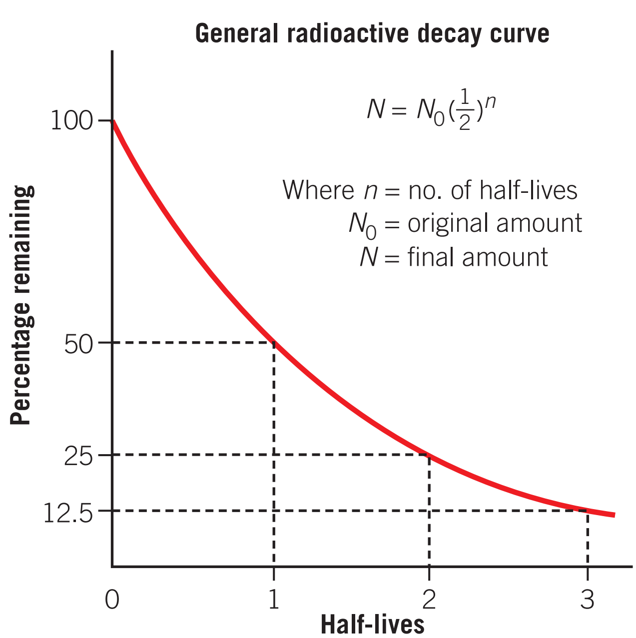

Figure 3C–2 The general radioactive decay curve is shown here. Note that after each period of one half-life, $t_{\frac{1}{2}}$, another half of the original sample has decayed.

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Formula 3C–1 General formula for radioactive decay

$$N = N_O\left(\frac{1}{2}\right)^n$$

Where:

n = the number of half lives that have passed

N_O = Original amount of radioactive substance

N = Final amount of the substance after n half-lives

The half-life of any given radioactive isotope is constant and is unaffected by any external conditions such as temperature, magnetic fields or the chemical environment. It is related only to the instability of the nucleus of the particular radioactive isotopes.

The half-life of a radioactive isotope is also a factor in its application. For example, most medical applications using a radioactive isotope as a tracer require a short half-life (e.g. technetium-99m, 6.0 hours). Medical radiotherapy treatment of thyroid cancer needs an isotope with a slightly longer half-life (e.g. iodine-131, 8 days). In both of these cases, this is so no radioactivity remains in the body any longer than necessary. The radioactive isotope used in a household smoke detector is chosen because of its long half-life (e.g. americium-241, 460 years), so although you have to replace the battery annually the radioactive isotope never has to be replaced.

Carbon-14 dating techniques

Figure 3C–3 shows how radioactive carbon-14 decays as a function of time. Radioactive carbon-14 has a half-life of 5730 years. If 50% of the original carbon-14 remains, this indicates that the object being dated is 5730 years old, if 25% of the original carbon-14 remains, it is 11 460 years old (2 × 5730), and so on. Carbon-14 dating depends on living matter containing an amount of C-14 that corresponds to that in the atmosphere. When that living matter dies, then the C-14 fraction (compared to C-12) decreases.

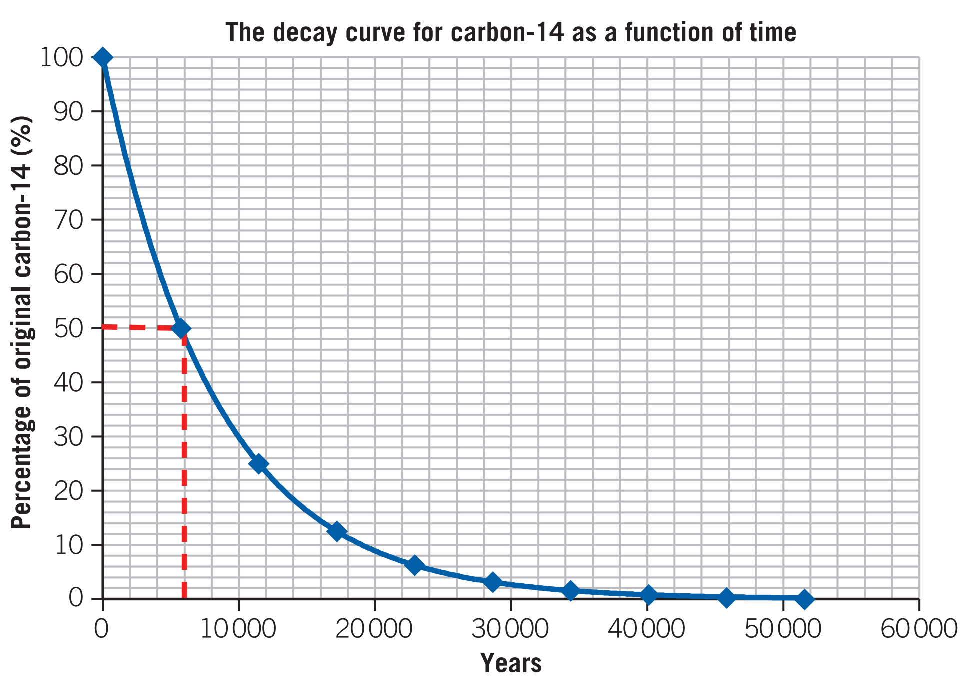

Figure 3C–3 Graph showing how radioactive carbon-14 decays as a function of time. The percentage of radioactive carbon-14 present in a sample determines its age.

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NOTE

Samples that have been radiocarbon dated include charcoal, wood, twigs, seeds, bones, shells, leather, peat, lake mud, soil, hair, pottery, pollen, wall paintings, corals, blood residues, fabrics, paper or parchment, resins and water.

Worked example 3C–1 Half-life of carbon

Carbon-14 has a half-life of 5730 years. A bone fragment from an archaeological dig has one-eighth of the original carbon-14 remaining. How old is the bone fragment?

Solution

$$\frac{1}{8} = \left(\frac{1}{2}\right)^3$$

Therefore, n = 3 half-lives.

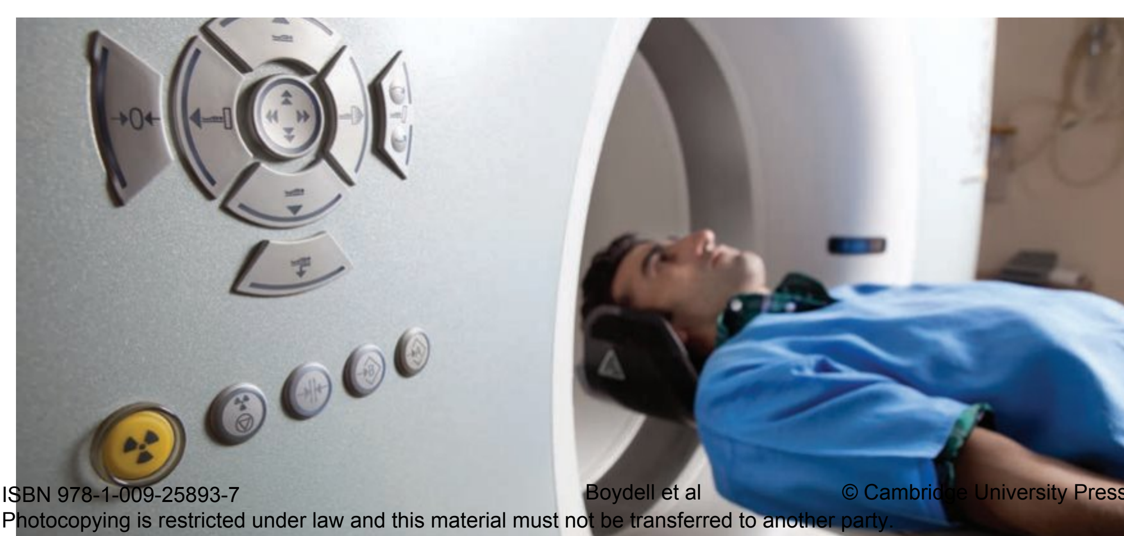
$$\begin{aligned}\text{age of bone} &= 5730 \times 3 \\ &= 17\,190 \text{ years}\end{aligned}$$

Technetium-99m (Tc-99m) is the most widely used radioactive isotope for medical diagnostic studies. (The ‘m’ stands for 'metastable' but that is not important here.) Hospitals prefer short-lived radioactive isotopes for medical diagnostic purposes. One standard method involves using a particle accelerator to form the radiation nuclides. However, accelerators are expensive and fairly bulky. A much cheaper alternative is to produce radioactive substances using a radioactive ‘cow’. These radioactive generators contain a radioactive substance with a relatively long life, known as the mother nuclide. The mother nuclide disintegrates and produces the decay product, called the daughter nuclide. This daughter nuclide has a short half-life. The daughter nuclide is drained from the generator and is then used for medical diagnostic purposes. This is called ‘milking the radioactive cow’.

One common type of radioisotopic generator produces the γ-emitter technetium-99m, which has a half-life of 6.0 hours. The mother nuclide in this case is molybdenum-99 with a half-life of 67 hours. Molybdenum-99 decays via β decay and produces the desired technetium-99m:

$$^{99}_{42}\text{Mo} \rightarrow {}^{99\text{m}}_{43}\text{Tc} + {}^{0}_{-1}\beta$$

$$^{99\text{m}}_{43}\text{Tc} \rightarrow {}^{99\text{m}}_{43}\text{Tc} + {}^{0}_{0}\gamma$$



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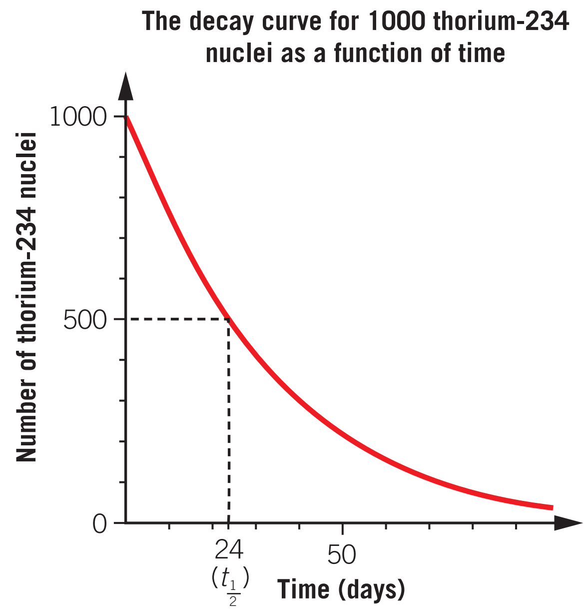
Check-in questions – Set 1

1 The graph shows the decay curve for 1000 thorium-234 nuclei as a function of time in days.
Using the decay curve determine the:
  a half-life of thorium-234
  b number of thorium-234 nuclei remaining after 48 days
  c time (in days) when 100 thorium-234 nuclei remain.



2 Molybdenum-99 has a half-life of 67 hours.

Using the formula $N = N_0\left(\frac{1}{2}\right)^n$ calculate the:
  a percentage of molybdenum-99 remaining after 201 hours have elapsed
  b time it takes to have only $\frac{1}{16}$th of the original molybdenum-99 remaining.

Activity the number of radioactive nuclei that decay each second; measured in becquerel (Bq)

Strength (activity) of radioactive sources

The 'strength' of any given radioactive source is determined by its **activity**.

The activity is defined as the number of nuclei that decay each second; that is, the number of disintegrations per second. The unit of activity is the becquerel (Bq), where

1 becquerel is defined as 1 disintegration per second (1 Bq = 1 disintegration s^{-1}).

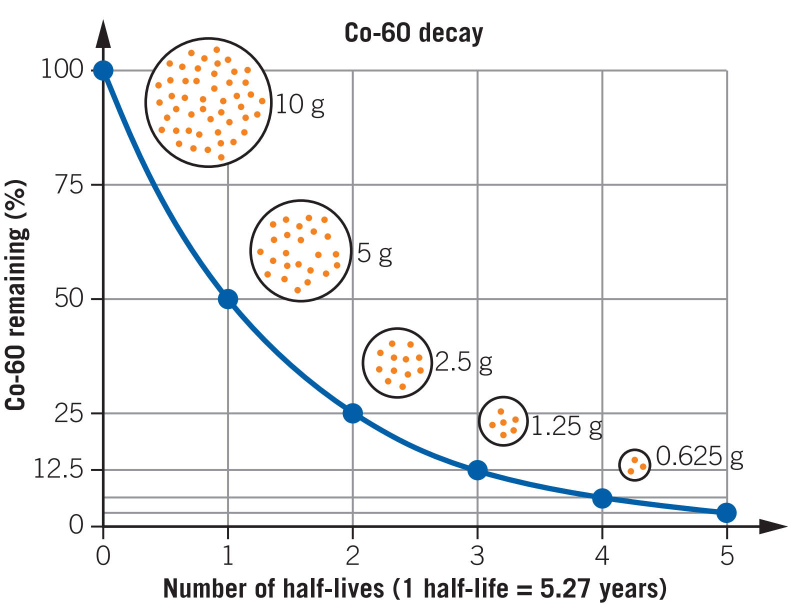


Figure 3C–4 The decay curve for cobalt-60 showing the decrease in its activity

Radioactive cobalt-60 has a half-life of 5.27 years. It is produced from cobalt-59 by neutron bombardment in a nuclear reactor. It is a γ-ray emitter and used in the sterilisation of medical equipment, in external radiotherapy and in industrial radiography.

A radioactive medical source containing 10 g of cobalt-60 is used for external radiation therapy. It has an initial activity of 440 TBq (4.40×10^{14} Bq). Figure 3C–4 shows the amount of radioactive cobalt-60 remaining (and therefore its activity) as a function of time. After 5.27 years, only 5 g of radioactive cobalt-60 remains and its activity is therefore 220 TBq. After 2 half-lives, only 2.5 g of radioactive cobalt-60 remains and its activity is now 110 TBq.

This decrease in activity has implications for the lifespan of the medical radioactive cobalt-60 radiotherapy units used in hospitals (see Worked example 3C–2).

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Natural radioactivity on Earth

Physicists believe that ever since Earth was formed 4500 million years ago, there have been two major mechanisms at work that continually produce the natural radiation that is within Earth's biosphere: terrestrial radiation from Earth and cosmic radiation from space.

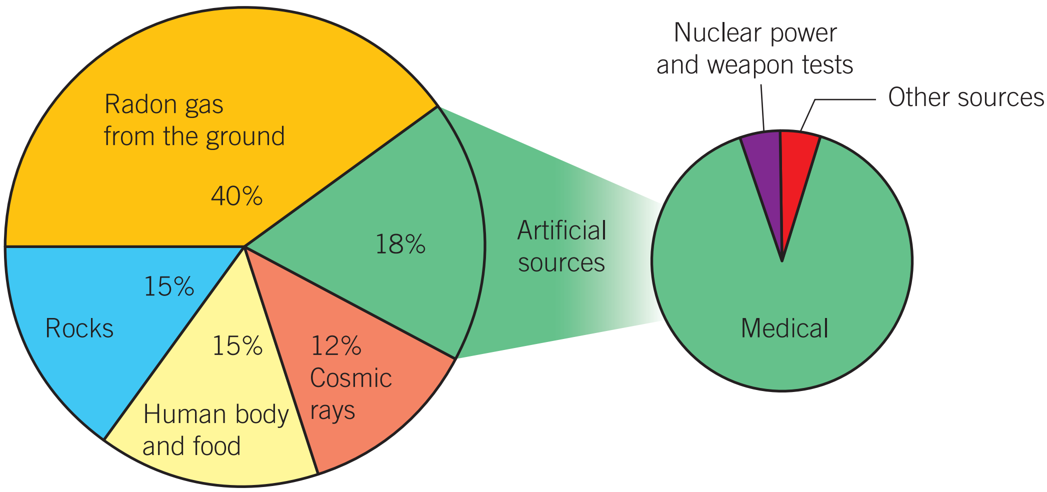

Figure 3C–5 Approximately 82% of the average annual radiation that people receive comes from natural sources.

Table 3C–3 shows the activities of some everyday items including humans. Both you and the person sitting next to you are mildly radioactive! But don't worry, it has been that way for the human species for many tens of thousands of years. Humans have trace amounts of potassium-40, a γ-ray emitter that produces ~100 Bq per kilogram of body mass. The half-life of potassium-40 is 1.25 billion years.

Table 3C–3 Activities of some radioisotopes in everyday life

Item	Radioisotope	Activity
1 kg bananas	Potassium-40	100 Bq
1 kg brazil nuts	Radium-226	250 Bq
Australian home (100 m^2)	Radon-222	3 kBq
70 kg adult human	Potassium-40	7 kBq
Smoke detector	Americium-241	30 kBq
Medical diagnosis	Fluorine-18	5 MBq
Medical therapy	Caesium-137	100 TBq

NOTE

Potassium-40 is the primary source of radiation from the human body for two reasons. First, the concentration of potassium-40 in the body is fairly high. Potassium is ingested in many foods that we eat, like bananas, and is a critically important element for proper functioning of the human body; it is present in pretty much all the tissues of the body. The activity of the radioactive isotope potassium-40 in a 70 kg person is about 7000 Bq, which represents 7000 atoms undergoing radioactive decay each second.

Figure 3C–6 Even the bananas you have for breakfast are mildly radioactive.

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Table 3C–4 gives the half-lives of a range of radioactive isotopes. When Earth formed 4.5 billion years ago, there would have been twice as much radioactive uranium-238 as there is in Earth now.

Table 3C–4 Half-lives of some radioactive isotopes

Isotope	Half-life, $t_{\frac{1}{2}}$
Uranium-238	4.5 billion years
Potassium-40	1.25 billion years
Carbon-14	5730 years
Radium-226	1600 years
Amercium-241	460 years
Strontium-90	28 years
Iodine-131	8.1 days
Technetium-99m	6.0 hours
Bismith-214	20 minutes
Polonium-214	0.15 milliseconds

Worked example 3C–2 Half-life of cobalt-60

A 10 g radioactive medical cobalt-60 source has an initial activity of 440 TBq and a half-life of 5.27 years. The radioactive medical source of cobalt-60 needs replacement when its activity decreases to $\frac{1}{16}$ of its initial value.

a When will it need to be replaced?
b What will its activity be at that time?
c How many grams of radioactive medical cobalt-60 will be remaining at this time?

Solution

a $\frac{1}{16} = \left(\frac{1}{2}\right)^4$

Therefore 4 half-lives have elapsed:

$5.27 \times 4 = 21.08$ years

b $\frac{440}{16} = 27.5$ TBq

c $\frac{10}{16} = 0.625$ g

WORKSHEET 3C–1 MODELLING RADIOACTIVE DECAY

Check-in questions – Set 2

1 a What is the unit of activity of radioactive sources?
  b What is the unit defined as?
2 a Is the half-life of any given radioactive isotope constant?
  b Can the half-life be affected by temperature, magnetic fields or the chemical environment?
3 In 12 hours, the activity of a sample of a radioactive element falls from 240 Bq to 30 Bq. What is the half-life of this element?
4 Potassium-40 has a half-life of 1.25 billion years. The activity of a rock sample of potassium-40 is measured at 30 MBq. What would the activity of the potassium-40 have been 3.75 billion years ago?

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3C SKILLS

VIDEO 3C–1 SKILLS: USING THE HALF–LIFE EQUATION

Using the half-life equation

The general formula for radioactive decay is:

$$N = N_0\left(\frac{1}{2}\right)^n$$

Where N_0 is the original amount of radioactive substance, and N is the final amount of the substance after n half-lives.

It is important to be able to use this equation both ways.

1 Finding the final amount of the substance after n half-lives
2 Finding the number of half-lives that have elapsed given the final amount of substance

Highly radioactive plutonium-239 generated in a nuclear reactor has a half-life of 24 100 years.

1 How long does it take for one-eighth of the original plutonium-239 to remain?

Solution

$$N = N_0\frac{1}{8}$$

$$= N_0\left(\frac{1}{2}\right)^3$$

number of half-lives, $n = 3$

$$\text{time} = 24\,100 \times 3$$

$$= 72\,300 \text{ years}$$

It is not safe to put highly radioactive plutonium-239 into the environment until 241 000 years have elapsed.

2 What percentage of the original plutonium-239 does this represent?

Solution

number of half-lives, $n = 10\left(\frac{241\,000}{24\,100}\right)$

$$N = N_0\left(\frac{1}{2}\right)^{10}$$

$$= N_0\,(0.000\,98)$$

$$\text{percentage} = 0.000\,98 \times 100$$

$$= 0.098\%$$

Section 3C questions

Multiple-choice questions

1 The half-life of Zn-71 is 2.4 minutes. There is 200.0 g of Zn-71 initially. Which one of the following is closest to the number of grams that would be left after 9.6 minutes has elapsed?

A 12.5 g
B 25 g
C 50 g
D 100 g

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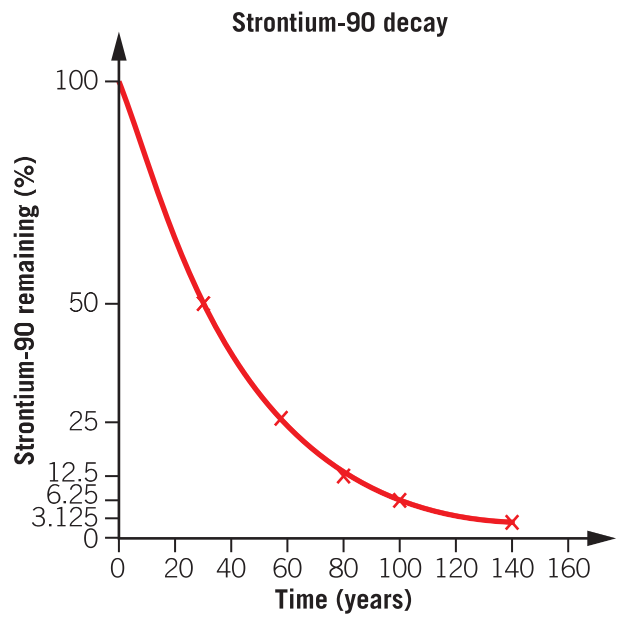
2 All radioactive sources have a half-life. Which of the following statements best explains the concept of the half-life of a source?
A It is half the time it takes for an atom to decay.
B It is half the time it takes the activity of the source to decrease to zero.
C It is the time it takes the activity of the source to decrease by half.
D It is half the time for the radioactive source to become safe.

3 A radioactive source has a half-life of 20 days. How long will it take for seven-eighths of the source to decay?
A 30 days
B 40 days
C 60 days
D 80 days

Short-answer questions

4 The graph on the right shows the decay curve for strontium-90 as a function of time in years.
Using the decay curve estimate the:
a half-life of strontium-90
b percentage of strontium-90 remaining after 140 years
c time (in years) when 12.5% strontium-90 nuclei remain.



5 Gold-198 has a half-life of 2.7 days.
Using the formula $N = N_0\left(\frac{1}{2}\right)^n$ calculate the:
a percentage of gold-198 remaining after 8.1 days have elapsed
b time it takes to have only $\frac{1}{16}$ th of the original gold-198 remaining.

6 The cobalt-60 used in medical radiography is a γ-ray emitter with a half-life of 5.3 years. If the original activity of a particular sample is 64 MBq, calculate the activity after 26.5 years.

7 Why do medical diagnostic radioisotopes usually have short half-lives measured in hours or days (e.g. technetium-99m, 6 hours; iodine-131, 8 days)?

8 Why do medical therapy radioisotopes usually have longer half-lives measured in years or decades (e.g. cobalt-60, 5.3 years; caesium-137, 30 years)?

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3D Analysing decay series diagrams

Study Design:
Analyse decay series diagrams with reference to type of decay and stability of isotopes

Glossary:
Daughter nucleus
Decay chain
Parent nucleus
Radioactive decay series

ENGAGE

The habitable blue planet

Our planet is warm. The heat generated by Earth's radioactivity slows down the cooling rate. Geologists have used temperature measurements from more than 20 000 boreholes around the world to estimate that some 44 TW (44 trillion watts) of heat continually flows from Earth's interior and eventually into space. Half of that heat (22 TW) comes from radioactive decay chains. The three naturally occurring actinide alpha decay chains – thorium, uranium/radium (from U-238) and actinium (from U-235) – each generates heat on its way to ending with its own specific lead isotope (Pb-208, Pb-206 and Pb-207 respectively). The uranium and thorium amounts in the Earth's crust and mantle are estimated to be 50 000 billion and 160 000 billion tonnes respectively. According to this estimate, the uranium decay chain alone would release the equivalent energy produced by 4600 nuclear power plants each producing 1 GW of power.

Figure 3D–1 The habitable blue planet. It is theorised that the heat generated by radioactive decay has played a major role in ensuring Earth remains habitable.

The importance of the heat supplied by radioactive decay is that it means the rotating Earth has a molten iron core, which in turn creates Earth's magnetic field, which in turn makes the planet habitable!

EXPLAIN

Radioactive decay series

The naturally occurring radioactive isotopes of the heaviest elements fall into chains of successive disintegrations, or decays, and all the species in one chain constitute a radioactive family, or **radioactive decay series**. Three of these series include most of the naturally radioactive elements of the periodic table. They are the uranium series, the actinium series and the thorium series.

Radioactive decay series the sequence of stages a radioisotope passes through to become more stable. The chain ends when a stable isotope forms.

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Each series is characterised by a parent (first member) that has a long half-life and a series of daughter nuclides that ultimately lead to a stable end-product – that is, a nuclide on the band of stability. In all three series, the end-product is a stable isotope of lead.

Parent nucleus the decaying nucleus

Daughter nucleus a nucleus formed by the radioactive decay of another nucleus (the parent)

Decay chain the sequence of stages a radioisotope passes through until it reaches a stable nucleus

NOTE

The neptunium series is a fourth series. However, since neptunium-237 has a relatively short half-life (21 million years), neptunium-237 is no longer present in the crust of Earth but the rest of its decay series is still present and continuing to decay.

The decay chain of uranium-238

A **parent nucleus** of uranium-238 decays by alpha emission to form a **daughter nucleus**, thorium-234. The thorium produced in turn undergoes β^--decay and transforms into protactinium-234, which then undergoes β^--decay to produce uranium-234. This last isotope changes slowly by alpha decay (with a half-life of 245 000 years) into thorium-230, yet another unstable nucleus and so on.

Any such **decay chain** is only stopped by the formation of a stable nucleus. This occurs at the 14th generation of the uranium-238 family, when lead 206 is finally produced (Figure 3D–2).

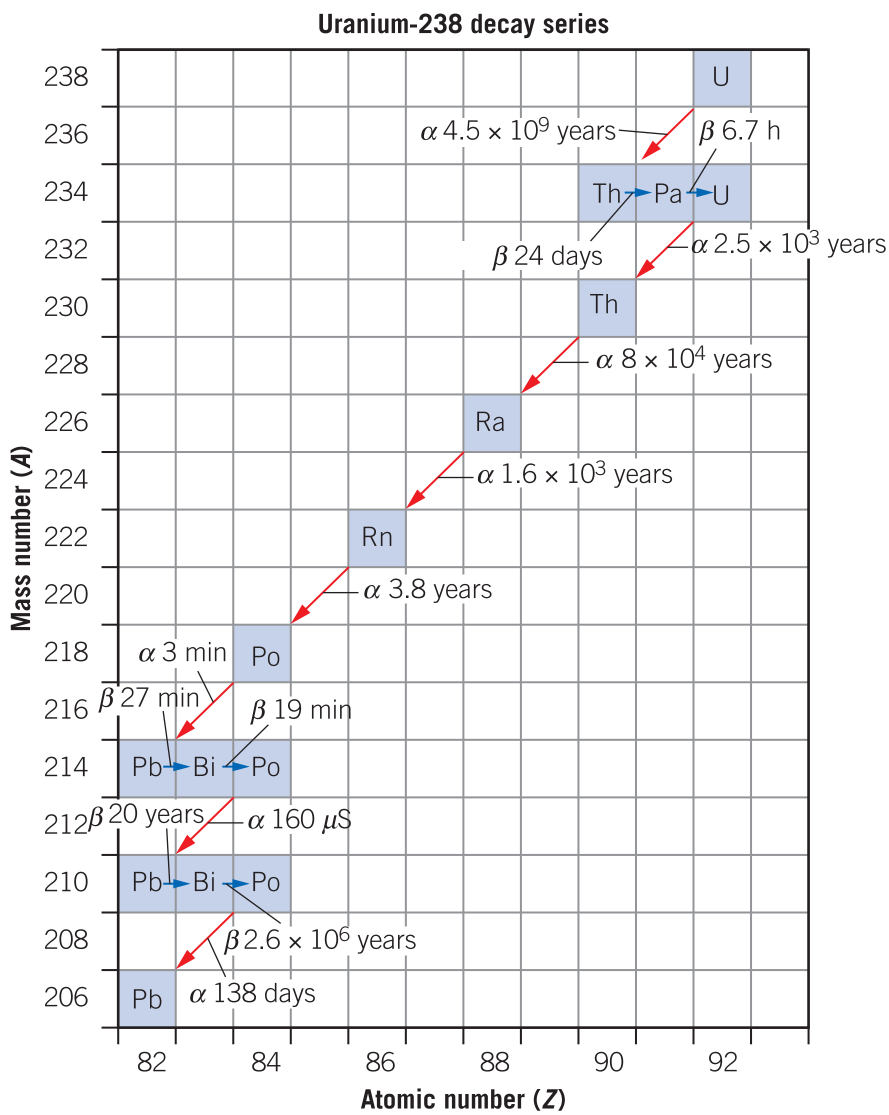

Figure 3D–2 The uranium-238 decay series. The half-life and emission type are indicated on each of the decays as the radioactive uranium-238 is eventually transformed into stable element lead-206.

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Note that the daughters of α-decay shown in Figure 3D–2 always have two fewer protons and two fewer neutrons than the parent. Therefore, uranium-238 under α-decay becomes thorium-234.

Note that the daughter thorium-234 produced has two fewer protons and four fewer nucleons than the parent uranium-238:

$$^{238}_{92}\text{U} \rightarrow {}^{234}_{90}\text{Th} + {}^{4}_{2}\text{He}$$

The daughters of β-decay have one fewer neutron and one more proton than their parent. Beta decay therefore produces daughter nuclei that move up the periodic table.

Therefore, a thorium-234 nucleus beta decays to protactinium-234 and in turn protactinium-234, which is also a β-emitter, produces uranium-234.

$$^{234}_{90}\text{Th} \rightarrow {}^{234}_{91}\text{Pa} + {}^{0}_{-1}\beta$$

$$^{234}_{91}\text{Pa} \rightarrow {}^{234}_{92}\text{U} + {}^{0}_{-1}\beta$$

It was noted earlier that α-decay and β-decay are often associated with subsequent γ-decays (Section 3B). For example, in the α-decay of U-238, two γ-rays of different energies are emitted in addition to the α-particle:

LINK 3B ALPHA, BETA AND GAMMA RADIATION

$$^{238}_{92}\text{U} \rightarrow {}^{234}_{90}\text{Th} + {}^{4}_{2}\text{He} + 2\ {}^{0}_{0}\gamma$$

No γ-decays are shown in the chart in Figure 3D–2, because they do not produce a daughter nucleus that differs from the parent nucleus. For example, an excited magnesium-24 nucleus (with the asterisk * indicating an excited nucleus) emits a γ-ray but still remains a magnesium-24 nucleus:

$$^{24}_{12}\text{Mg}^{*} \rightarrow {}^{24}_{12}\text{Mg} + {}^{0}_{0}\gamma$$

Not all naturally occurring radioisotopes are part of a decay series. For example, the potassium-40 found on Earth is a remnant of the supernova explosion that created Earth. The half-life of 1.25 billion years is so long that these radioisotopes are still decaying from when they were formed.

WORKSHEET 3D–1 ANALYSING DECAY SERIES DIAGRAMS

Check-in questions – Set 1

1 a Using Figure 3D–2 write down the decay equation for $^{214}_{83}\text{Bi}$.
  b What is the half-life of bismuth-214?
  c Write down the decay equation for $^{210}_{83}\text{Bi}$.
  d What is the half-life of bismuth-210?

3D SKILLS

VIDEO 3D–1 SKILLS: INTERPRETING DECAY CHAIN DIAGRAMS

Interpreting decay chain diagrams

It is important to be able to interpret decay chain diagrams such as the decay chain of uranium-238 shown in Figure 3D–2.

The vertical axis shows the mass number (A) and the horizontal axis the atomic number (Z). Uranium-238 appears in the box where A = 238 and Z = 92. This is because uranium-238 is $^{238}_{92}\text{U}$.

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Alpha decays are shown by red diagonal arrows running left at 45°, which end up in a box where the mass number (A) has decreased by 4 and the atomic number (Z) by 2. This makes sense as the α-particle ejected is ${}^{4}_{2}\text{He}$.

This means when radium-226 (${}^{226}_{88}\text{Ra}$) α-decays, the new element is ${}^{222}_{86}\text{X}$. A quick check of the periodic table shows that element 86 is radon, which is shown in the box correctly as Rn (${}^{222}_{86}\text{Rn}$).

Beta decays are shown as blue horizontal arrows to the right, which end up in a box where the mass number (A) is unchanged and the atomic number (Z) increases by 1. This also make sense as the β-particle ejected is ${}^{0}_{-1}\beta$. This means when lead-214 (${}^{214}_{82}\text{Pb}$) β-decays, the new element is ${}^{214}_{83}\text{X}$. A quick check of the periodic table shows that element 83 is bismuth, which is shown in the box correctly as Bi (${}^{214}_{83}\text{Bi}$).

The other important information in the decay chain diagram is the half-life, $t_{\frac{1}{2}}$, of each of the elements undergoing decay, which is given variously in units of years, days, hours, minutes, seconds, milliseconds (ms) and microseconds (μs).

For example: for uranium-238, $t_{\frac{1}{2}} = 4.5 \times 10^9$ years and for polonium-214, $t_{\frac{1}{2}} = 160$ μs.

Section 3D questions

Multiple-choice questions

1 Which one of the following correctly describes what a decay series diagram like that shown in Figure 3D–2 indicates?

A the parent nuclei and daughter nuclei

B the type of emission (α or β)

C the half-life of the parent

D all of the above

2 In the uranium-238 decay chain, uranium-238 decays via thorium-234 and protactinium-234 to uranium-234. How many α- and β-decays occur in this process?

A 1 α and 2 β

B 1 α and 3 β

C 2 α and 2 β

D 2 α and 3 β

Short-answer questions

Use Figure 3D–2 to answer the following questions.

3 Uranium-238 existed in the earth 4.5 billion years ago. How much uranium-238 was there then compared to now?

4 Why are γ-decays not shown on Figure 3D–2?

5 Write the decay equation for, and the half-life of, the parent nucleus when:

a radium-226 → radon-222

b radon-222 → polonium-218

c lead-214 → bismuth-214

d bismuth-214 → polonium-214

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3E The effect of radiation on humans

Study Design:
Explain the effects of α, β and γ radiation on humans, including:
- different capacities to cause cell damage
- short- and long-term effects of low and high doses
- ionising impacts of radioactive sources outside and inside the body
- calculations of absorbed dose (gray), equivalent dose (sievert) and effective dose (sievert)

Evaluate the use of medical radioisotopes in therapy including the effects on healthy and damaged tissues and cells

Glossary:
Absorbed dose
Dose equivalent
Dose–risk relationship
Dosimeter
Effective dose
External radiation
Geiger counter
Genetic effects
Gray (Gy)
Internal radiation
Radiation weighting factor
Radiotherapy
Sievert (Sv)

ENGAGE

Radium girls

In 1917, many patriotic young women counted themselves lucky to have landed well paid war work at a large warehouse complex in Orange, New Jersey. Their main job was to apply a new glowing paint to the faces of clocks, instrument gauges, and wristwatches for the United States Radium Company.

While the men who moved kilograms of radioactive radium around the factory wore lead aprons to protect themselves from the radiation, the women were given nothing as they were told that they were only handling very small quantities of radium. The so called 'Radium girls' were even told to lick their brushes with their lips to get a fine point on the brush for the detailed work required.

Figure 3E–1 Women painting radium onto the clock hands and numbers of alarm clock faces so that the clocks would glow in the dark

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The girls who placed the radium paint in their mouths were ingesting a small amount of radium every time they painted a clock, a watch or instrument. This was repeated many hundreds of times a day.

Figure 3E–2 'Radium girl' worker who developed rotten teeth, huge tumours on her face and had glowing bones from α-particle radiation from UnDark radium paint

The young women, reassured by their supervisors that they were completely safe, even playfully painted their nails and teeth with the luminous paint, known as UnDark.

However, by 1927 more than 50 women had died as a direct result of radium paint poisoning.

EXPLAIN

Discovering the effects of radiation on humans

VIDEO 3E–1 EFFECT OF RADIATION ON HUMANS

Soon after radiation was discovered researchers became involved with one of the drawbacks of radiation – its effect on living tissues. Henri Becquerel, for example, placed a vial of radium in his pocket only to notice later that his skin was severely burned.

Marie Curie died of a malignant blood disease because of her exposure to radiation from both the radium and polonium she discovered. It is estimated that more than 300 of the early radiation researchers and workers died from radiation doses that they had received.

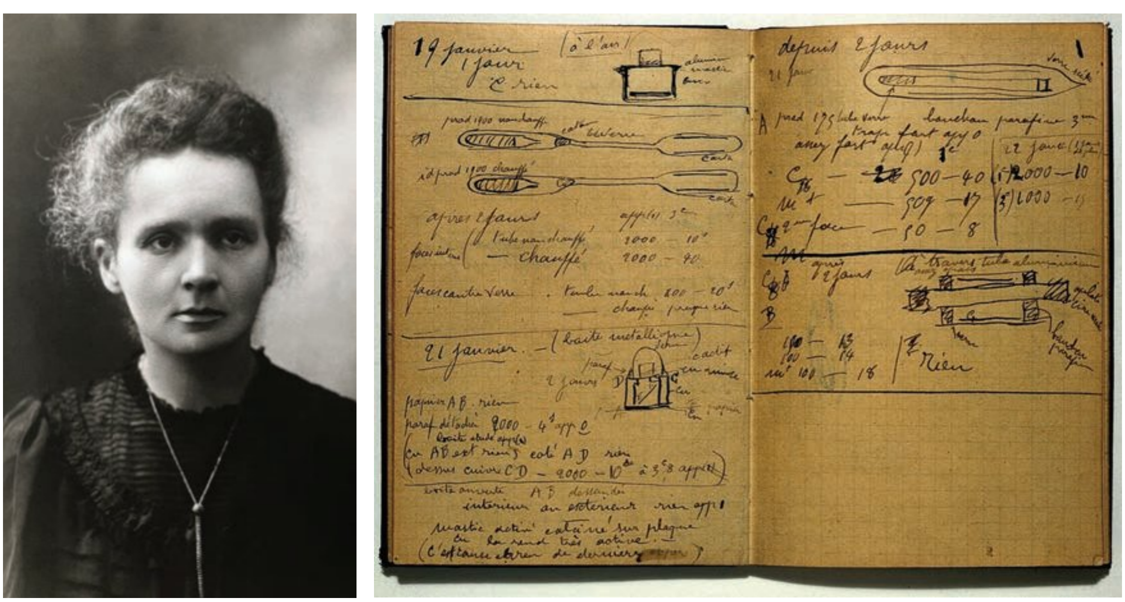

Figure 3E–3 Left: Marie Skłodowska-Curie, the Polish scientist working in France, who in 1898 discovered radium and polonium and was later awarded two Nobel Prizes. The work was onerous because 1 tonne of pitchblende only yielded about one-seventh of a gram of radium. Right: Marie's notebooks are still stored in lead-lined boxes in France today because they were so contaminated with radium they are still highly radioactive and will be for many years.

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The idea of using radioactive elements to treat cancer probably also started with Becquerel's severe skin burn caused while accidentally carrying a tube of radium in his vest pocket for 14 continuous days in 1901.

In 1896, medical doctors had successfully used X-rays to treat stomach cancer in France, only a year after Roentgen's discovery of X-rays in 1895.

Doctors reasoned that the rays emanating from radium could also be used to treat cancers. In 1902, radium was successfully used to treat a patient with cancer of the throat in Vienna. By 1904, patients in New York were undergoing implantation of radium tubes directly into their cancerous tumours. The Standard Chemical Company began commercially marketing radium from its Colorado mines by 1913, and this new 'miracle wonder drug' subsequently found its way into many products and applications.

Hundreds of thousands of people drank radium-infused tonic water (Figure 3E–4), brushed their teeth with radium toothpaste, and wore radium cosmetics that gave their skin a bright, cheery glow. Incredibly to us now, Marie Curie's discovery of radium was treated as if it was just what was required for healthy living!

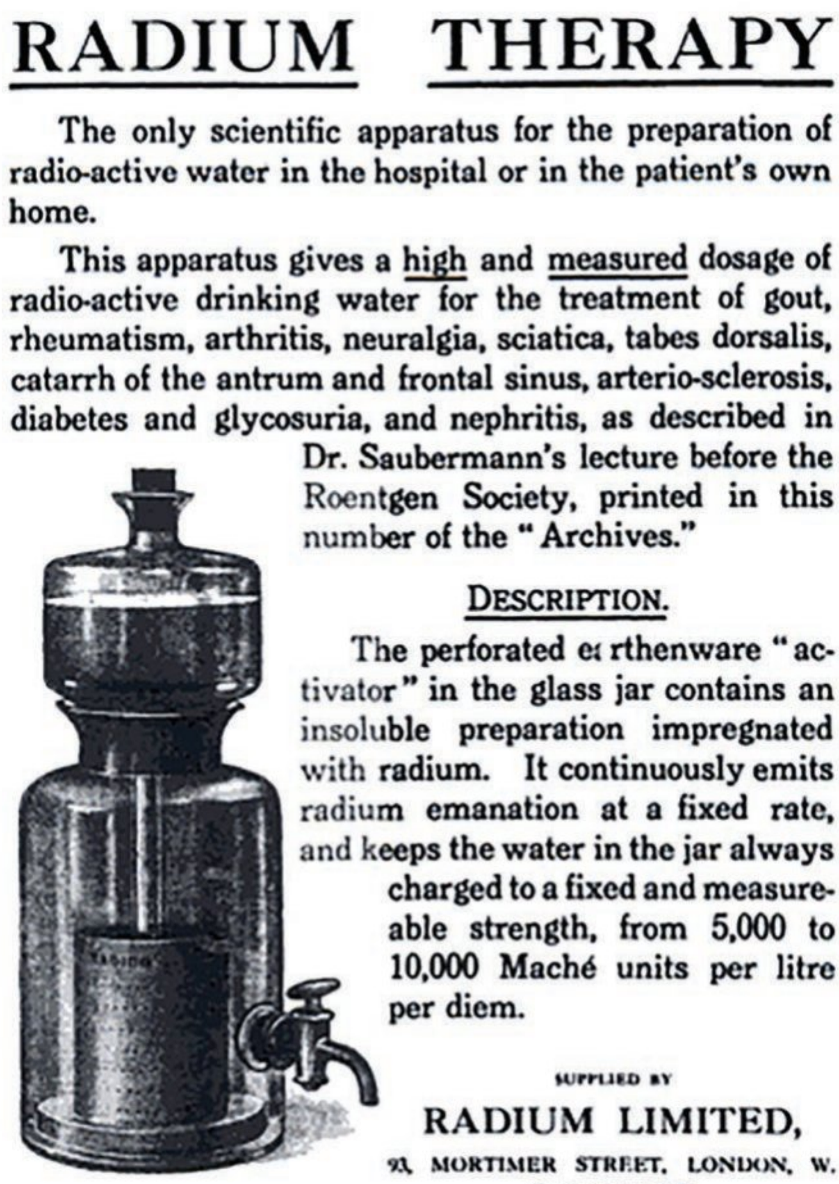

Figure 3E–4 Advertisement for making your own radium water to drink at home

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3B ALPHA, BETA AND GAMMA RADIATION LINK

Unfortunately, radium can be dangerous. Radium-226, which has a half-life of 1600 years, emits α-particles in all directions. A single gram of radium has an activity of 37 000 MBq, that is 3.7×10^{10} α-particles per second. As noted in Section 3B, α-particle radiations are capable of ionising a large number of atoms over their very short range of penetration. This makes α-particle radiation relatively harmless for most external sources that are about a metre or more away from us, as the radiation will be easily absorbed by the intervening air. But if the α-radiation sources are close to sensitive organs and tissues in the body then α-particle radiation becomes extremely dangerous.

The reason that ionising radiation is harmful to living beings is that it causes ionisation within the cells; that is, it creates ions that are chemically reactive. Such ions can immediately start undesirable chemical reactions in the cell, and possibly even cell death may occur. However, most cases of radiation damage to a cell affect the mechanism that regulates the division of cells. Therefore, the cell may lose the capacity to divide, either temporarily or permanently, or it may divide in an unexpected way. For example, an uncontrolled division of cells may result in the production of a large mass of such cells – a cancerous tumour.

The capacity of alpha, beta and gamma radiation to cause cell damage

Given all the radiation in our environment from both natural and artificial sources (Figure 3E–5), it is important to know how radiation might affect our health.

Our bodies are unable to sense lethal high intensity doses of radiation. This perhaps makes radiation more dangerous than other life-threating situations because it is impossible to detect without using specialised radiation detection equipment (e.g. a Geiger counter).

The damage done to living systems when α-particles, β-particles or γ-rays strike tissue, cells or molecules is that it significantly alters them. For example, if the radiation alters the molecular structure, then the damaged cells may no longer carry out their proper function. Molecules, such as DNA, may get damaged and no longer carry the correct information. In most cases, the radiation will damage a small number of cells by breaking the cell wall or otherwise preventing a cell from reproducing. Obviously, large amounts of unplanned radiation are very dangerous and often deadly. If for medical reasons large radiation doses are recommended, then it has to be precisely targeted to minimise damage to neighbouring cells.

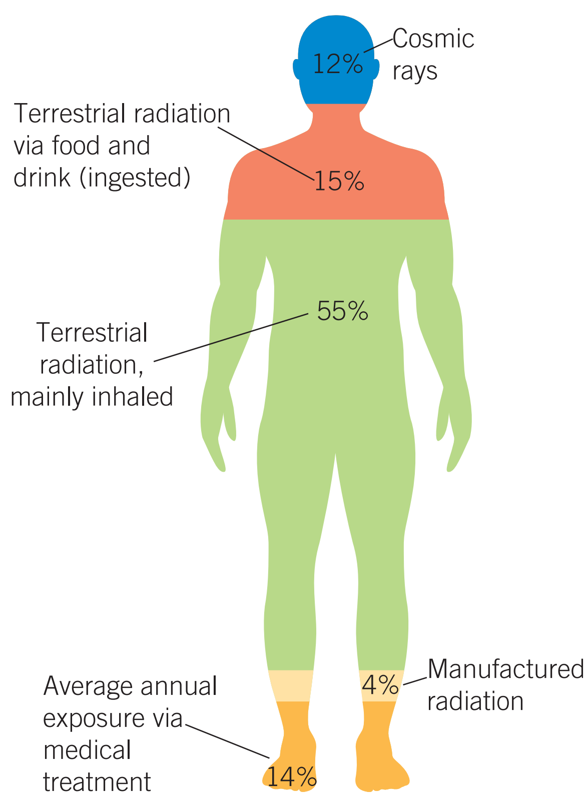

Figure 3E–5 About 82% of the average annual radiation that people receive comes from natural sources.

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Radiation can interact with DNA directly and cause damage by breaking the bonds in the DNA or indirectly by breaking water molecules surrounding the DNA (on average ~60% of our body mass is water). When these water molecules are broken, they produce ions – for example, unstable oxygen molecules that can damage cells and organs.

Once a cell is damaged, there are three likely outcomes (Figure 3E–6).

1 If the damage is not too severe, the cell repairs itself and would go back to normal.
2 If the cell damage is not repaired or is incorrectly repaired, then this change may eventually lead to a tumorous cancer.
3 If there is too much damage to the cell, then the cell dies.

Cell death is not always a bad option. If a few radiation-damaged cells die, your body will recover and you do not have the risk of those cells potentially turning into cancer. However, widespread cell death, such as that caused by high radiation doses, can lead to organ failure and ultimately death.

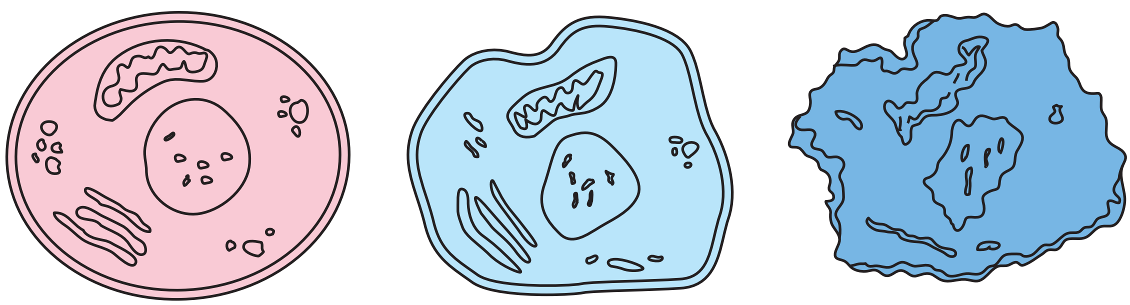

Figure 3E–6 Possible outcomes of cells exposed to ionising radiation

The ability of radiation to damage tissue, cells, organs and molecules relates to the ionising power and penetration of the radiation.

Alpha particles are highly ionising and have a short range (being stopped by skin or paper). Beta particles are less ionising and more penetrating but can be stopped by aluminium ~2 mm thick. Gamma rays are very penetrating and easily pass through the human body. Lead ~5 cm thick or concrete ~1 m thick will absorb 97% of the γ-rays (Figure 3E–7).

Lead aprons, lead thyroid shields and lead eyeglasses are therefore considered essential for medical personnel working with any form of penetrating radiation (see Figure 3E–8). Gamma rays and X-rays are both highly penetrating forms of radiation.

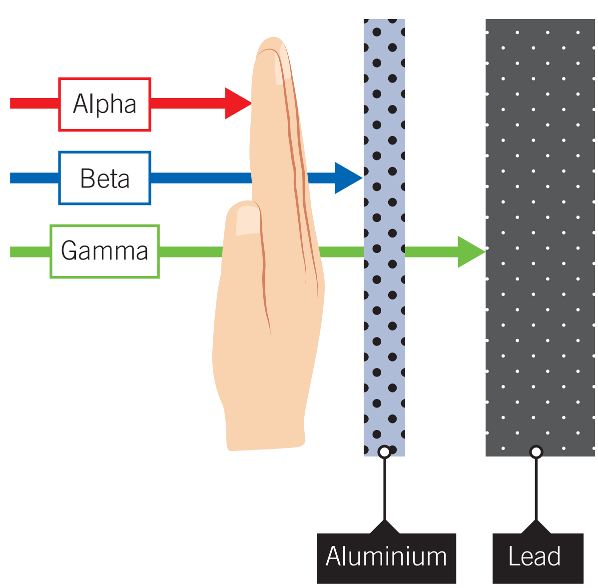

Figure 3E–7 Relative approximate penetration of alpha particles, beta particles and gamma rays

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Figure 3E–8 Veterinary personnel working with X-ray machines wearing lead aprons to protect against radiation

Table 3E–1 compares the penetration, ionising ability and shielding required for α-particles, β-particles and γ-rays.

Table 3E–1 Comparison of the penetration, ionising ability and shielding required for α-particles, β-particles and γ-rays

Particle	Symbol	Penetration	Ionising ability	Shielding
Alpha	α	Very low	Very high	Paper, skin
Beta	β	Intermediate	Intermediate	Aluminium 2 mm
Gamma	γ	Very high	Very low	Lead 5 cm

Comparing the three types of ionising radiation, α-particles have the highest ionising power and the greatest ability to damage tissue. Conversely that also means that α-particles are less able to penetrate matter. This means the threat of cell damage from α-particle radiation is very small from external sources. However, if the α-emitters are inhaled or taken in with food or water then there is very little protection (refer back to the Engage box for this section).

Events like a nuclear explosion or nuclear accident, where radioactive α-emitters are spread in the environment, are therefore extremely dangerous to all life forms because the radioactive particles become part of the food chain (see Chernobyl nuclear accident in Chapter 4).

CHAPTER 4 LINK

β-particles have much less ionising power and hence less ability to damage tissue than α-particles. However, this gives β-particles much greater penetration than α-particles. β-particles can be stopped by a sheet of aluminium a few millimetres thick. Once again, the greatest danger occurs when the β-emitters are inhaled or taken in with food or water as there is then very little protection (see strontium-90 in Chapter 4).

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Gamma rays are a very high frequency form of electromagnetic radiation. Gamma rays have very high penetration and require ~ 5 cm of very dense material (like lead) to shield them. Gold would also be a suitable shield but, apart from specialist use by astronauts, is too expensive. Many γ-rays may pass all the way through a human body without striking anything, but when they do hit they have enough energy to cause cell death. This is the process adopted when targeting cancerous tumours with intense beams of γ-rays (see Section 3B – cobalt-60 γ-ray radiotherapy).

LINK 3B ALPHA, BETA AND GAMMA RADIATION

Naturally, except for medical treatment, the safest amount of radiation to the human body is zero. However, it is not possible to be exposed to absolutely no ionising radiation as we are all subject to background radiation, so the way to minimise risk is to be exposed to as little radiation as possible. The best ways to minimise exposure are to limit the time of radiation exposure, increase distance from the radioactive source and use appropriate shielding.

Check-in questions – Set 1

1. What are the three possible outcomes once a cell is damaged by nuclear radiation?
2. Why do medical personnel working with radiation wear lead aprons and lead thyroid shields?
3. Specify the relative ionising power and penetration for each of α-, β- and γ-radiation using the terms least, medium and most.
4. Which form of radiation (α, β or γ) requires the most shielding? Why?

Radiation doses

Our bodies are unable to sense high-intensity doses of radiation. For example, a dose of gamma radiation large enough to be lethal to a human being would only increase the body temperature by about one thousandth of a degree Celsius. In fact, without specialised radiation detection equipment such as **Geiger counters** (Figure 3E–9), we would be blissfully unaware that we were in a life-threatening situation.

Geiger counter an instrument for detecting the presence and intensity of ionising radiations

Figure 3E–9 Using a Geiger counter, a yellow-suited hazmat crewmember checks for radioactivity in toxic waste drums disposed of in the desert.

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NOTE

Geiger counters are suitable for measuring α-, β- and γ-radiation. Their maximum capacity is about 10 000 particles per second (10 kBq). They can be made in portable versions and are very useful, for example, in monitoring radiation in factories and hospitals, monitoring radiation leaks, and searching for radioactive geological formations.

Dosimeter an instrument that measures personal exposure to ionising radiation over a given time period

Geiger counters are devices for measuring radiation. They provide real-time measurement of the activity of radioactive isotopes. For people working in radiation environments, there are various dosimeters. A radiation **dosimeter** does not provide protection against radiation exposure but instead detects and measures radiation that you already have been exposed to. These are monitored to ensure that people working in radiation environments do not exceed their annual limits. They are specifically designed to detect high-energy beta, gamma or X-ray radiation.

The optically stimulated luminescence (OSL) monitor measures potential occupational doses from γ- and X-rays.

Figure 3E–10 An OSL monitor is used by radiation workers for monitoring personal levels of radioactivity.

In all situations involving ionising nuclear radiation (e.g. medical, industrial, scientific, nuclear reactors, nuclear accidents and environmental studies for example) it is important to be able to determine the exact doses of radiation being emitted by the radioactive sources and the exact doses being received at the target areas. The source needs to be clearly labelled and identified, the amount of radioactive material specified, its half-life and activity known and/or determined, as well as the type(s) of radiation it is emitting.

Absorbed dose the amount of energy absorbed by each kilogram of tissue that is irradiated; measured in grays (Gy)

Gray (Gy) the SI unit of the absorbed dose of ionising radiation, corresponding to 1 J kg^{-1}

Sievert (Sv) the SI unit of dose equivalent (the biological effect of ionising radiation), equal to an effective dose of a joule of energy per kilogram of recipient mass

Dose equivalent dose equivalent (Sv) = absorbed dose (Gy) × radiation weighting factor

Measuring radioactivity and radiation

Physicists use three different units to quantify radioactivity and radiation.

The activity of a given radioactive source is measured in becquerels (Bq), which represents the number of nuclear transformations occurring per second.

Ionising radiation loses energy in any matter it travels through. The measure of the radiation energy that is absorbed at the target site is called the **absorbed dose** – the energy absorbed per kilogram of an irradiated object at the actual target site. The unit used is the **gray (Gy)**, where 1 Gy = 1 J kg^{-1}.

The amount of damage 1 Gy of absorbed dose does to the body depends on the nature of the radiation. For example, α-particles are 20 times more damaging than γ-rays or β-particles. To quantify the potential of radiation to damage – and ultimately kill – cells, physicists use the **sievert (Sv)**, which is a measure of the **dose equivalent** (the biological effect of ionising radiation).

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The radiation weighting factor

The number of ionisations in a cell for a given dose of radiation is much greater for α-radiation than for either β- or γ-radiation. To ensure that the effects of different types of radiation are taken into account, the **radiation weighting factor** is used. This is a form of weighting that takes into account the biological damage caused by the radiation. For both β- and γ-radiation, the radiation weighting factor is 1. An absorbed dose of 1 μGy of β- or γ-radiation has a dose equivalent of exactly 1 μSv. For the more strongly ionising α-radiation, the radiation weighting factor is 20; the same absorbed dose of 1 μGy of α-radiation has a radiation dose equivalent of 20 μSv.

$$\text{dose equivalent (Sv)} = \text{absorbed dose (Gy)} \times \text{radiation weighting factor}$$

Radiation weighting factor a factor by which the absorbed dose (Gy) is to be multiplied to obtain a quantity that expresses, on a common scale for all ionising radiation, the biological damage (Sv) to an exposed individual

NOTE

Equivalent dose is calculated for the whole body. This is the most frequently used dose in radiological protection.

Worked example 3E–1 Radiation dose

A 60 kg adult absorbs 180 mJ of energy due to ionising radiation.

a Calculate the absorbed dose in mGy.

b **i** Calculate the dose equivalent, in mSv, if the radiation is γ-radiation.

ii Calculate the dose equivalent, in mSv, if the radiation is α-radiation.

Solution

a $$\text{absorbed dose} = \frac{180 \times 10^{-3}}{60}$$

$$= 3 \times 10^{-3}$$

$$= 3 \text{ mGy}$$

b **i** γ-radiation has a radiation weighting factor of 1.

$$\text{dose equivalent (Sv)} = \text{absorbed dose (Gy)} \times \text{radiation weighting factor}$$

$$= (3 \times 10^{-3}) \times 1$$

$$= 3 \times 10^{-3}$$

$$= 3 \text{ mSv}$$

ii α-radiation has a radiation weighting factor of 20.

$$\text{dose equivalent (Sv)} = \text{absorbed dose (Gy)} \times \text{radiation weighting factor}$$

$$= (3 \times 10^{-3}) \times 20.$$

$$= 60 \times 10^{-3}$$

$$= 60 \text{ mSv}$$

There are also different risk-weighting factors for different parts of the human body.

Organs in which many cell divisions occur, such as bone marrow or lungs, are more vulnerable to radiation damage. This gives rise to the notion of **effective dose**.

Effective dose applies to a specific organ or organs

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Figure 3E–11 shows some relative risk-weighting factors for the human body.

A given effective dose equivalent of radiation is four times more likely to cause a possibly fatal cancer in the lungs than in the thyroid gland (0.12:0.03). Note that our reproductive organs (ovaries and testes) are very sensitive to radiation damage. This has important medical implications when using radiation therapy to treat testicular cancer in men and ovarian cancer in women, as the side-effects from medical radiation exposure can functionally impair the testes and ovaries and significantly reduce the quality of life.

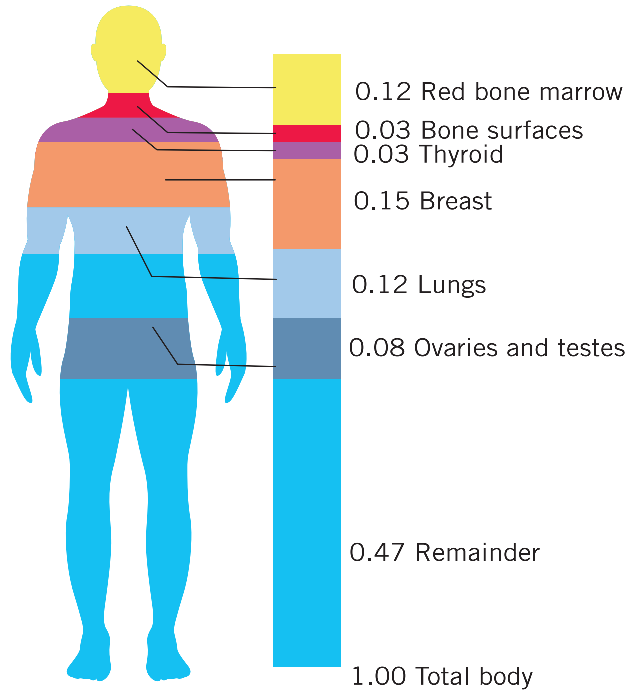

Figure 3E–11 Various parts of the body have different radiation weighting factors. The numbers are decimal fractions of the whole (1.00). This leads to the notion of equivalent dose for the whole body.

Equivalent dose is calculated for the whole body. It is the addition of effective doses to all organs, each adjusted to account for the sensitivity of each organ to radiation.

Equivalent dose is given in sieverts (Sv) or, more frequently, millisieverts (mSv). This is the most frequently used dose in radiological protection. Unless you see mention of a specific organ, a 'dose' in Sv or mSv is the effective dose.

In the simplest cases, for uniform whole-body exposure to γ-radiation or β-radiation, the radiation weighting factor is 1, and the tissue weighting factors add up to 1. Therefore, for example, an absorbed dose of 1 mGy equals an equivalent dose of 1 mSv.

Check-in questions – Set 2

1 Which of our five senses tells us that we are experiencing a lethal dose of γ-radiation?

2 a What are the units for absorbed dose, dose equivalent and effective dose?

  b What are the definitions for absorbed dose, dose equivalent and effective dose?

3 Alpha radiation has a radiation weighting factor of 20. What is the dose equivalent for an absorbed dose of 20 mGy?

Short- and long-term effects of low and high doses

Somatic effects arise when ordinary body cells are damaged, and the effect depends on the size of the dose. Very high doses lead to almost immediate symptoms, whereas lower doses could lead to symptoms developing years later. The period between the initial exposure to radiation and the appearance of the damage is called the latent period. If the dose is more than 1 Sv (1000 mSv), then symptoms of radiation illness such as nausea, headaches, vomiting and diarrhoea can occur within a few days. These are short-term effects.

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The effects of lower doses may not be observed for a few decades. The effects of radiation that appear months or even years after exposure to radiation are called delayed effects or long-term effects. The most important delayed effects are leukaemia and the formation of cancerous tumours. Table 3E–2 shows the effects of whole-body radiation doses.

Table 3E–2 Effects of various radiation doses

Whole-body dose (Sv)	Symptoms
<1	Non-fatal Only minor symptoms such as nausea White blood cell level drops
2	Death unlikely in most cases Radiation sickness, i.e nausea, vomiting, diarrhoea Skin burns, possible hair loss Bone marrow damage
3–5	50% likelihood of death within 1–2 months Severe radiation sickness High probability of leukaemia and tumours for survivors
8	Almost certain death within 1 or 2 weeks Acute radiation sickness, convulsions, lethargy

Acute effects

Most of the acute effects of radiation can become evident hours, days and months after a single-dose exposure to the entire body. Acute radiation syndrome (ARS), also known as radiation sickness or radiation poisoning, is a collection of health effects that are caused by being exposed to high amounts of ionising radiation in a short period of time. Apart from damage to the reproductive organs and the lens of the eye (which is also very susceptible to radiation), there will be damage to bone marrow, the gastrointestinal system and the central nervous system. Dose equivalents greater than 8.0 Sv are normally lethal to humans (Figure 3E–13).

Figure 3E–12 Radiation burns on a Hiroshima atom bomb survivor

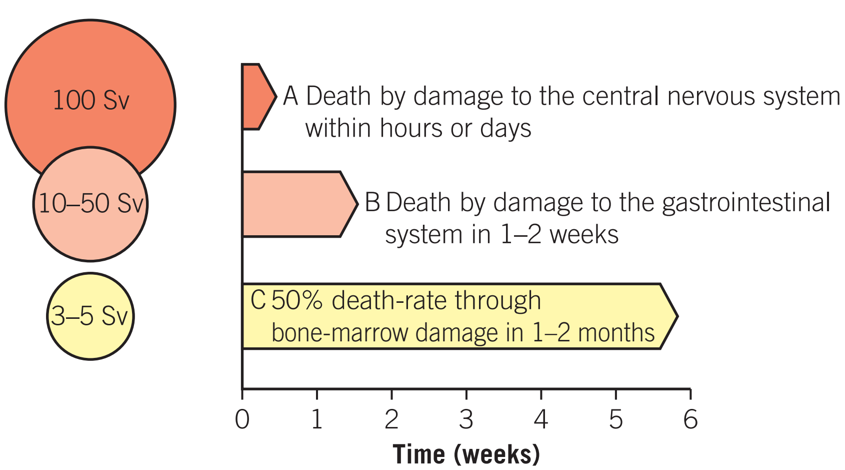

Figure 3E–13 The whole body dose radiation received in sievert (Sv) for acute effects and their associated symptoms

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Radiation standards

The relationship between the radiation dose received and its effect on humans is not a simple one. The International Atomic Energy Agency (IAEA) has published a graph of the **dose–risk relationship** currently used for radiation protection purposes Figure 3E–14. This graph shows the probability of incurring a severe radiation effect versus the dose of radiation received and is based on existing radiobiological data. However, many scientists do not agree with the shape of the curve in the low-dose region. Some argue that any radiation, even a minute amount, is undesirable and can cause harmful effects. Others argue that there is a certain threshold of radiation that all humans can tolerate before it becomes dangerous.

Dose–risk relationship the probability of incurring a severe radiation effect versus the dose of radiation received

NOTE

To obtain an accumulated 1 Sv dose of radiation, you would need to receive an average of 15 times the normal annual background radiation dose of 2.3 mSv for a period of about 30 years.

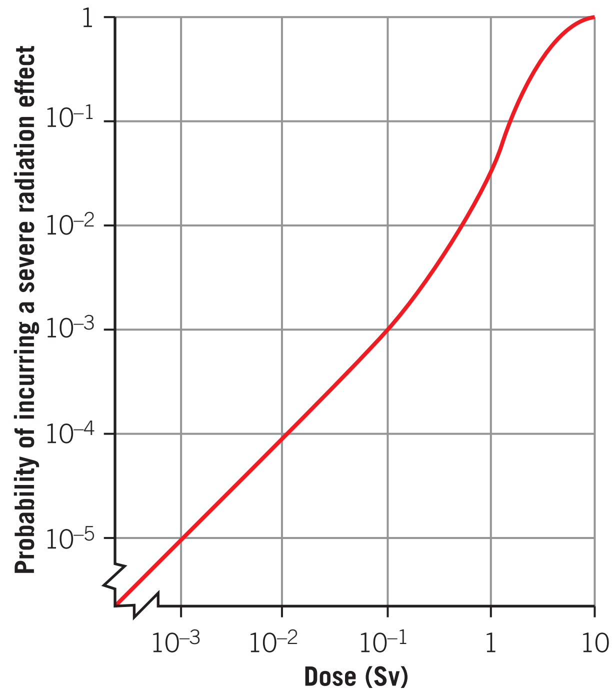

Figure 3E–14 The dose–risk relationship used for the protection of workers in radiation industries. A dose of 100 mSv (10^{-1} Sv) implies a 1 in 1000 probability of a severe effect, and a 1 Sv dose implies a 1 in 50 chance of a severe radiation effect (note the scales used are increasing by a power of 10 each time).

The International Commission for Radiological Protection (ICRP) currently recommends a whole-body dose limit of 1 mSv per year for members of the general public and for workers in the radiation industry 20 mSv per year averaged over 5 years, and not more than 50 mSv received in any one year for effective (whole body) dose. That is, workers in the radiation industries can receive 20 times the dose that members of the public receive per year.

These dose limits are in addition to the natural background radiation that we all receive (approximately 2.3 mSv per year). The ICRP argues that this dose limit standard gives a probability of 1 in 100 000 for a member of the general public dying and 1 in 5000 for a radiation industry worker dying from radiation-induced illnesses over a 30-year period.

Genetic effects

Genetic effects chromosome aberrations and genetic mutations resulting from exposure to radiation

It is difficult to accurately assess the **genetic effects** of radiation on humans. It may be many generations before genetic effects become apparent (for humans, perhaps 50–200 years); there is little reliable data available and many of the genetic defects noted are hard to directly link to radiation exposure.

There are two main known genetic effects of radiation:

- chromosome aberrations involving changes in the actual number or structure of the chromosomes
- genetic mutations involving an alteration of the nucleotide sequence of a gene, which can lead to birth defects in future generations.

Results from work done on other animal species suggest that an accumulated 1 Sv dose of radiation on human populations will cause between 1000 and 2000 severe genetic mutations, and up to 1000 severe effects due to chromosome aberrations, per million births.

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Long-term studies of more than 27 000 children of parents exposed to relatively high doses from the nuclear bombs dropped at Hiroshima and Nagasaki are inconclusive. It may be a number of generations before any substantial conclusive evidence is available.

Although we know that the Simpson's three-eyed Blinky is a fictional fish found outside in the cooling ponds of Mr. Burns nuclear power plant there is considerable research going into real genetic effects associated with nuclear reactor accidents at Chernobyl and Fukushima. The effects of the nuclear disaster in Fukushima have now become visible in deformed butterflies (Figure 3E–15). Researchers worry similar genetic radiation effects may soon start to be seen among humans.

Figure 3E–15 The butterflies found to be deformed as a result of radiation from the nuclear meltdown in Fukushima belong to the butterfly family of gossamer-winged butterflies.

Check-in questions – Set 3

1 What is meant by the term latent period when referring to the effect of nuclear radiation on humans?
2 What are some common short-term effects of radiation doses > 1 Sv?
3 What are some common long-term effects of radiation doses > 4 Sv?

External and internal radiation

Radiation irradiates us (bathes us in radiation) in one of two distinct ways. If the radiation source remains outside the body and irradiates us from the outside, then it is said to be **external radiation**. If the radiation source is inhaled into our lungs via the air or is swallowed when eating or drinking, it irradiates us from inside our bodies and is said to be **internal radiation**.

External radiation the radiation source remains outside the body and irradiates us from the outside

Internal radiation the radiation source irradiates us from inside our bodies

This is a useful distinction to make when discussing radiation and its effect on people as the different properties of various types of radiation make them more or less dangerous, depending on whether they are external or internal sources.

Alpha particles, beta particles and gamma rays are all ionising. The reason is that ionising radiation is harmful to living beings is because the radiation has enough energy to break the bonds of molecules within the cells. For example, a gamma ray has enough energy to break the bonds of a water molecule (Figure 3E–16). This creates chemically reactive ions (OH^- and H^+), which in turn may lead to an uncontrolled division of cells resulting in the production of a large mass of such cells – a cancerous tumour.

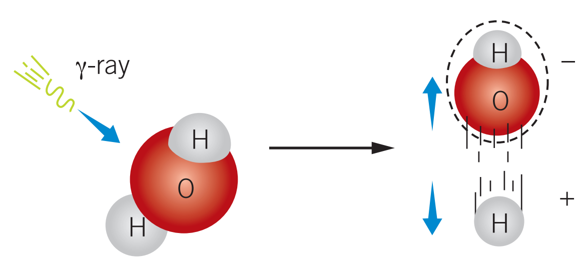

Figure 3E–16 A γ-ray hitting a water molecule has enough energy to break the bonds and form an OH^- and an H^+ ion.

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Check-in questions – Set 4

1 What is the difference between external and internal exposure to nuclear radiation?
2 Which of α-, β- and γ-radiation are ionising forms of radiation?
3 Why can ionising radiation be harmful to humans?

Nuclear medicine

Nuclear radiation is a powerful tool in modern medicine, both as an aid to diagnosis (finding out the problem) and as a means of treatment. In medical diagnosis the strategy is to keep the radiation dose extremely small while gaining the maximum information.

Small amounts of short-lived radioactive isotopes are injected, taken orally or inhaled by the patient. The radioisotope then circulates through the body or is taken up only by certain tissues. Its distribution can be tracked according to the radiation it gives off.

The emitted radiation can be captured by various imaging techniques, such as single photon emission computed tomography (SPECT) or positron emission tomography (PET), depending on the radioisotope used. Through such imaging, physicians are able to examine blood flow to specific organs and assess organ function or bone growth. The radioisotopes used typically have short half-lives and decay before their emitted radioactivity can cause damage to the patient's body.

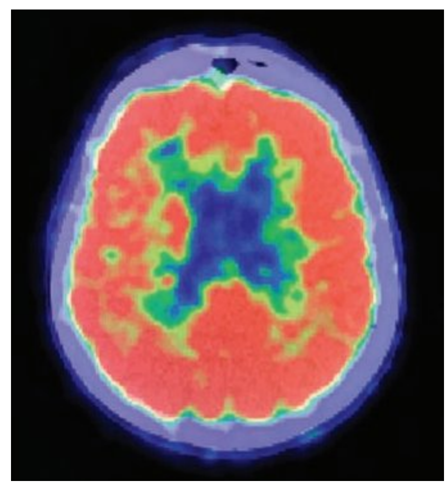

Figure 3E–17 A PET scan of a patient's brain used in diagnosing the severity of Alzheimer's disease

PET scans

When a positron meets an electron, there is complete annihilation and two γ-rays are produced. This forms the basis of PET scans. These are very useful in a variety of different medical brain scans (Figure 3E–17).

Radiotherapy a strategy to target cancerous tumours with maximum effect by using large doses of lethal (to the targeted cells) radiation while minimising collateral damage to healthy cells

In **radiotherapy** the strategy is to target cancerous tumours with maximum effect by using large doses of lethal (to the targeted cells) radiation while minimising collateral damage to healthy cells.

Radioactive iodine-123 (diagnostic) and radioactive iodine-131 (therapy)

Two different isotopes of iodine are used for diagnosis and treatment of the thyroid gland. Iodine, in the form of iodide, is made into two radioactive isotopes that are commonly used in patients with thyroid diseases: iodine-123 (which is relatively harmless to thyroid cells) and iodine-131 (which destroys thyroid cells).

To accurately diagnose the functioning of the thyroid, the best radioactive isotope to use is iodine-123, a γ-ray emitter with a radioactive half-life of 13 hours. The thyroid has a great affinity for iodine. In order to check the function of a patient's thyroid gland, iodine-123 is injected into the bloodstream. If after one hour as much as 98% of the radioactive iodine is collected in the thyroid, and it is evenly distributed, then the gland is functioning normally. If the gland is not functioning properly, then it may be taking up the iodine-123 more quickly (an overactive thyroid condition) or more slowly (an underactive thyroid condition). If the iodine-123 is not evenly distributed throughout the gland, it probably indicates that the thyroid gland contains a cancerous tumour.

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The diagnostic radiologist measures the uptake rate and the distribution of radioactive iodine-123 by moving a γ-ray detector slowly across the thyroid gland. The intensity of the radiation emitted by the radioactive iodine-123 in the thyroid is measured at numerous points, as a function of time. The distribution of the radiation is then normally represented using 'false' or enhanced colours (Figure 3E–18).

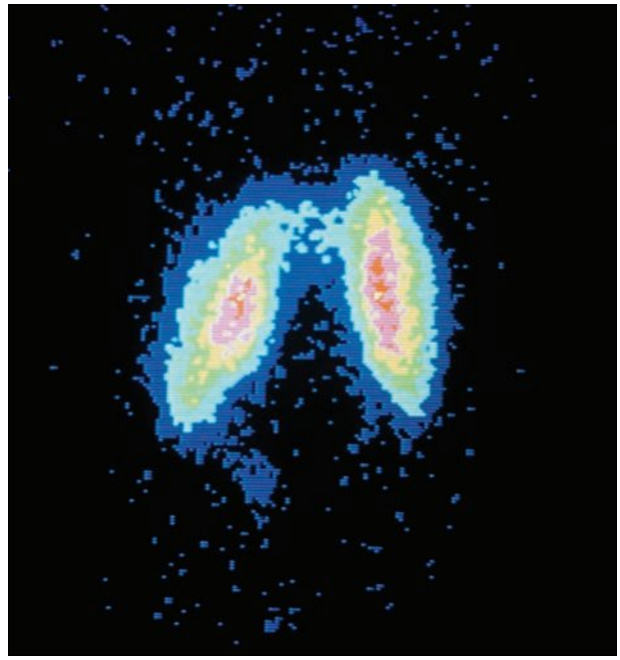

Figure 3E–18 A common radiotracer used in nuclear medicine diagnosis is the iodine-123 isotope, which emits γ-radiation. The image is captured by SPECT. This image shows a completely healthy thyroid gland.

In the treatment of cancer of the thyroid gland a radiopharmaceutical containing another iodine isotope, radioactive iodine-131, is taken orally.

Again, most of this iodine will end up at the thyroid gland. Iodine-131 is both a β- and γ-emitter with a half-life of 8 days. The β-particles, with their relatively low penetrating ability, irradiate only the tissue within the thyroid gland and destroy the cancerous cells, while the γ-rays are able to penetrate the patient's body. This obviously exposes the healthy body cells to some γ-radiation but has the side benefit of allowing the medical treatment to be externally monitored with a gamma ray camera.

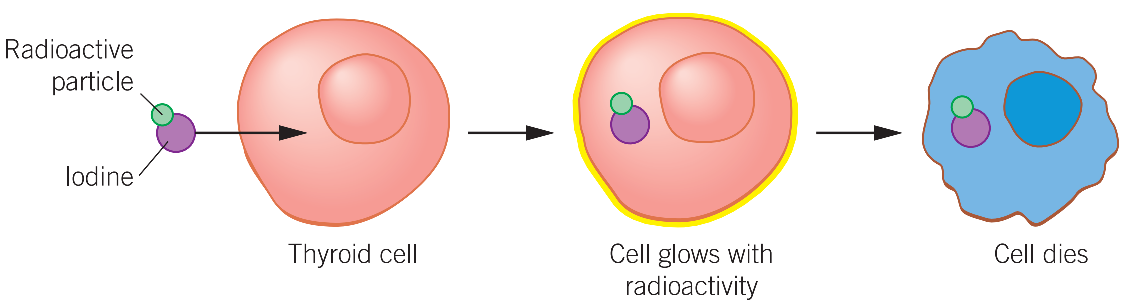

Figure 3E–19 Radioactive iodine-131 enters a living cell and 'glows' with γ-radiation until the cell dies from the beta radiation.

Radiation therapy

In radiation therapy the strategy is to deliver a lethal radiation dose to a selected site while keeping the dose to surrounding areas at a minimum. The most common methods involve selecting radioactive isotopes that are organ specific, or using shielding and rotation techniques to target specific sites.

In Australia, approximately 50 000 deaths each year are attributed to cancer-related causes. The probability of surviving cancer depends on two things: early detection and the type of cancer. If the cancer is detected early enough, then the probability of survival could be good, depending on the type of cancer detected. For example, early detection of breast cancer leads to an average 5-year survival rate of 91%.

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The usual methods employed for treating cancer are surgery, chemotherapy (the use of radiopharmaceuticals), irradiation (the use of radiation beams, Figure 3E–20) or a combination of these methods. For example, the surgical removal of a tumour is often combined with medical radiation technology that destroys the new cancerous growths.

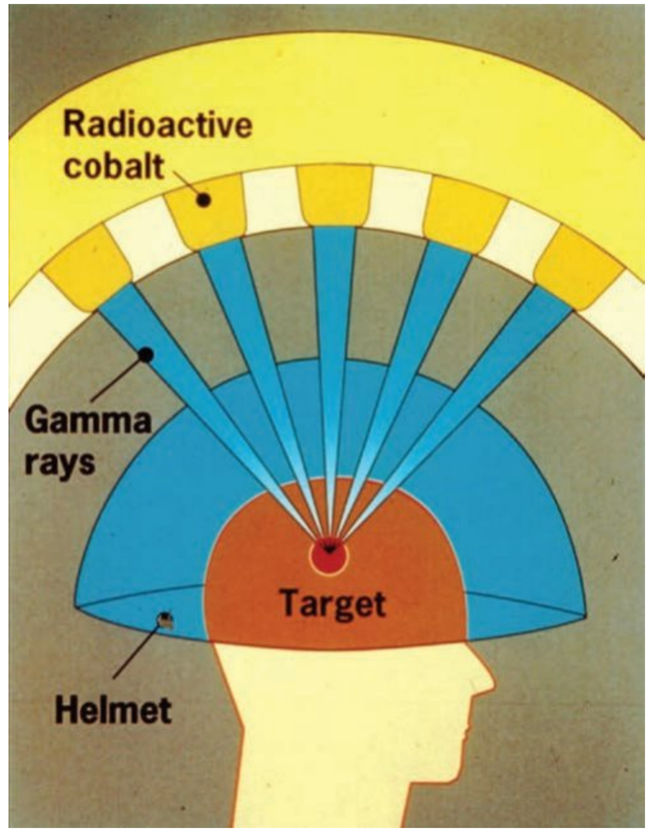

Figure 3E–20 Stereotactic radiosurgery (SRS) is a type of radiotherapy that allows precise and high-dose radiation beams to be delivered to a small, localised area of the body, mostly in the brain to destroy a cancerous tumour.

It is obvious that in diagnostic applications of medical radiation the objective is to minimise radiation damage. However, in the treatment of cancers the purpose is to cause cell damage, to reduce the growth of tumour cells or to kill them.

Most people receive only a relatively small amount of artificial radiation as a result of medical intervention. A few people, because of their particular diagnosed cancers, receive thousands of times the radiation dose they would receive from all other sources combined. In these very high-dose cases medical radiographers plan their treatment using the principle of acceptable risk. This principle involves radiographers carefully weighing the advantages and disadvantages to the patient of using radiation treatment as well as the consequences of treatment. Although in many cases the dose of radiation may cause some permanent damage to the patient (e.g. hair loss and reduced resistance to disease for example), it may be the only possible means of realistically attempting to save their lives.

The production of abnormal cells as a result of cell damage can be due to many things, including exposure to carcogenic (cancer-causing) materials like asbestos, smoke and radon gas. The abnormal cells can reproduce in a rapid and uncontrolled manner, usually resulting in the formation of a lump or tumour. These lumps are considered to be cancerous if they continue to grow or spread throughout the body.

Cancerous cells do not perform the tasks required of healthy cells. They are dysfunctional cells. As the number of abnormal cells increases, debilitating biological problems can arise as the body struggles to function normally.

Fortunately, cells that are rapidly reproducing (such as cancerous cells) are much more sensitive than normal cells to radiation (Figure 3E–21). Therefore, techniques that irradiate specific sites of cancerous cells can be used to administer doses that are effectively up to 1000 times greater than the radiation dose received by neighbouring healthy cells.

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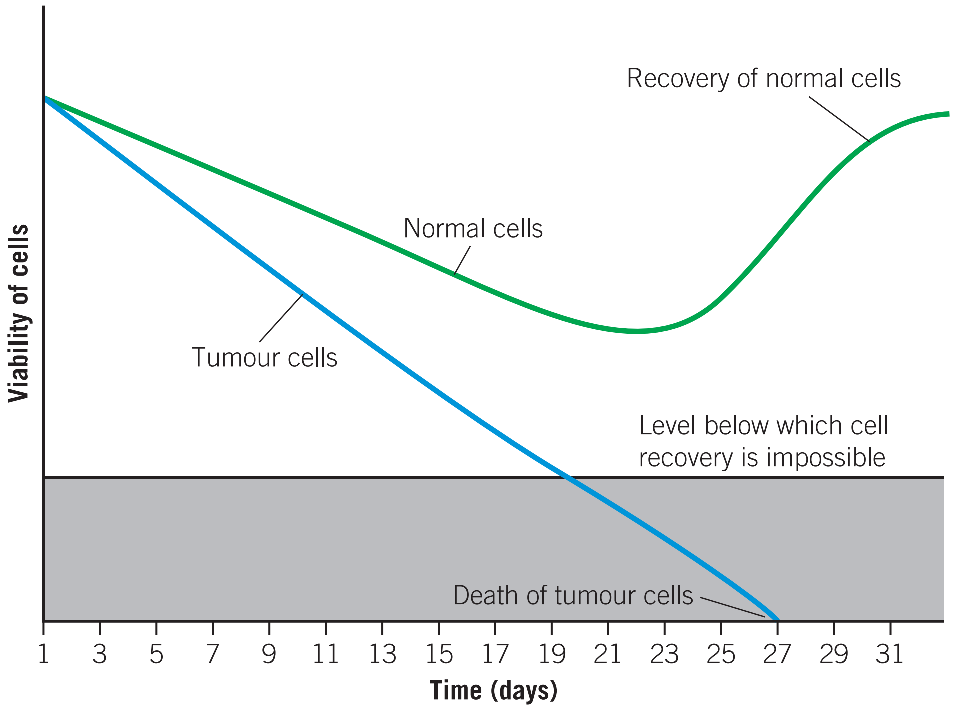

Figure 3E–21 These graphs show the effect of a fractionated radiation treatment plan on both normal and tumour cells. The total radiation dose (e.g. 20 Gy) is split into ten doses each of 2.0 Gy, which is administered every second day for 10 days.

WORKSHEET 3E–1 THE EFFECT OF RADIATION ON HUMANS

Check-in questions – Set 5

1 What is the strategy in using radiation doses for medical diagnosis?
2 What is the strategy in using radiation doses for medical therapy?
3 Why are cancerous cells more sensitive to radiation than normal cells?

3E SKILLS

VIDEO 3E–2 SKILLS: IDENTIFYING EXACT MEANING FOR KEY TERMS

Identifying exact meaning for key terms

In detecting and measuring radioactivity and radiation, there are many terms that have very specific meanings. It is important to note all of these terms and their specific definitions. One way of doing this is to create a specific glossary of definitions for areas of study that introduce many new terms, such as this section.

As noted previously to *define* is to state the precise meaning of the terms. For example, if you were asked to define 'absorbed dose (gray)', then the following definition might appear in your glossary of notes in this section.

Definition: The measure of the radiation energy that is absorbed at the target site is called the *absorbed dose* – the energy absorbed per kilogram of an irradiated object at the actual target site. The unit used is the *gray (Gy)*, where 1 Gy = 1 J kg^{-1}.

In this section you should have learned what Geiger counters and dosimeters are, what they do and what their similarities and differences are.

Similarly you should know, apart from the gray, what the other measurement units – becquerel (Bq) and sievert (Sv) – are and where and when they are used. Also, your glossary for this section should include where and when the terms *activity, absorbed dose, dose equivalent, radiation weighting factor* and *effective dose* are used.

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Section 3E questions

Multiple-choice questions

1 Which type of human tissue is most sensitive to ionising radiation?
- A tissue of the lower limb
- B tissue with cells that divide quickly
- C tissue that receives the largest dose
- D tissue with cells that no longer divide

2 What type of device is used to monitor radiation levels for people working in radiation environments?
- A dosimeter
- B thermometer
- C gamma camera
- D a radio receiver

3 Which one of the following units is used to measure the dose equivalent?
- A becquerel
- B gray
- C sievert
- D joule

4 How much energy, absorbed via γ-rays, would cause the death of a 60 kg person within 50 hours due to a radiation exposure dose of 40 Sv?
- A 120 J
- B 1200 J
- C 2400 J
- D 3000 J

Short-answer questions

5 a What were the names of the two new elements Marie Curie discovered?
  b What was dangerous about these new elements?

6 Why is it more dangerous for pregnant women to be exposed to high radiation levels than for other people?

7 Gold is a very good shield for α-, β- and γ-radiation and is less poisonous than lead. Why don't medical personnel working with radiation wear gold aprons, gold thyroid shields and gold glasses?

8 Alpha radiation has a radiation weighting factor of 20. What is the dose equivalent for an absorbed dose of 15 mGy?

9 A 20 kg child absorbs 40 mJ of energy due to ionising radiation.
  a Calculate the absorbed dose in mGy.
  b i Calculate the dose equivalent, in mSv, if the radiation is γ-radiation.
    ii Calculate the dose equivalent, in mSv, if the radiation is α-radiation.

10 Radium is a very strong emitter of α-particles. One gram of radium has an activity of 37 GBq (3.7×10^{10} Bq). Each α-particle emitted has an energy of 4.6 MeV.
  a Calculate the total energy per second released by 1 g of radium in MeV and in J.
  b What is the power of 1 g of radium in W?
  c Calculate how much energy (J) 1 g of radium would release in 1 year.

11 Why can the formation of ions be damaging to living cells?

12 Ionising radiation can cause cancer, yet it also can cure cancer. Explain this apparent contradiction.

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Chapter 3 review

Summary

Create your own set of summary notes for this chapter on paper or in a digital document. A model summary is provided in the Teacher Resources, which can be used to compare with yours.

Checklist

In the Interactive Textbook, the success criteria are linked from the review questions and will be automatically ticked when answers are correct. Alternatively, print or photocopy this page and tick the boxes when you have answered the corresponding questions correctly.

	Success criteria – I am now able to:	Linked questions
3A.1	Know that nuclear stability depends on proton to neutron ratios	1☐, 2☐, 11☐, 12☐, 13
3A.2	Understand the roles of the electrostatic force, the strong nuclear force and the weak nuclear force	3☐, 14☐
3A.3	Know that electrostatic forces on protons in the nucleus are extremely large repulsive forces	13☐
3A.4	Know that the nucleus contains a short-range strong nuclear force that can overcome electrostatic repulsion forces	13☐
3A.5	Know that the weak force explains the transformation of protons into neutrons and vice versa	3☐
3A.6	Interpret the binding energy curve	15☐
3B.1	Know the properties of α-, β^--, β^+- and γ-radiation	4☐, 5☐, 16☐, 17☐, 18☐, 19☐, 20☐, 25☐
3B.2	Explain nuclear transformations using decay equations involving α-, β^--, β^+- and γ-radiation	19☐, 20☐
3C.1	Understand the concept of half-life for radioactive sources	6☐, 21☐, 22☐
3C.2	Determine the strength (activity) of radioactive sources after a whole number of half-lives have elapsed	10☐, 21☐, 22☐
3D.1	Analyse radioactive isotope decay chains (e.g. U-238) and understand that a decay series is a sequence of stages a radioisotope passes through before eventually reaching a stable isotope	7☐, 23☐
3E.1	Explain effects of α-, β^--, β^+- and γ-radiation on humans	10☐
3E.2	Understand the different capacity of α-, β^--, β^+- and γ-radiation to cause cell damage	24☐, 25☐, 26☐, 27☐, 28☐,
3E.3	Understand the short- and long-term effects of low and high doses of radiation	29☐, 30☐
3E.4	Understand the ionising impacts of external and internal radiation sources	9☐, 26☐
3E.5	Be able to calculate absorbed dose (gray), equivalent dose (sievert) and effective dose (sievert)	8☐
3E.6	Evaluate the use of medical radioisotopes in therapy including the effects on healthy and damaged tissues and cells	10☐, 22☐, 24☐, 25☐, 28☐, 29☐, 30☐

Multiple-choice questions

1 Uranium-234 has 92 protons in the nucleus. The number of neutrons in the nucleus is

A 92
B 142
C 234
D 326

2 The element carbon has a number of isotopes. Two isotopes of carbon are carbon-12 and carbon-14. Which one of the following statements is true?

A The two isotopes of carbon are physically identical but chemically different.
B The two isotopes of carbon are chemically identical but physically different.
C Carbon-14 has more protons in its nucleus than carbon-12.
D Carbon-14 has more electrons in its nucleus than carbon-12.

3 The weak force or weak interaction is used to explain

A α-decay.
B β-decay.
C γ-decay.
D none of the above.

4 A radioactive source is placed 2 cm from a detector. The count rate decreases slightly if a sheet of paper is inserted between the source and the detector. It is reduced to background radiation level if the sheet of paper is replaced by a 1 cm thick sheet of aluminium. The radiation emitted by the radioactive source is most likely to be

A α only.
B α and β.
C β and γ.
D γ only.

5 Which one of the following correctly identifies α-particles, β^--particles, β^+-particles and γ-rays?

	α-particles	β^--particles	β^+-particles	γ-rays
A	Helium nuclei	Electrons	Photons	Positrons
B	Electrons	Negative helium ions	Positive helium ions	Photons
C	Photons	Negative photons	Positive photons	Helium nuclei
D	Helium nuclei	Electrons	Positrons	Photons

6 The half-life of Zn-69 is 56 minutes. There is 100.0 g of Zn-69 initially. Which one of the following is closest to the number of grams that would be left after 168 minutes have elapsed?

A 12.5 g
B 25 g
C 50 g
D 100 g

7 A radioactive decay chain stops when the

A first parent radioisotope no longer exists.
B first daughter radioisotope no longer exists.
C last daughter radioisotope is a stable element.
D last daughter isotope is a stable element.

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8 A 50 kg person absorbs 200 mJ of energy due to ionising α-particle radiation. The dose equivalent is closest to

A 4 mGy
B 4 mSv
C 80 mGy
D 80 mSv

9 Which one of the following is not a use for ionising radiation?

A in radiotherapy
B to sterilise food
C microwave ovens
D as a tracer in the body

10 A point radioactive source is emitting γ-radiation in all directions. A Geiger counter measures a reading of 200 Bq at a distance of 1 m from the source. The Geiger counter reading at a distance of 2 m from the source

A will be less than 200 Bq.
B will be 200 Bq.
C will be more than 200 Bq.
D cannot be determined from the information given.

Short-answer questions

11 Use the periodic table (Figure 3A–4 or see page 551 of Appendix 2) and the internationally accepted format $^{A}_{Z}X$ to write the elements containing the following nucleons and name them as isotopes.

a 6 neutrons and 6 protons (1 mark)
b 15 protons and 31 nucleons (1 mark)
c 30 protons and 40 neutrons (1 mark)

12 The stability of any nucleus depends on the number of protons and neutrons in the nucleus. What is the approximate neutron/proton ratio for:

a small nuclei to be stable (1 mark)
b larger nuclei to be stable. (1 mark)

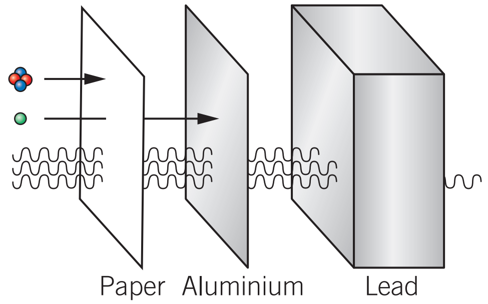
13 **a** What are nucleons? (1 mark)
b Explain how individual nucleons are held together in a nucleus, given that like charges repel. (2 marks)

14 **a** What particle was proposed by Wolfgang Pauli in 1930 to ensure that the law of conservation of energy held in radioactive beta decay? (1 mark)
b What were the properties of this hypothetical particle? (2 marks)

15 What is the binding energy of a nucleus? (2 marks)

16 From where in an atom are α- and β-particles and γ-rays emitted? (1 mark)

17 Label this diagram with the correct nuclear radiations. (3 marks)



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18 List the three types of radiation in order of:

a least ionising power to greatest ionising power (3 marks)

b least penetrating power to greatest penetrating power. (3 marks)

19 Americium-241 (Am-241) used in smoke detectors is made in the core of a nuclear reactor from plutonium-239 (Pu-239) when it captures 2 neutrons. The atomic number of americium is 95 and the atomic number of plutonium is 94.

a Write the nuclear transformation equation for making americium-241. (2 marks)

b Write the nuclear transformation equation for americium-241 when it decays via alpha decay to neptunium-237 (Np-237). (2 marks)

c Explain why alpha radiation emitters are used in preference to gamma or beta radiation emitters for smoke detectors. (2 marks)

20 **a** How is β^--decay of a nucleus possible when a nucleus does not contain any electrons? (1 mark)

b How is β^+-decay of a nucleus possible when a nucleus does not contain any positrons? (1 mark)

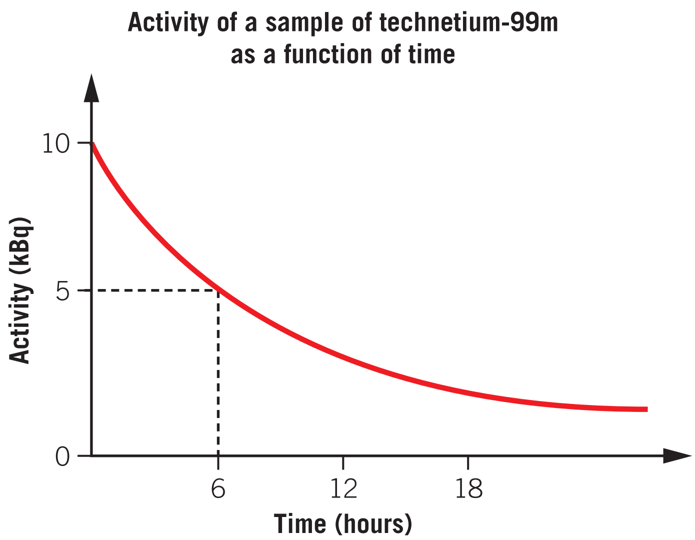
21 Uranium-238 decays via alpha decay. The half-life of U-238 is 4.5 billion years. A physicist is studying a rock sample containing uranium-238 with an activity of 400 kBq.

a Explain what is meant by the term 'half-life'. (1 mark)

b Explain what is meant by the term 'activity'. (1 mark)

c How many years will it take before the activity of the uranium-238 sample is 50 kBq? (2 marks)

22 The manufactured radioactive element technetium-99m is often used for medical diagnosis. The activity versus time graph for a sample of technetium-99m is shown below.



a Determine the half-life (in hours) of technetium-99m. (1 mark)

b What will the activity be after 18 hours have elapsed? (1 mark)

c Explain why the half-life of technetium-99m makes it a useful radioisotope for medical diagnostics. (2 marks)

23 **a** When mining uranium-238, miners have to be aware that there will be a deadly cocktail of radioactive substances. Explain why this is the case. (2 marks)

b What is the stable nucleus produced for the uranium-238 decay chain? (2 marks)

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24 Radioactive isotopes are used for both diagnostic and treatment purposes in medicine.

a Explain some of the characteristics needed for γ-ray radioisotopes used for medical diagnostic purposes. (3 marks)

b Explain some of the characteristics needed for γ-ray radioisotopes used for external medical treatment of malignant cancers. (3 marks)

25 The radioactive isotope chromium-51 is used in medical diagnosis (e.g. gastrointestinal bleeding) to label red blood cells. The half-life of Cr-51 is 27.7 days. It is a γ-ray emitter. It is stored behind lead shielding. An unshielded vial of Cr-51 has an activity of 37 MBq.

a Why is chromium-51 stored behind lead shielding? (2 marks)

b Why do staff handling chromium-51 have to wear whole body dosimeters while handling Cr-51 sources with activities of 37 MBq or more? (2 marks)

c What is the approximate activity of Cr-51 after 4 months have elapsed? (2 marks)

26 A patient has a 20 g cancerous tumour, which absorbs 0.006 J of energy from an external cobalt-60 γ-emitter radiotherapy unit.

a Calculate the absorbed dose for this tumour. (2 marks)

b Calculate the dose equivalent of the source. (2 marks)

Another patient with advanced prostate cancer has a 40 g cancerous tumour, which absorbs 0.004 J of energy from internally implanted radium-223 α-emitting pellets.

c Calculate the absorbed dose for this tumour. (2 marks)

d Calculate the dose equivalent of the source. (2 marks)

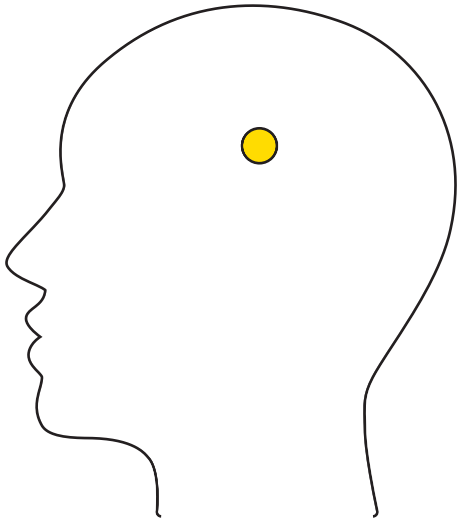
27 **a** Why are none of our senses useful in detecting radiation? (2 marks)

b What is the difference between using a Geiger counter or an OLP dosimeter for measuring radiation exposure? (2 marks)

28 What is the difference between the somatic effects and genetic effects of ionising radiation? (2 marks)

29 Ionising radiation creates ions such as OH^- and H^+. Why are these ions dangerous for humans? (2 marks)

30 In external beam radiotherapy, why are there a large number of low-dose beams aimed at a brain tumour from different angles rather than just a single, fixed, high-dose beam of radiation from only one angle? You should use the diagram below in your explanation. The brain tumour is shown in yellow. (4 marks)



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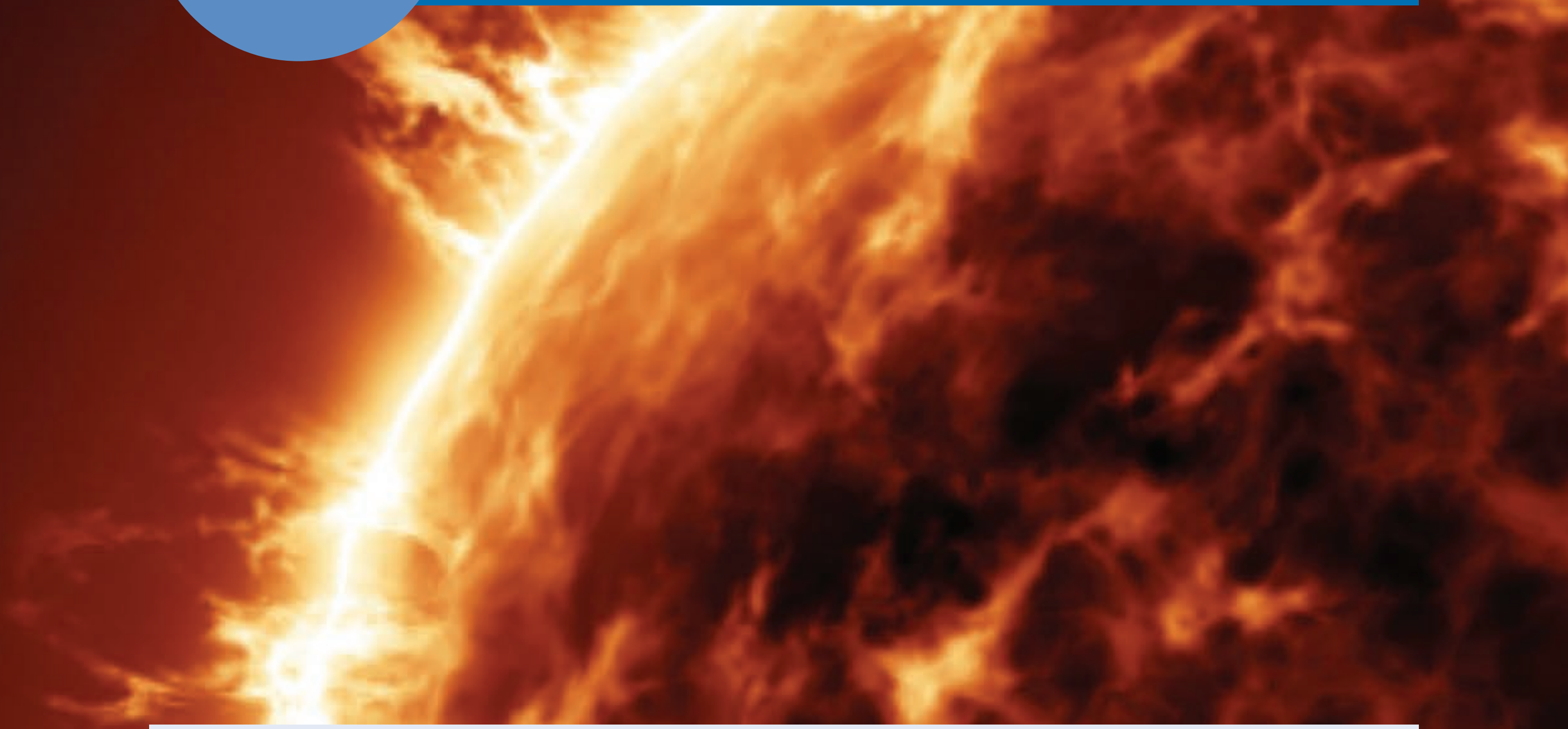
UNIT 1 HOW IS ENERGY USEFUL TO SOCIETY?

CHAPTER 4 NUCLEAR ENERGY



Introduction

We live in a nuclear age. Albert Einstein predicted in his special theory of relativity, published in 1905, that huge amounts of energy were locked up in ordinary matter, summarised by his now famous equation $E = mc^2$.

This chapter explains how nuclear energy results from this energy–mass equivalence. You will understand how fission chain reactions can be initiated and the effect of mass and shape on criticality. You will explore the role of moderators and neutron absorbers. You will compare the processes of nuclear fusion and nuclear fission and learn why fusion and fission are both nuclear reactions that release energy. This chapter also considers the future for both nuclear fission reactors and nuclear fusion reactors.

The chapter concludes by investigating the viability of nuclear energy as an energy source for Australia. An understanding of nuclear physics, nuclear reactors and nuclear weapons is necessary for developing informed opinions about these important topics in the modern world. Although specific historical aspects of nuclear energy are not included in the VCE Study Design, they help in understanding the theory. Furthermore, they are relevant to discussions on the viability of nuclear energy in Australia, since the history of nuclear weapons and nuclear power accidents affect public opinion.

Curriculum

Area of Study 2 Outcome 2
How is energy from the nucleus utilised?

Study Design	Learning objectives – at the end of this chapter I will be able to:
Nuclear energy • Explain, qualitatively, nuclear energy as energy resulting from the conversion of mass • Explain fission chain reactions including: ▸ the effect of mass and shape on criticality ▸ neutron absorption and moderation	**4A Nuclear energy and energy–mass equivalence** **4A.1** Explain, qualitatively, nuclear energy as energy resulting from the conversion of mass to energy **4A.2** Explain fission chain reactions **4A.3** Discuss the effect of mass and shape on criticality in fission chain reactions **4A.4** Discuss the role of neutron absorption and moderators in fission chain reactions
• Compare the processes of nuclear fusion and nuclear fission • Explain, using a binding energy curve, why both fusion and fission are reactions that release energy	**4B Comparing fusion and fission** **4B.1** Compare and understand the processes of nuclear fusion and nuclear fission **4B.2** Explain, using a binding energy curve, why fusion and fission are both nuclear reactions that release energy
• Investigate the viability of nuclear energy as an energy source for Australia	**4C Nuclear energy for Australia** **4C.1** Investigate and analyse the viability of nuclear energy as an energy source for Australia **4C.2** Discuss the advantages and disadvantages of nuclear energy for Australia

Glossary

Binding energy
Binding energy curve
Chain reaction
Control rods
Controlled chain reaction
Critical mass
Enrichment
Fissile
High-level waste
Low-level waste
Mass defect
Medium-level waste
Moderator
Non-fissile
Nuclear energy
Nuclear fission
Nuclear fusion
Plasma
Subcritical
Supercritical
Thermonuclear bomb
Tokamak
Uncontrolled chain reaction

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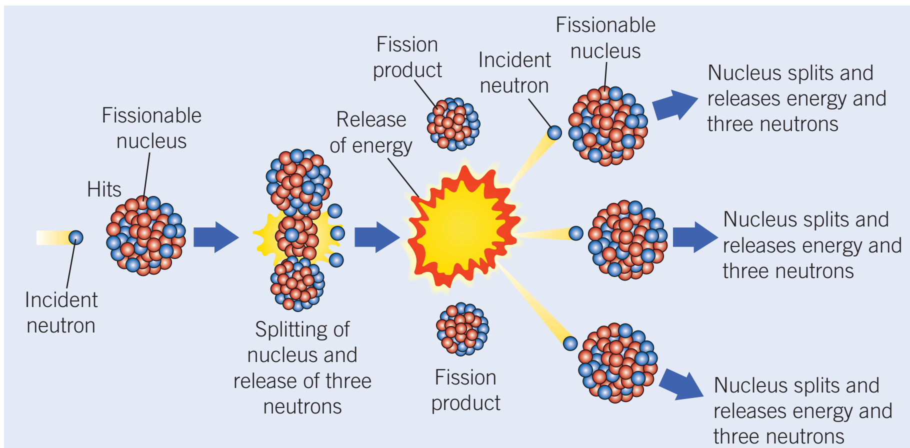
Concept map

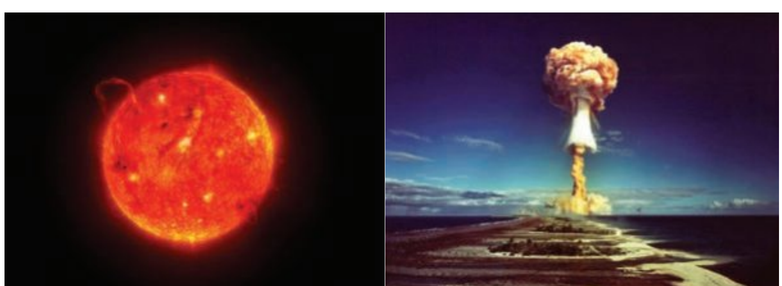
Understanding Einstein's mass–energy equivalence, $E = mc^2$, enables us to explain how nuclear energy can be produced using fission chain reactions

4A Nuclear energy and energy–mass equivalence



Understanding binding energy curves enables us to compare the similarities and differences between nuclear fusion and nuclear fission

4B Comparing fusion and fission



Understanding the status of nuclear energy technologies in Australia enables us to investigate the viability of using nuclear energy as a means of generating electric power

4C Nuclear energy for Australia

See the Interactive Textbook for an interactive version of this concept map interlinked with all concept maps for the course.

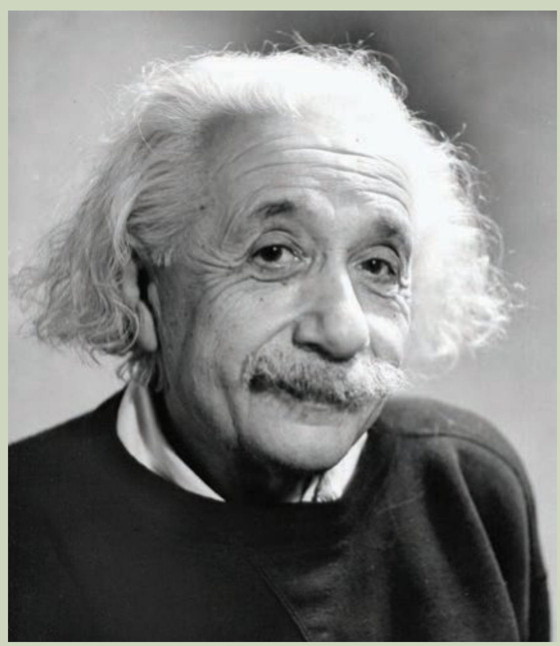
4A Nuclear energy and energy–mass equivalence

Study Design:
- Explain, qualitatively, nuclear energy as energy resulting from the conversion of mass
- Explain fission chain reactions including:
  - the effect of mass and shape on criticality
  - neutron absorption and moderation

Glossary:
Chain reaction
Control rods
Controlled chain reaction
Critical mass
Enrichment
Fissile
Moderator
Non-fissile
Nuclear energy
Nuclear fission
Nuclear fusion
Subcritical
Supercritical
Tokamak
Uncontrolled chain reaction

ENGAGE

How was $E = mc^2$ received?



On 27 September 1905, while employed at a patent office in Bern, Switzerland, Albert Einstein (pictured) published the last of four papers he had submitted during that year to the journal *Annalen der Physik*. The first paper explained the photoelectric effect that eventually won him the Nobel Prize. The second paper gave an explanation of Brownian motion, based on the hypothesis of atoms. The third paper introduced the theory of special relativity.

In the fourth paper, Einstein explained the relationship between energy and mass, which we now know as $E = mc^2$.

Scientific opinion at the time was that it would be virtually impossible to harness the energy locked up in ordinary matter. Atoms were so small and their nuclei so resistant to being damaged. For example, in the most violent chemical reactions, the nucleus is untouched; it seemed unlikely the energy within could ever be unlocked. More importantly, at the time of Einstein's paper, the neutron – which turned out to be the key to fission reactions – was unknown.

Also in 1932, John Cockcroft and Ernest Walton had discovered how to split the lithium atom by bombardment with high-energy protons. The Australian physicist Mark Oliphant had joined the same laboratory and in 1933 started experiments involving energetic collisions of heavy hydrogen (deuterium) nuclei, which led to his discovery of nuclear fusion.

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However, it seemed that the very high-energy input needed to split or transmute atoms by these methods prevented any chance of useable energy being released. Rutherford commented at the time:

> *These transformations of the atom are of extraordinary interest to scientists but we cannot control atomic energy to an extent which would be of any value commercially, and I believe we are not likely ever to be able to do so ... Our interest in the matter is purely scientific, and the experiments which are being carried out will help us to a better understanding of the structure of matter.*
>
> Ernest Rutherford, 1933

Rutherford was right about the importance of pure research but was wrong about its practical value. In 1934, the Italian born physicist Enrico Fermi and his team bombarded uranium-235 with neutrons, but they were puzzled by the results. Lise Meitner and Otto Frisch reasoned that Fermi's experiment had actually resulted in successfully splitting the uranium nucleus into two, with each part being approximately the same size. Meitner named the process 'fission'.

The full practical impacts of Einstein's $E = mc^2$, involving harnessing the energy locked up in ordinary matter, were realised by the end of the 1930s, using fission chain reactions involving neutrons. On 16 July 1945, the first atomic fission bomb (codenamed 'Trinity') using fissile plutonium-239 was exploded on a test site in the Alamogordo Desert of New Mexico, USA. Three weeks later on 6 and 9 August 1945, two atomic bombs ('Little Boy' and 'Fat Man') were dropped on Japan to end World War II. In 1952 the world's first hydrogen fusion bomb was exploded on Elugelab Island, in the Pacific Ocean, resulting in the total vaporisation of the island.

In 1956, the first commercial nuclear fission reactor, Calder Hall, was built in Britain for civilian power generation. It was directly connected to a national electrical grid. In 1958, the Scylla fusion reactor created a plasma in a magnetic bottle that reached a temperature of 15 million kelvin and demonstrated the first controlled thermonuclear fusion in a laboratory.

EXPLAIN

What are fission and fusion?

UNIT 4 LINK

Nuclear energy the energy released during nuclear fission or fusion

Nuclear fission the process of splitting a large nucleus to form two smaller, more stable nuclei

Nuclear fusion the process of joining together two small nuclei to form a larger, more stable nucleus

We are living on the cusp of a **nuclear energy** revolution. Albert Einstein's $E = mc^2$ can be used to help us to understand not only how nuclear bombs and **nuclear fission** power reactors work but also how **nuclear fusion** powers the Sun and the ~10^{24} stars in the known universe. $E = mc^2$ is also true for chemical reactions, but what is important about nuclear energy is that the strong force and binding energy are some million times larger than chemical bonds.

Nuclear fission is the splitting of a heavy, unstable nucleus into two lighter nuclei. Nuclear fusion is the process where two light nuclei combine together. Both processes release large amounts of energy. The mass of the fragments produced by the fission of a nucleus is less than the sum of the mass of the original nucleus and the initial colliding neutron. This mass difference, Δm, results in large amounts of energy being produced: $E = \Delta mc^2$. In a similar manner, the mass of the final nucleus produced by the fusion of two nuclei is also less than the mass of the original nuclei, and again large amounts of energy are produced: $E = \Delta mc^2$.

Humans currently have the ability to make uranium undergo fission explosively in a bomb in about one-billionth of a second, or more slowly in a power reactor over a period of years.

Physicists understand how the Sun converts 600 million tonnes of hydrogen per second into helium through nuclear fusion. This local nuclear fusion reactor creates a mass difference of

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4.2 million tonnes per second and generates an output of 3.8×10^{26} W.

The largest hydrogen bomb tested, the Tsar Bomba, converted hydrogen to helium in a nuclear fusion reaction with a total mass difference of 2.3 kg to produce an explosion equivalent to 50 megatonne of TNT – or as much as 3500 Hiroshima bombs (Figure 4A–2 left).

The ultimate goal of nuclear fusion physicists and engineers is to create miniature suns on Earth and unlock controlled nuclear fusion with its promises of almost unlimited, clean and carbon-free energy and no associated long half-life radioactive by-products.

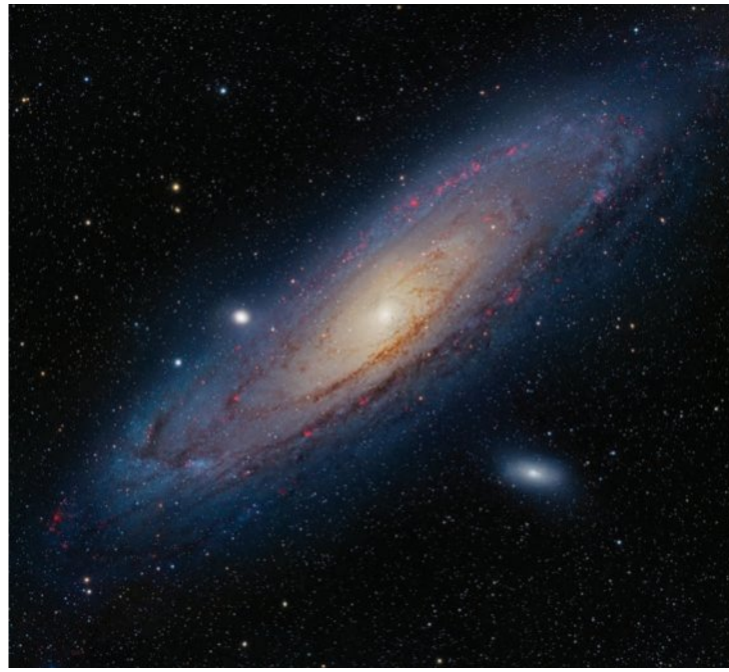

Figure 4A–1 Our nearest neighbouring galaxy, the Andromeda Galaxy, contains over a trillion stars ($\sim 10^{12}$) converting mass to energy by nuclear fusion.

Figure 4A–2 (right) shows an artist's impression of the world's largest **tokamak**, the International Thermonuclear Experimental Reactor (ITER). The ITER is a magnetic fusion device being built in France that has been designed to prove the feasibility of nuclear fusion as a large-scale and carbon-free source of energy based on the same fusion processes that power our Sun and the stars. A model of the ITER is shown in Figure 4B–8, and that section has a description of fusion reactors. The artist's impression in Figure 4A–2 shows a ring of glowing deuterium-tritium plasma, surrounded by a vacuum, and being confined in place by the enormously powerful magnetic field of the tokamak. By a combination of squeezing the plasma with very strong magnetic fields, subjecting it to electromagnetic radiation (a bit like a microwave oven), and using accelerators to inject particles, the plasma reaches a temperature of about 150 million degrees Celsius at which fusion takes place. Heat then radiates from the plasma to the tokamak walls, through which water circulates, heats up and produces steam. The steam is fed into turbines which produce electricity in the same way as conventional thermal power stations.

LINK **4B** COMPARING FUSION AND FISSION

Tokamak a device that uses a very strong magnetic field to confine plasma in the shape of a torus (a donut-shaped ring)

Up to 2022, no fusion reactor has released more energy than it consumes to produce the required magnetic field and to heat the plasma.

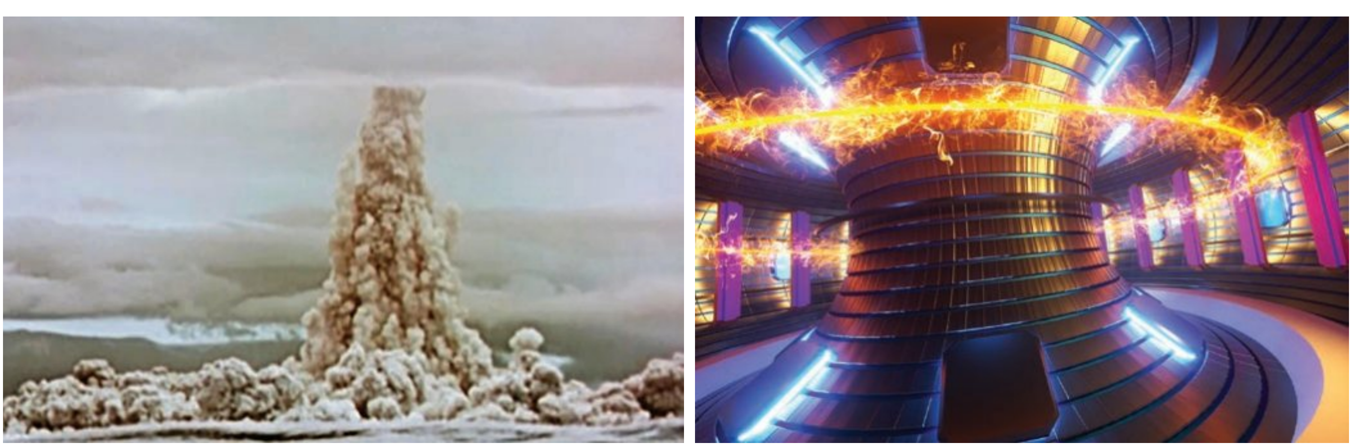

Figure 4A–2 Left: Russia's Tsar Bomba 50 Mt nuclear fusion hydrogen bomb being tested in 1961. Right: Artist's impression of unlocking $E = mc^2$ in controlled nuclear fusion in a tokamak magnetic fusion reactor on Earth.

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VIDEO 4A–1 NUCLEAR ENERGY

Mass into energy

The energy stored in mass according to Einstein's equation $E = \Delta mc^2$ is enormous because the speed of light, c, in a vacuum is 3.0×10^8 m s^{-1}, making the value of $c^2 = 9 \times 10^{16}$. If you could turn every one of the atoms in a paper clip (mass of 1.0 g) into pure energy, leaving no mass whatsoever, the paper clip would yield 21 kilotonnes of TNT. That's approximately the size of the bomb that destroyed Nagasaki in 1945 (Figure 4A–3).

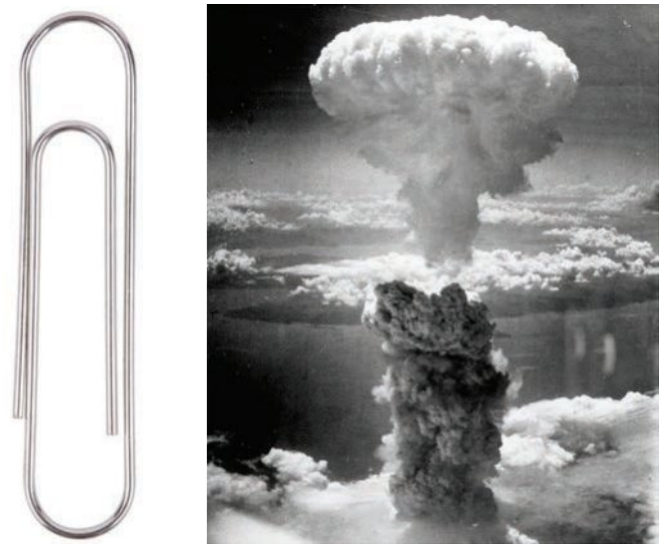

Figure 4A–3 If you could turn all the atoms of a 1.0 g paper clip into pure energy, the yield would be equivalent to 21 kilotonnes of TNT – the same as the atom bomb dropped on Nagasaki.

For tens of thousands of years, humans have been burning fuels such as wood and coal. This involves rearranging the outer electrons of atoms of carbon and oxygen into more stable combinations. The outer electrons of an atom are bound to the nucleus by the electromagnetic force, and it takes only a few electronvolts to pull an electron out. This is the realm of chemical reactions.

3A NUCLEAR STABILITY: FORCES IN THE NUCLEUS LINK

When energy is extracted by using uranium-235 as a fuel in a nuclear reactor, it involves rearranging the nucleons in the uranium nucleus into more stable combinations. The nucleons are held in nuclei by the strong force, and it takes many millions of electronvolts to pull a nucleon out. This is the realm of nuclear reactions. This is reflected in the fact that many millions of times more energy is obtained from a kilogram of uranium than from a kilogram of coal.

In both atomic and nuclear 'burning', the release of energy is accompanied by a decrease in mass, according to the equation $E = mc^2$. The central difference between burning uranium and burning coal is that, 'burning' uranium consumes a much larger fraction of the available mass (by a factor of many millions).

The mass loss is tiny but can nevertheless be measured: if all of 1.0 kg of uranium-235 were to undergo fission, the mass difference is only 1.0 g (0.1%). The calculated mass difference corresponding to the combustion of 1.0 kg of carbon is an almost imperceptible 0.33 μg.

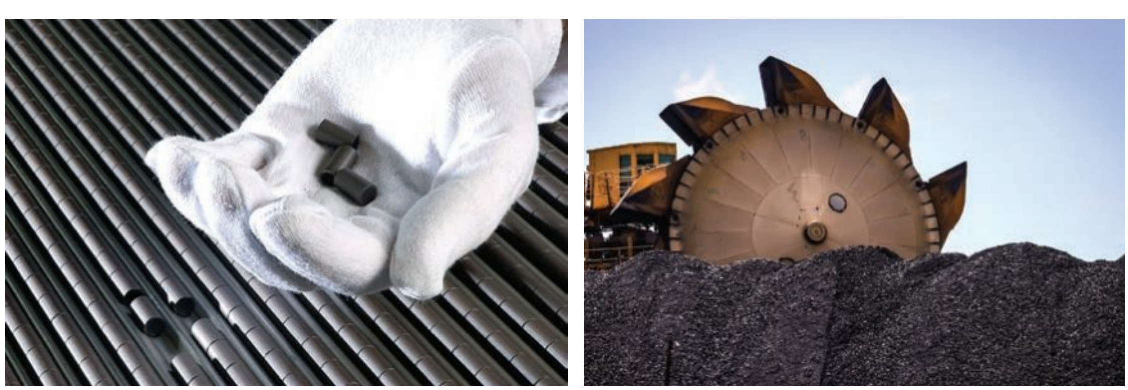

Figure 4A–4 Left: Pellets of uranium fuel each containing about 0.33 g of uranium-235 (which would amount to a tiny speck hardly visible to the naked eye) releases as much energy as burning 1.0 tonne of coal! Right: Excavating coal at Newcastle, New South Wales. Each scoop of the excavator carries 10 tonnes of coal with the energy equivalent of 10 uranium pellets!

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Worked example 4A–1 Mass conversion

Mass into energy: U-235 versus C-12

When 1.0 kg of uranium-235 undergoes fission, the mass difference is 1.0 g.

When 1.0 kg of carbon-12 combusts, the mass difference is 0.33 μg.

Use $E = mc^2$ to compare the amount energy released by the fission of U-235 and the combustion of C-12 and determine how many kilograms of coal would release the same amount of energy as 1.0 kg of U-235.

Solution

Use $E = mc^2$

Where:

E = Energy (J)

m = Mass (kg)

c = Speed of light in a vacuum (3.0×10^8 m s^{-1})

For U-235, m = 1.0 g:

$$E = mc^2$$
$$= (1.0 \times 10^{-3})(3.0 \times 10^8)^2$$
$$= 9.0 \times 10^{13} \text{ J}$$

For C-12, m = 0.33 μg:

$$E = mc^2$$
$$= (3.3 \times 10^{-10})(3.0 \times 10^8)^2$$
$$= 3.0 \times 10^7 \text{ J}$$

Energy released:

$$\frac{\text{U-235}}{\text{C-12}} = \frac{9.0 \times 10^{13}}{3 \times 10^7}$$
$$= 3.0 \times 10^6$$

Therefore, the combustion of 3.0×10^6 kg of coal releases the same amount of energy as the fissioning of 1.0 kg of uranium-235.

Table 4A–1 shows the total energy released by a kilogram of different fuels and the percentage of mass that has been converted to energy.

Table 4A–1 Energy released by 1 kg of matter

Fuel (type of matter)	Process	% mass converted to energy	Energy released from 1 kg (J)	Coal equivalent* (kg)
Coal	Combustion	3.3×10^{-8}	3.0×10^7	1
3.0% uranium-235	Fission in a reactor	0.003	2.7×10^{12}	900 000
100% uranium-235	Complete fission in bomb	0.1	9.0×10^{13}	30 million
Hydrogen bomb	Fission triggered fusion bomb	0.66	5.9×10^{14}	200 million
Hydrogen→Helium	Fusion in Sun	0.71	6.4×10^{14}	210 million
Matter and antimatter	Complete annihilation	100	9.0×10^{16}	30 billion

* Equivalent mass of coal needed to release the same energy as released by 1 kg of the fuel using the mass-to-energy conversion percentages given. For example, 210 million kilograms of coal are needed to release the same amount of energy as 1 kg of hydrogen fusing to helium in the Sun at 0.71% mass-to-energy conversion.

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NOTE

Although matter–antimatter interstellar spaceship drives are a common feature of science fiction movies (such as the *Star Trek* series), there is only a total of about 20 nanograms (20×10^{-12} kg) of confined antimatter in the form of positrons in the whole world at any given time. Most of these are created, and used, in high-energy particle accelerators.

Check-in questions – Set 1

1 What is nuclear fission? Give an example of how nuclear fission is used.
2 What is nuclear fusion? Give an example of where nuclear fusion occurs.
3 Use Table 4A–1 to answer the following questions.
   a How much mass from an original 1.0 kg mass of uranium-235 has been converted into other forms of energy via nuclear fission in a bomb?
   b Approximately how many kilograms of coal would need to be burned to release the same amount of energy as the fissioning of a 1.0 kg mass of uranium-235 in a bomb?
   c What is the ratio of mass-to-energy conversion for nuclear fusion compared to nuclear fission?

Figure 4A–5 Lise Meitner: co-discoverer of nuclear fission, the forgotten woman of nuclear physics, who deserved a Nobel Prize. A leading Austrian-Swedish physicist, she co-discovered the element protactinium, Meitner coined the term 'nuclear fission' and, along with her nephew Otto Frisch, explained the splitting (fissioning) of a uranium nucleus into barium and lanthanum. Although she was nominated 48 times for Physics and Chemistry Nobel Prizes she never won one. Recent research indicates that she should have shared the 1944 Nobel Prize that was awarded by the Swedish Academy solely to Otto Hahn for 'his' discovery of nuclear fission.

The role of neutrons

In 1934, the Italian born physicist Enrico Fermi and his team were trying to produce radioactive isotopes of various elements by using the newly discovered neutron to bombard nuclei. The great advantage of using neutrons is that they are neutral and are not repelled by other particles, whereas electrons are repelled by electrons in the outer shell of atoms, and protons are repelled by other protons in the nucleus.

Fermi reasoned that if they could bombard uranium with neutrons, they should be able to create via beta decay 'transuranic' elements – new elements beyond uranium. However, when they investigated the bombarded uranium samples, they found a cocktail of different radioactive elements, many of which they could not easily identify. It was only later that year that Lise Meitner and Otto Frisch reasoned that Fermi's original experiment had actually resulted in successfully splitting the uranium nucleus into two, with each part being approximately the same size. Because this process was akin to how living cells split themselves in half by 'binary fission', Lise Meitner named the process 'fission'. We now know that uranium-235 nuclei can undergo fission into any of over 40 different pairs of fragments.

When a large nucleus like uranium-235 captures an additional neutron, the uranium-235 nucleus is able to absorb the neutron to become (very briefly) uranium-236. The uranium-236 can then undergo fission to form two new nuclei called fission products. The two new nuclei each have approximately half the atomic mass number of the original nucleus. This 'splitting' of the nucleus induced by neutrons is called fission (Figure 4A–6).

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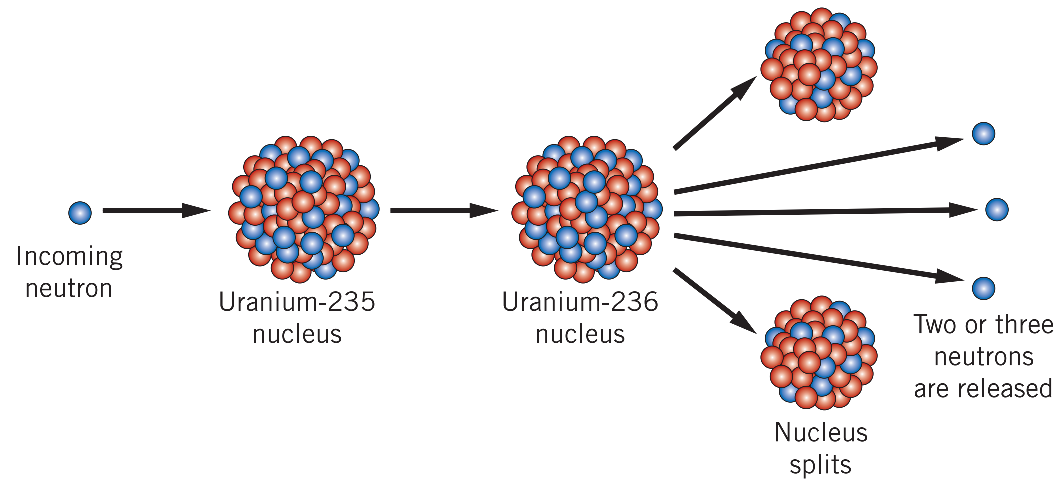

Figure 4A–6 The fission of uranium-235, a step in a chain reaction. An incoming neutron strikes the uranium-235 nucleus, which briefly becomes a uranium-236 nucleus that splits apart, and two new nuclei ('fragments') are formed, releasing energy and two or three neutrons. The fragments vary in mass number, as shown in Figure 4A–7.

Chain reaction when neutrons, emitted from the fission of one atomic nucleus, initiate further fission in the surrounding atomic nuclei, and so on

Fissile elements that are capable of undergoing fission

Non-fissile elements that are not capable of undergoing fission

The following heavy nuclei are also found to have a probability of undergoing fission: uranium-235, plutonium-239 and thorium-232. Any materials that are capable of sustaining a nuclear fission **chain reaction** after neutron capture are said to be **fissile**, while those that aren't are said to be **non-fissile**.

Uranium-235 and plutonium-239 are the fissile nuclides most commonly used in nuclear reactors and for making nuclear weapons. When a uranium-235 or plutonium-239 nucleus absorbs either a slow- or a fast-moving neutron, it becomes unstable and spontaneously undergoes fission. However, it was soon discovered that fission is more likely to be induced by a slow-moving neutron.

When uraninium-235 undergoes fission, the average mass number of the fragments is about 118, but very few fragments are found near that average. Experiments show that it is more likely that they break into unequal fragments with mass numbers about 95 and 137 . This graphs shows, for example that nearly 10% of the fragments have a mass number of 95 and nearly 10% have a mass number of 137 (Figure 4A–7).

The experiments also showed that as well as the larger fission fragments, approximately 2.5 neutrons on average and 200 MeV of energy were released every time a uranium-235 nucleus was split. This led physicists to believe that the excess neutrons could initiate a self-sustaining chain reaction.

Chain reactions

When neutrons that are emitted from the fission of a fissile nucleus like uranium-235 initiate further fissions in the immediate surrounding uranium-235 nuclei, it is possible to generate a completely self-sustaining chain reaction. If controlled, this chain reaction can lead to stable nuclear reactors to generate electrical power, or if triggered to be uncontrolled lead to massively explosive nuclear weapons.

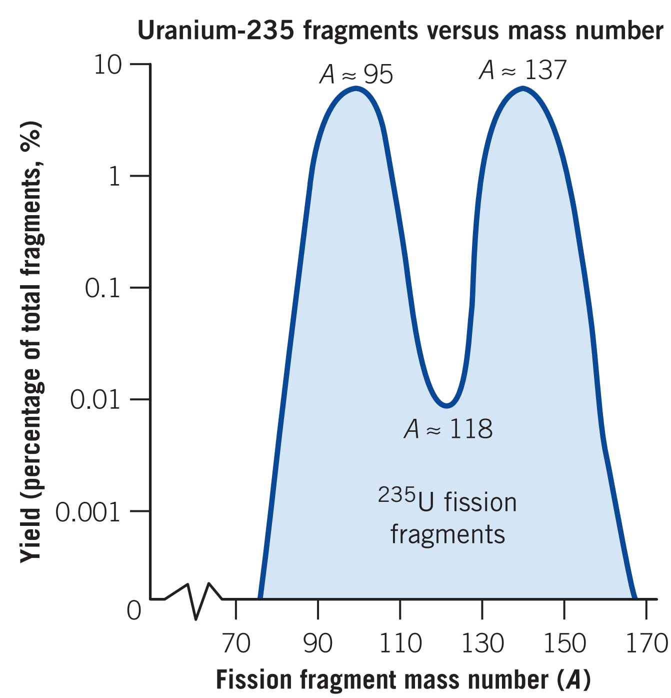

Figure 4A–7 The percentage yield of uranium-235 fragments versus mass number. Note the logarithmic scale on the *y*-axis.

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The reaction shown below is only one of the large number of possible fission routes available for a uranium-235 nucleus. The uranium-235 nucleus is able to absorb the neutron to become (very briefly) uranium-236. The uranium-236 then undergoes fission to form two new nuclei called fission products:

$$^{235}_{92}U + ^{1}_{0}n \rightarrow ^{236}_{92}U \rightarrow ^{141}_{56}Ba + ^{92}_{36}Kr + 3\,^{1}_{0}n + \text{energy}$$

The fission process exemplified by this equation is very important and forms the basis for our understanding of nuclear reactors and fission-based nuclear weapons. On the right-hand side of the nuclear equation, apart from the fission products barium-141 and krypton-92, there are three neutrons and energy. For each uranium atom splitting like this, the typical energy released from the mass difference ($E = \Delta mc^2$) of the products compared to the original nucleus is approximately 200 MeV. It is important to note that only a very small proportion of the original mass of the nuclei becomes available as useable energy – typically 0.1%.

The one incident neutron (on the left-hand side of the nuclear equation) has not only split the uranium-235 nucleus and created large quantities of energy from the mass difference of the products compared to the initial nucleus, it has also generated a further three neutrons to allow the whole process to become self-sustaining. As noted above, this is the basis of what is called a chain reaction.

Controlled chain reaction for every two or three neutrons released by the fissile nucleus, only one neutron is allowed to strike another fissile nucleus

Moderator any material that slows neutrons down

Controlling chain reactions

However, as a result of the fission reaction, these extra neutrons are travelling very fast and are not suitable to create a **controlled chain reaction**. If they can be slowed down enough to initiate further reactions, then a chain reaction can be sustained. This is the role of **moderators**. Moderators absorb some of the kinetic energy of fast neutrons, resulting in 'slow' neutrons, also described as 'thermal' neutrons. These slow neutrons have a very much higher probability than a fast neutron does of being absorbed and causing fission. Typical moderators used are water, graphite and beryllium. Moderators are essential if the chain reaction needs to be sustained (e.g. in a nuclear reactor).

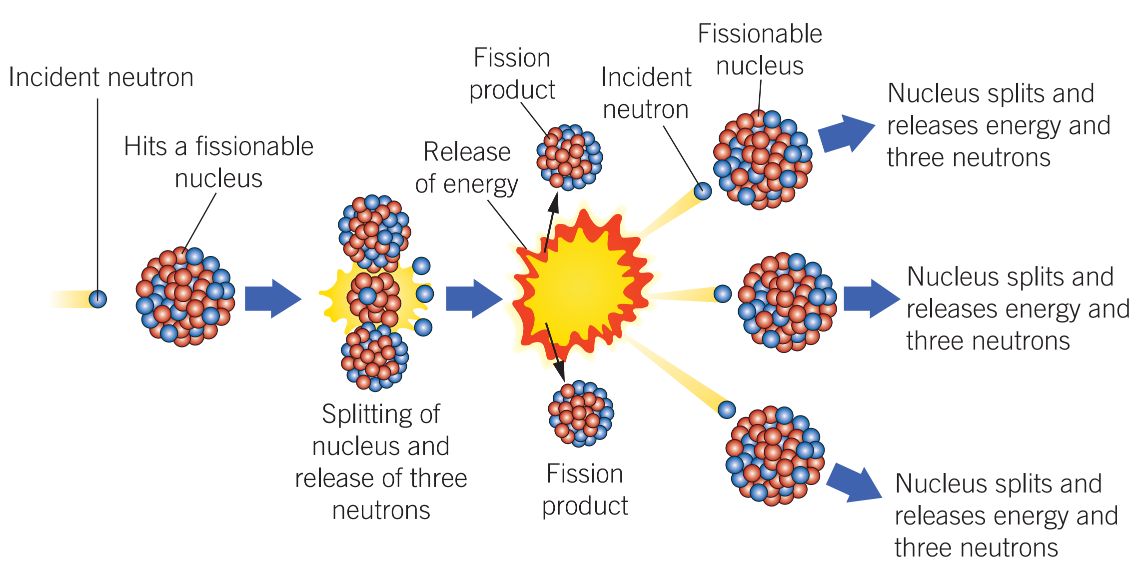

Figure 4A–8 A typical fission chain reaction initiated by a neutron coming in from the left and hitting a fissionable nucleus. This releases two or three more neutrons to hit other fissionable nuclei, and so it continues.

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The fission reaction in the explosion of a nuclear weapon, once initiated, is allowed to continue. For example, if two of the extra neutrons created by the fission of uranium-235 induce two further fission reactions, which in turn each generate a further two or three neutrons and fission reactions (and so on), a situation of exponential growth is created. This is known as an **uncontrolled chain reaction**, which is the basis of nuclear weapons (Figure 4A–9).

Uncontrolled chain reaction every two or three neutrons released by the fissile nucleus are allowed to strike other fissile nuclei. This grows exponentially to produce a massive explosion.

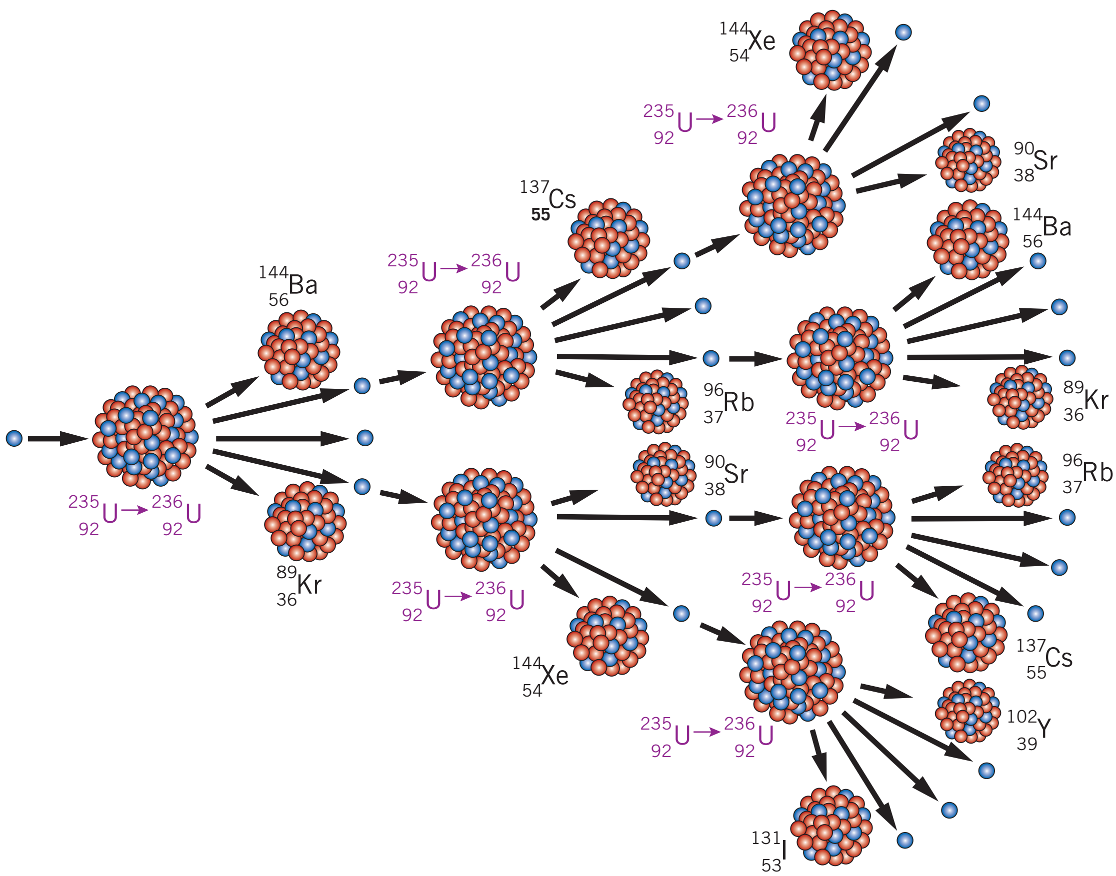

Figure 4A–9 An uncontrolled chain reaction. A uranium-235 atom – when hit by an incident neutron – very briefly becomes a uranium-236 nucleus, which then splits and initially releases three neutrons (this can be called one generation), which can then split other uranium nuclei, releasing two or three neutrons and so on. Eighty generations in a few microseconds produces a vast explosion, releasing the energy equivalent of tens of thousands of tonnes of TNT.

Aside from the massive potential damage of the initial explosion of a nuclear weapon, there is also the legacy of all the radioactive fragments created by the explosion that are dispersed throughout the environment. Some of the dangerous radioisotopes from atmospheric nuclear tests conducted in the 1950s to the 1970s are still present in the world's atmosphere, land, lakes and oceans.

LINK 3E THE EFFECT OF RADIATION IN HUMANS

However, if the chain reaction is strictly controlled so that on average only one extra neutron is allowed to initiate one further fission reaction each time, then a controlled chain reaction is created. This is the basis for nuclear reactors used in generating electricity, research and radioactive isotope generation. The first nuclear reactor was constructed by Enrico Fermi in 1942.

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Fermi's pile

On 2 December 1942, the world's first self-sustaining nuclear chain reaction took place in a squash court underneath the University of Chicago's football stadium. This first atomic 'pile' (which we now call a nuclear reactor) was carefully built by Enrico Fermi using lumps of natural uranium oxide and very pure graphite (as the moderator) arranged into a special critical geometry (Figure 4A–10). The pile was controlled by cadmium rods (control rods), which could be lowered quickly into the pile, absorbing neutrons and stopping the fission process. Fermi's pile had an initial power output of only 0.6 watts (W) but demonstrated the feasibility of creating controlled nuclear energy for the first time. It also introduced the possibility of creating an atom bomb.

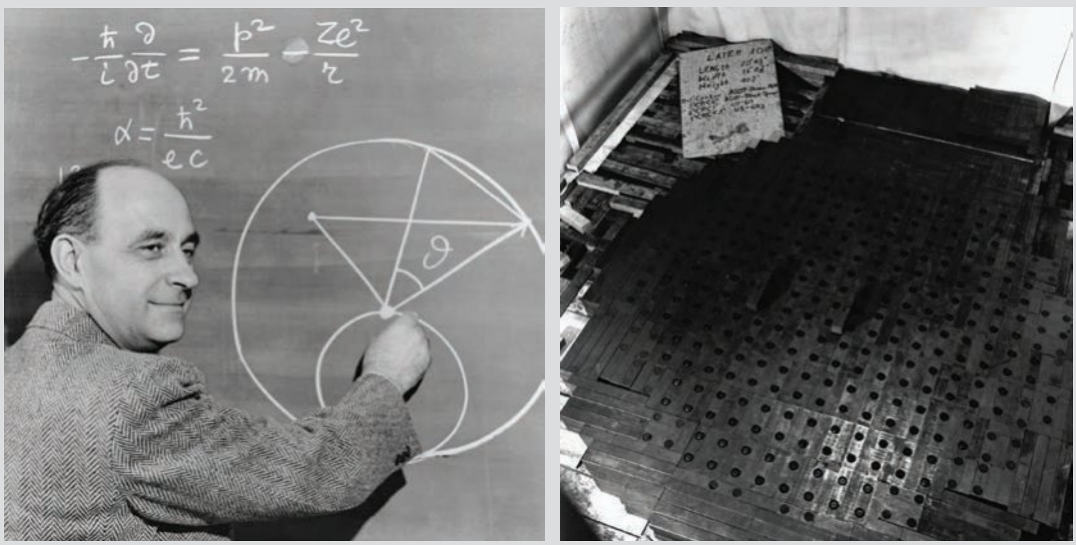

Figure 4A–10 Left: Enrico Fermi. Fermi was awarded the Nobel Prize in Physics for producing the first transuranic elements. In 1955, the element with atomic number 100 was artificially produced and named fermium, Fm. Right: This was the tenth layer of Fermi's (and the world's) first nuclear reactor. This tenth level had graphite blocks that contained pieces of natural uranium oxide. Once a critical mass of such pieces was assembled, a controlled (and very low powered) nuclear reaction started.

Check-in questions – Set 2

1 What is a fissile material?
2 What is a chain reaction?
3 What is the role of a moderator in nuclear reactors? Give an example of a moderator.
4 What is a controlled chain reaction?

Critical mass

Over a vast number of different uranium-235 fission reactions, the average number of neutrons emitted is approximately 2.5 neutrons per reaction. By varying the parameters of the size, shape and purity of the uranium-235 fuel – and by controlling the neutrons available for further reactions through geometry, neutron speed and neutron absorption – it is possible to organise the following three conditions: a **subcritical** mass, a **critical mass** and a **supercritical** mass.

Subcritical when the rate of neutron loss is greater than the rate of neutron release by fission

Critical mass the smallest mass of a fissionable substance that will sustain a controlled chain reaction, when the rate of neutron loss equals the rate of neutron release by fission

Supercritical when the rate of neutron loss is less than the rate of neutron release by fission

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For example, if the geometric shape is a sphere, then a large sphere of almost pure U-235 can create a large nuclear bomb, but a small sphere of pure U-235 won't necessarily create a small nuclear bomb. The reason relates to the ratio of the volume, V, to the surface area, A. If you double the radius, r, you can have eight times the volume ($V \propto r^3$) of U-235 but only have four times the surface area ($A \propto r^2$) for neutrons to escape from (see Figure 4A–11). This means a larger sphere has a greater chance of using the neutrons produced by fission to initiate further fusions. A critical mass is achieved when the rate of neutron creation in the sphere is matched by the rate of neutron loss.

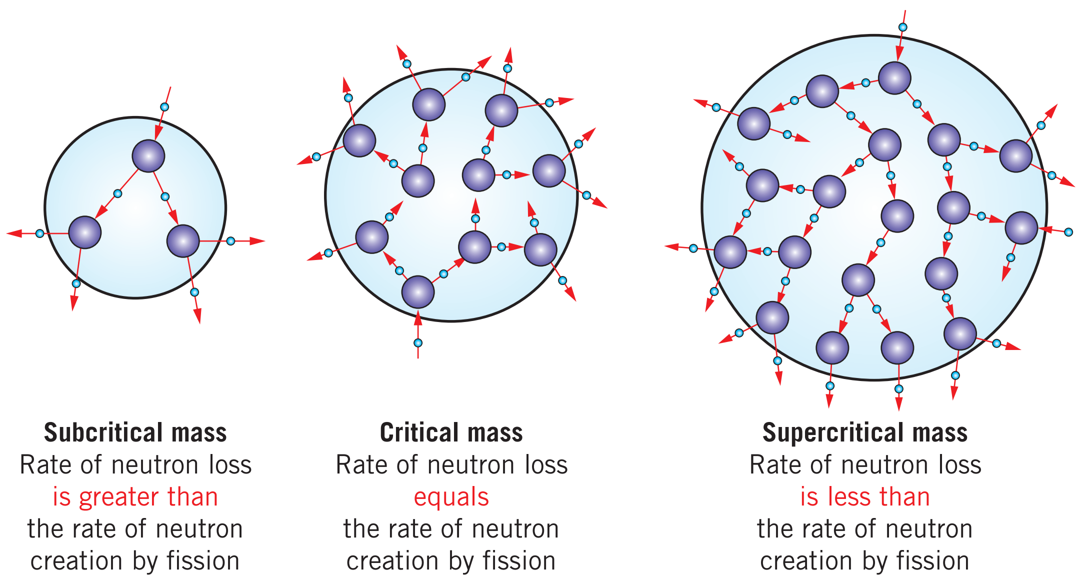

Figure 4A–11 Different size spheres can create different states of criticality. Other geometric shapes and different percentages of fissile U-235 will have different critical configurations; for example, the thin cylindrical tubes used in nuclear reactors.

If some neutrons can be reflected back into the critical mass by using neutron reflectors (such as beryllium), then the mass goes supercritical more readily (see the Case study below).

A fatal critical mass accident – Louis Slotin (1910–46)

As part of the Manhattan Project that created the atomic bombs that ended World War II, Louis Slotin performed experiments with uranium and plutonium cores to determine their critical mass values. After World War II, Slotin continued his research. On 21 May 1946, Slotin's screwdriver slipped, allowing the top beryllium reflector to fall down and accidentally began a fission reaction, which released a burst of lethal neutron radiation. At the time, the scientists in the room observed the blue glow of air ionisation and felt a heat wave. Slotin was rushed to the hospital and died nine days later on 30 May.

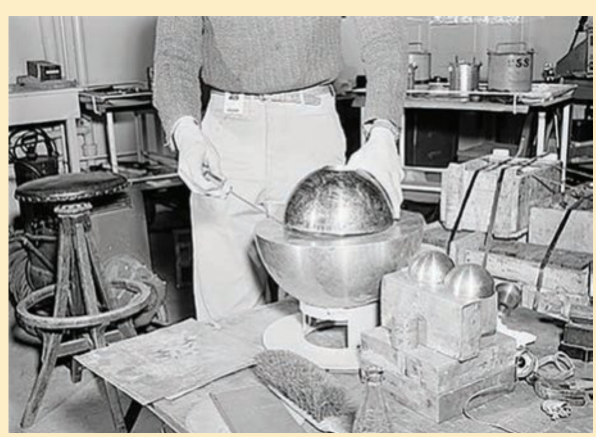

Figure 4A–12 Recreation of the Slotin experiment. Two half-spheres of beryllium (a neutron reflector) are placed around a spherical plutonium-239 core.

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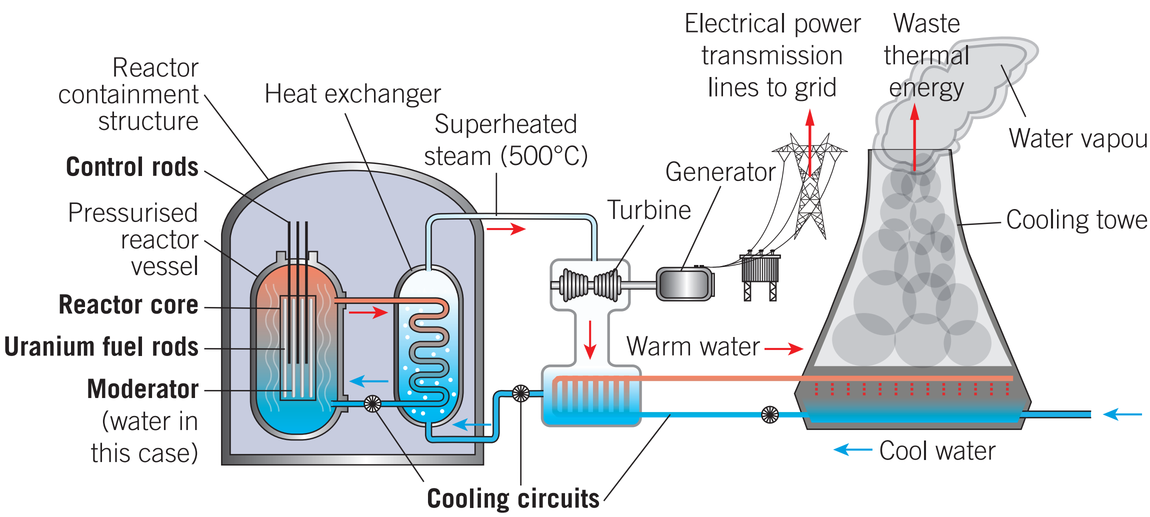
Control rods

Control rods rods made of materials that readily absorb neutrons

When designing nuclear reactors for power generation or for scientific research (e.g. Australia's Open Pool Australian Lightwater (OPAL) reactor), criticality is controlled by the geometrical arrangement of the fuel rods, by the type of moderators used to slow down neutrons and by the type of **control rod** used to absorb excess neutrons. Control rods include chemical elements such as boron, cadmium, silver, hafnium or indium that all readily absorb large numbers of neutrons.

Nuclear fission reactors for electricity generation

Figure 4A–13 shows how these components are arranged in a typical 1000 MW thermal nuclear reactor used to generate electricity. The purpose of the reactor core is to use the heat generated by the nuclear fission of the U-235 to create superheated steam, which turns the turbines to generate the electricity. In contrast, the equivalent heat could be generated by burning 9000 tonnes of coal per day in a 1000 MW coal-fired power station, which pumps 27 000 tonnes of CO_2 per day into the atmosphere.



Reactor core: where the fission takes place to produce thermal energy. It contains the uranium fuel rods, control rods, moderator and coolant. A containment structure of concrete and steel surrounds the reactor to prevent radiation and material escaping, in case of rupture of the reactor vessel.

Uranium fuel rods: consist of a number of thin tubes full of pellets of enriched uranium-235. Fission occurs inside the fuel rods, releasing the nuclear energy as heat and radiation.

Moderator: used to slow down the neutrons released during fission. Slow-moving, so-called 'thermal', neutrons are more likely than fast neutrons to cause a uranium-235 nucleus to undergo fission. Water is often used as a moderator.

Control rods: Cadmium–boron control rods absorb neutrons. This allows the chain reaction to be controlled. When the reactor is just starting, the rods are raised to allow the number of nuclei undergoing fission each second to increase until the nuclear reactor is running in a controlled critical state. In the case of an emergency, the control rods and extra safety control rods drop fully into the core, absorbing most of the neutrons, and shut down the chain reaction. See Figure 4A–14.

Cooling circuits: this design has three separate circuits. The first two extract the thermal energy to drive the turbines and generators. The third removes the waste thermal energy, to the atmosphere in this case with water vapour and clouds of condensed water.

Figure 4A–13 Diagram of the layout of a typical 1000 MW thermal nuclear power station used to generate electricity. This is a pressurised water reactor design. The primary coolant is water kept under very high pressure to keep it liquid is the primary coolant. This water is also the moderator.

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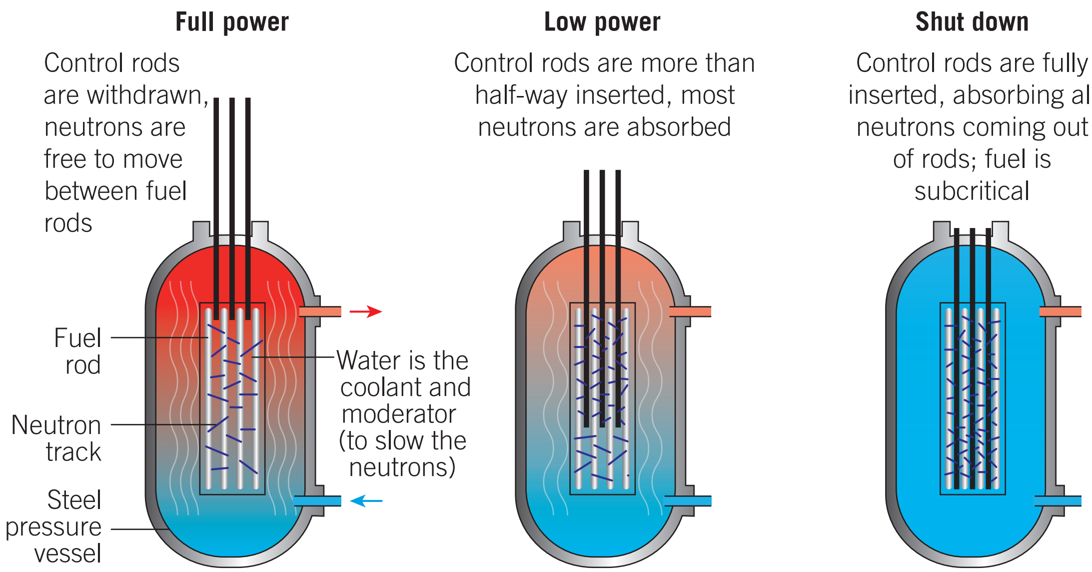

Figure 4A–14 How control rods regulate the power level in a nuclear fission reactor core. This is a pressurised water reactor. Control rods absorb neutrons coming out of the fuel rods so they don't cause chain reactions in neighbouring rods, and the fuel becomes subcritical.

The domed cylindrical structures on the left in Figure 4A–15 are reactor containment buildings, while the giant 'pepperpot' towers on the right are cooling towers. Warm water from the cooling circuits, bringing heat from the turbine, is sprayed at the bottom of the tower and cools by evaporation of some of the water. The water vapour rises and condenses into the clouds shown emerging at the top. The only outputs of the cooling towers are water and heat. In this way, the excess thermal energy is transferred to the atmosphere. (Note that coal-fired and other thermal power stations relying on steam turbines to turn generators also need to have cooling towers like these, or cooling ponds.)

Figure 4A–15 A nuclear power plant in France. More than 70% of the country's electrical energy needs are produced using nuclear energy.

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Uranium enrichment

Uranium mining of high-grade ore bodies typically requires 1 tonne of ore to produce 3 kg of uranium oxide. The processed uranium oxide extracted consists mainly of two isotopes: uranium-235 (0.7%) and uranium-238 (99.3%). It is the uranium-235 isotope which undergoes fission most readily, releasing thermal energy. Processed uranium often undergoes **enrichment** before it is used as a nuclear fuel; the ratio of the isotopes is changed to include a greater concentration of uranium-235. As isotopes of any element have the same chemical properties, we cannot use chemical methods to separate them. Any separation must involve physical differences. In the case of uranium-235 and uranium-238, there is a very small difference in mass and this can be used to separate the isotopes. Three commonly used enrichment methods involve electromagnetic separation, ultracentrifuges and gaseous-diffusion techniques. Nuclear weapons and thermal power stations require different enrichment factors. Typically, weapons-grade material has to be enriched to more than 90% pure uranium-235, while most conventional nuclear reactors use uranium fuel enriched to 3.5–4.5% uranium-235. Reactor-grade uranium fuel is therefore not suitable for constructing nuclear weapons.

Enrichment increasing the percentage of the fissile isotope of an element in a nuclear fuel

Uranium-235 found in the ground is usually subcritical.

For thermal nuclear reactors (those that use slow or thermal neutrons), the situation is slightly more complex. It is vital that the reactor is critical (but not supercritical) and that the control of criticality remains well within human reaction times. A nuclear reactor is designed to maintain criticality and avoid meltdowns due to supercritical episodes.

However, when designing nuclear weapons, it is important to have the component pieces of the fissile nuclear materials in a subcritical condition and only to bring them into a supercritical mass when the weapon explodes.

This was the case with the original U-235 bomb Little Boy that was dropped on Hiroshima to end World War II in 1945. This was designed as a 'gun type' nuclear weapon. A chemical explosive fired the hollow uranium 'bullet', a subcritical mass of 39 kg of enriched uranium-235, into the cylinder 'target' mass – a subcritical mass of 25 kg of enriched uranium-235. The two masses together suddenly formed a supercritical mass that exploded in less than a millisecond. Less than a kilogram of the uranium-235 underwent nuclear fission and of this mass, only 0.7 g was transformed into several forms of energy, mostly thermal energy as a result of the kinetic energy of the fission products, and radiation. The blast yield was equivalent to 15 kt of TNT.

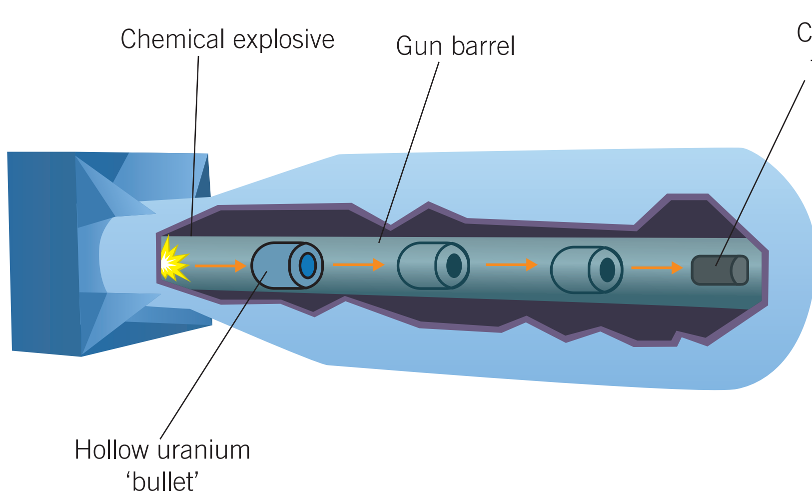

Figure 4A–16 Schematic diagram of the 'Little Boy' uranium bomb dropped on Hiroshima. The bomb contained 64 kg of enriched uranium-235 with an overall enrichment factor of 80%.

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Worked example 4A–2 Energy of a nuclear bomb

The bomb dropped on Hiroshima transformed 0.7 g of mass into several forms of energy, mostly thermal energy as a result of the kinetic energy of the fission products and radiation. 1 kt (kilotonne) of TNT releases 4.18 TJ (terajoules) of energy. Use $c = 3 \times 10^8\ \mathrm{m\,s^{-1}}$ for the speed of light.

a Calculate the amount of energy released by this bomb in TJ.

b Calculate the equivalent TNT amount, in kt, produced by the explosion of the 'Little Boy' bomb.

Solution

a $E = \Delta mc^2$

$= (7 \times 10^{-4})\ (9 \times 10^{16})$

$= 63 \times 10^{12}$

$= 63\ \mathrm{TJ}$

b $\dfrac{63}{4.18} = 15.1\ \mathrm{kt}$

Plutonium bombs

The design of the 'Fat Man' plutonium-239 bomb dropped on Nagasaki used a different method to achieve a supercritical state. The bomb contained many small subcritical pieces of plutonium-239 and used a spherical chemical implosion technique to force these subcritical masses together to make a single supercritical mass (Figure 4A–17).

The result was the fission of about 1 kilogram of the 6.19 kg of plutonium-239 in the core. Of this mass, only 0.97 g was transformed into several forms of energy, mostly thermal energy as a result of the kinetic energy of the fission products, and radiation. The detonation released the energy equivalent to the detonation of 21 kt of TNT or 88 TJ.

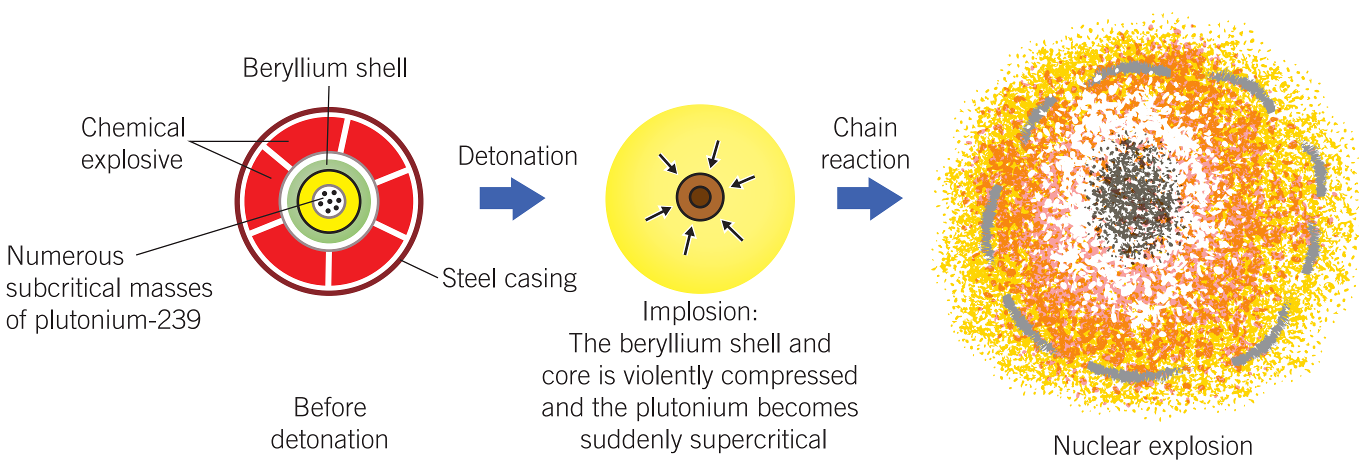

Figure 4A–17 A spherical fission bomb involves a large number of charges that are detonated simultaneously to compress numerous separate pieces of plutonium (each less than a critical mass) into a small ball that exceeds the critical mass. A shell of the metal beryllium reflects outgoing neutrons back into the core of the bomb. This type of bomb was dropped on Nagasaki.

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WORKSHEET 4A–1 NUCLEAR ENERGY AND ENERGY–MASS EQUIVALENCE

Check-in questions – Set 3

1 What is meant by a critical mass of a fissile material?

2 How does the geometric shape affect the criticality of fissile material; for example, a sphere versus a flat thin square with the same amount of fissile material?

3 How do you design just two sub critical uranium-235 enriched fissile masses to become a supercritical fissile mass in a nuclear weapon?

VIDEO 4A–2 SKILLS: NUCLEAR FISSION REACTION EQUATIONS

4A SKILLS

Nuclear fission reaction equations

The following fission reaction is one of many possible uranium-235 fission reactions:

$$^{235}_{92}\text{U} + {}^{1}_{0}\text{n} \rightarrow {}^{140}_{?}\text{Xe} + {}^{94}_{38}\text{Sr} + \ ?\,{}^{1}_{0}\text{n} \ + \text{energy}$$

a What are the names of the isotopes of the two fission fragments produced by this fission reaction?

b Determine the number of protons in the element Xe and the number of neutrons emitted by the fissioning of uranium-235

c Write the complete equation.

Solution

CHAPTER 3 LINK

a If you are not familiar with the symbols used for the elements of the isotopes, then use a periodic table (see Chapter 3, page 86 or page 551 of Appendix 2) to look them up. Note that the number after the element (indicating which isotope it is) is the number of nucleons.

xenon-140

strontium-94

b Use simple arithmetic to equate the protons and nucleons.

Equate the proton numbers (bottom line) on LHS and RHS:

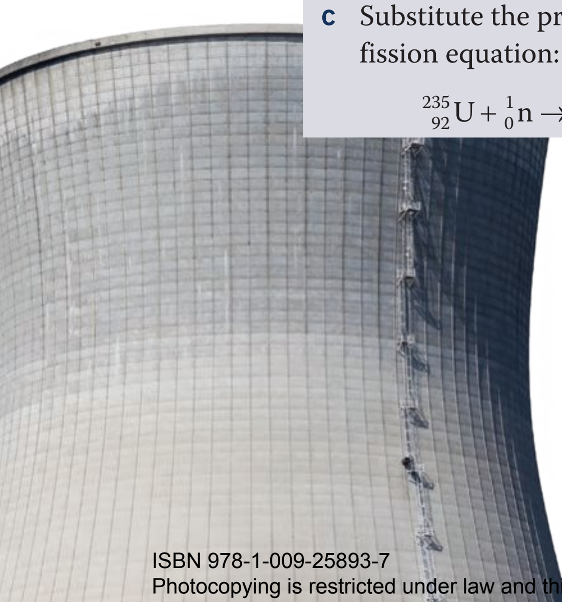
$$92 + 0 = ? + 38 + 0$$
$$? = 92 - 38 = 54$$

Equate the nucleon numbers (top line) on LHS and RHS:

$$235 + 1 = 140 + 94 + ?(1)$$
$$? = 236 - 234 = 2$$

c Substitute the proton number and the number of neutrons created into the nuclear fission equation:

$$^{235}_{92}\text{U} + {}^{1}_{0}\text{n} \rightarrow {}^{140}_{54}\text{Xe} + {}^{94}_{38}\text{Sr} + 2\,{}^{1}_{0}\text{n} \ + \text{energy}$$



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Section 4A questions

Multiple-choice questions

1 Which one of the following best explains the process of fission?
- A the joining of light nuclei to create a more stable nucleus like helium
- B the joining of light nuclei to create a more stable nucleus like uranium
- C the splitting of a heavy nucleus like uranium into two medium-sized nuclei
- D the creation of transuranic nuclei by bombarding uranium-238 with neutrons

2 A fissile nucleus is
- A a nucleus that can undergo fusion.
- B a nucleus that can undergo fission.
- C a nucleus that emits radioactivity.
- D none of the above.

3 What is critical mass?
- A the amount of nuclear material needed for a reaction to continue on its own
- B the amount of nuclear material needed for a reaction to happen at all
- C the amount of nuclear material needed for a reaction to stop on its own
- D none of the above

4 Which one of the following best describes the process of enrichment of uranium ore?
- A increasing the percentage of uranium-235 in the ore
- B increasing the percentage of uranium-238 in the ore
- C enriching the uranium-235 by changing it into plutonium-236
- D enriching the uranium-238 by changing it into plutonium-239

Short-answer questions

5 a In the equation $E = \Delta mc^2$, what does the term Δm refer to for a nuclear fission reaction?

b Calculate the energy released in joules if $\Delta m = 0.5$ g for a nuclear fission of a uranium-235 in a nuclear explosion.

6 The nuclear equation below shows the fission reaction of uranium-235.

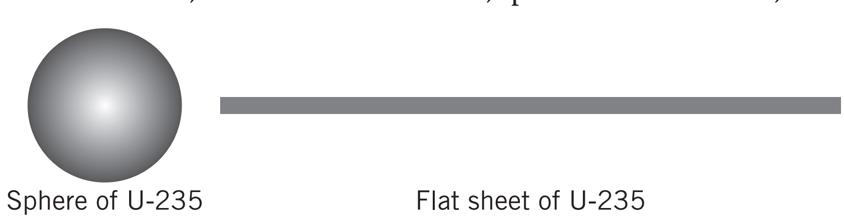
$$^{235}_{92}\text{U} + ^{1}_{0}\text{n} \rightarrow ^{141}_{56}\text{Ba} + ^{92}_{X}\text{Kr} + Y\,^{1}_{0}\text{n} + \text{energy}$$

Determine the numerical values of X (protons in krypton) and Y (number of neutrons emitted) by the fission reaction of uranium-235.

7 a Explain the role of control rods and moderators in a nuclear power reactor.

b Give an example of the type of material that can be used as a control rod and as a moderator.

8 Explain why a large spherical mass of weapons-grade uranium-235 may be able to sustain a chain reaction, whereas the same mass, spread into a flat sheet, cannot.



9 a What were the names of the isotopes used in the nuclear bombs dropped on Hiroshima and Nagasaki?

b How was criticality obtained in each of the nuclear bombs dropped on Hiroshima and Nagasaki?

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4B Comparing fusion and fission

Study Design:

- Compare the processes of nuclear fusion and nuclear fission
- Explain, using a binding energy curve, why both fusion and fission are reactions that release energy

Glossary:

Binding energy
Binding energy curve
High-level waste
Low-level waste
Mass defect
Medium-level waste
Plasma
Thermonuclear bomb

ENGAGE

The Manhattan Project

Most of the world's working knowledge about the physics of the nuclear fission of uranium-235 (U-235) and plutonium-239 (Pu-239) came from the Manhattan Project – a top-secret intensive research and development project undertaken in the United States during World War II. The project produced the nuclear weapons that ultimately ended the war.

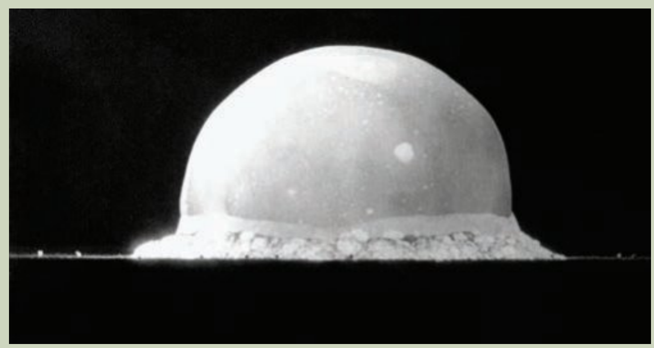

Figure 4B–1 The explosive fireball of the first nuclear bomb test, code-named Trinity, carried out in the United States on 16 July 1945. The image is a frame from a very high-speed film camera, 0.016 seconds after detonation. The fireball is about 200 metres high.

After the surprise Japanese bombing of Pearl Harbour in United States territory on 7 December 1941, US President Roosevelt authorised an intense program to build an atomic bomb, employing more than 130 000 people, most of whom did not know what the ultimate aim of their work was. The Manhattan Project ended up costing several billion dollars (equivalent to about US$30 billion today). It involved brilliant physicists from both US and non-US universities. It resulted in atomic bombs being dropped on Hiroshima and Nagasaki in Japan, killing an estimated 200 000 Japanese people. This was followed by the almost immediate surrender of Japan.

Most of the important research in theoretical nuclear physics had actually been done in the 1930s in Europe. When the war started, many physicists in the allied countries were concerned that Germany (under Adolf Hitler) might develop atomic weapons. Albert Einstein, the most famous living physicist of the time, wrote a letter to President Roosevelt in 1939 advising him of this possible danger. Although Einstein was an acknowledged pacifist, he wrote the letter in the hope that atomic weapons technology would be better under the control of the allies than under Hitler.

The basic physics principles of nuclear weapons were fairly straightforward: produce a critical mass of at least 95% enriched uranium-235 and it would automatically fission in a massive explosion, releasing huge amounts of energy.

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However, producing 95% pure uranium-235 is not easy. Natural uranium occurs in two main isotopes, with the uranium-235 isotope representing only 0.7% of the uranium ore and the remaining 99.3% the less fissile uranium-238.

Isotopes have identical chemical properties, so the uranium isotopes cannot be chemically separated from each other. However, isotopes do have different physical properties: a slight difference in their mass. What was needed was a physical means of extraction based on the slight mass difference between the two isotopes, so that the uranium-235 percentage could be enriched to 80%. The project physicists were aiming to produce approximately 64 kg of enriched uranium-235, which was the amount to create a useable critical mass.

If uranium-235 enrichment did not work, then the project physicists believed a fission bomb could be made using plutonium-239, an element that did not exist in nature, but which they believed could be tailor-made by bombarding uranium-238 atoms with neutrons. They calculated that the critical mass of plutonium-239 required would only be approximately 7 kg.

Three teams of physicists worked to separate out the amount of fissile material needed for a bomb. One team tried a technique on uranium known as electromagnetic separation. A second team also tried to separate uranium by a gas diffusion method. Fermi headed the third team. This team produced plutonium-239 by bombarding uranium-238 in a nuclear reactor. After almost four years of painstaking research, two of the methods were successful – gas diffusion to create enriched uranium-235 and the irradiation of uranium-238 to produce plutonium-239. These methods were used to produce nuclear fuel for three bombs.

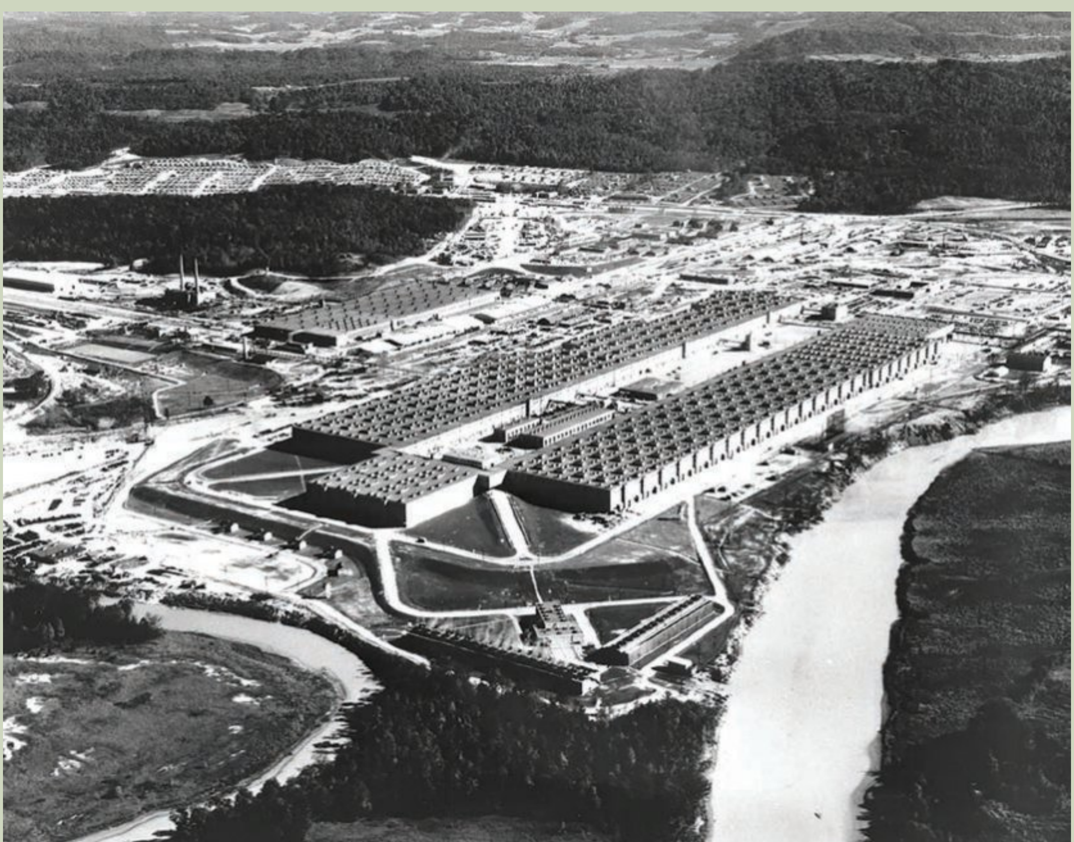

Figure 4B–2 The vast gas diffusion plant for uranium enrichment at Oak Ridge, Tennessee, was just one of the industrial sites of the Manhattan Project. At its peak production, Oak Ridge used one-seventh of all the electricity generated in the United States to run the gas centrifuge machines.

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On 16 July 1945, the atomic age began when the world's first atomic bomb was tested in the New Mexico desert. The plutonium-239 bomb exploded with an energy equivalent to 20 kt of TNT (Figure 4B–1). Only three bombs were built. The physicists were reasonably confident that the uranium-235 bomb would work, but they could not test it as they had just enough enriched uranium to build one. They built two plutonium-239 bombs. These two nuclear weapons, known as 'Little Boy' (using uranium) and 'Fat Man' (using plutonium), were dropped on Hiroshima and Nagasaki respectively (Figure 4B–3).

Figure 4B–3 Replicas of the 'Little Boy' (left) and 'Fat Man' (right) atom bombs dropped on Hiroshima (6 August 1945) and on Nagasaki (9 August 1945)

EXPLAIN

How much mass is converted to energy in fission and fusion?

VIDEO 4B–1 FISSION AND FUSION

As we have already seen, both fusion and fission are nuclear reactions that produce energy via the mass–energy relationship, $E = \Delta mc^2$. However, the processes are very different. Fusion is the process where two light nuclei combine to create a more stable nucleus, thereby releasing vast amounts of energy. Fission is the splitting of a heavy, unstable nucleus into two lighter, more stable nuclei, again releasing vast amounts of energy.

In fusion reactions, the amount of matter that is converted to energy is about 0.7%, while in fission reactions, the amount of matter that is converted to energy is about 0.1%. These numbers apply whether the process takes place in nuclear bombs, in nuclear reactors, in our Sun or in the stars (Figure 4B–4).

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Figure 4B–4 Left: Nuclear fusion powers the Sun. Right: Testing $E = mc^2$ in a fission–fusion nuclear weapon.

Electricity generation using nuclear energy

After World War II, governments and atomic scientists wanted to demonstrate the peaceful uses of atomic energy. In 1953, US President Eisenhower proposed his Atoms for Peace program, which reoriented significant research effort towards nuclear power plants for electricity generation and set the course for civil nuclear energy development in the United States. Similar projects were initiated in Russia and the United Kingdom.

Safety hazards of nuclear energy

Nuclear fuel can provide large amounts of energy, but this comes at a price. Every nuclear reactor produces nuclear waste – a form of pollution that neither the human species nor our fragile biosphere has ever had to cope with before. Some radioactive by-products from nuclear power stations may be hazardous for up to a million years (e.g. plutonium-239). Critics argue that there are still no generally acceptable long-term storage solutions for these radioactive wastes.

There are three types of nuclear waste, classified according to their radioactivity: **low-level**, **medium-level** and **high-level waste**. The vast majority of the waste (90% of the total volume) is composed of only low-level radioactive items, such as tools and work clothing. It contains only 1% of the total radioactivity. By contrast, high-level waste – mostly comprising used nuclear fuel rod material – accounts for just 3% of the total volume of waste but contains 95% of the total radioactivity. Although such waste does not take up a lot of space, it is highly radioactive. High-level waste will take about 1200 years to return to the same level of radioactivity as that of the original uranium ore and many millions of years before it is safe to return to the environment. High-level waste must be stored in shielded containers to prevent radiation escaping into the environment and must be continually cooled to stop overheating.

Low-level waste nuclear waste usually stored on site for short periods of time and then released into the environment

Medium-level waste nuclear waste requiring a longer storage time and requires shielding but not cooling

High-level waste nuclear waste that needs to be stored for a very long time in shielded containers and continually cooled to stop overheating

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Figure 4B–5 The Fukushima Daiichi Nuclear Power Plant disaster caused damage to the buildings housing reactors 1–4. The visible damage was caused by explosions of hydrogen gas released by the reaction of hot zirconium alloy with steam from the steam generators. Inside, the cores of reactors 1 and 2 have melted and pooled at the bottom of their concrete containment vessels. The cause of the disaster was the 2011 Tōhoku earthquake and tsunami that destroyed the emergency generators powering the reactor cooling pumps, leading to the reactors overheating.

Another area of concern with nuclear power plants is the possibility of nuclear accidents. Many critics of nuclear energy point to the accidents that occurred at Chernobyl (1986) and Fukushima (2011, see Figure 4B–5) as examples of the inadequacies of safety procedures in nuclear power stations.

Supporters of nuclear power suggest that it is an effective way of creating electrical energy that avoids the emission of large amounts of CO_2 and other atmospheric pollutants associated with the greenhouse effect. They also argue that it is a readily available source that is not dependent on wind or sunlight and can provide reliable base-load power.

4C NUCLEAR ENERGY FOR AUSTRALIA LINK

Nuclear fission reactors are also used to produce radioisotopes that have many applications in industry, medicine, agriculture and scientific research (see also OPAL, Section 4C).

Check-in questions – Set 1

1 What is the mass difference percentage energy conversion for nuclear fission and nuclear fusion?

2 a What were the code names used for the nuclear bombs dropped on Hiroshima and Nagasaki?

b Why were two different two fissile isotopes used for constructing the nuclear bombs dropped on Hiroshima and Nagasaki?

3 What is the major long-term environmental issue with producing electricity using nuclear fission reactors?

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How chemical elements are formed

Physicists believe that hydrogen, helium and lithium were all created as a result of the Big Bang explosion. They also believe that all of the other elements on Earth were made during the life and death of stars.

Most of the energy of a star comes from light elements combining into heavier elements in nuclear fusion. The Sun is currently burning, or fusing, hydrogen to helium. This is the process that occurs during most of any star's lifetime. After the hydrogen in the star's core is exhausted, the star can fuse helium to form progressively heavier elements such as carbon and oxygen and so on until iron and nickel are formed. Up to this point, the fusion process releases energy.

The formation of elements heavier than iron and nickel requires an extra input of energy. Supernova explosions result when the cores of massive stars have exhausted their fuel supplies and burned everything into iron and nickel. Many of the nuclei with masses greater than that of nickel are observed to be formed during these explosions.

More recently it has been discovered that colliding neutron stars are responsible for producing enormous amounts of heavy elements, including gold, silver and xenon.

Together with supernovas, colliding neutron stars produce all the elements of the periodic table and generate all the elements necessary to make rocky planets ready to host living organisms. We are all made of these stars.

Figure 4B–6 Left: Cassiopeia A, a remnant supernova, produced heavy elements. Right: An artist's impression of two colliding neutron stars producing heavy elements, including gold, silver and xenon.

Our Sun – a local nuclear fusion reactor

Nuclear fusion is the process that powers the Sun. In the series of nuclear reactions shown below, various isotopes of hydrogen are finally fused into helium-4 with the release of a tremendous amount of energy.

$$^{1}_{1}H + ^{1}_{1}H \rightarrow ^{2}_{1}H + ^{0}_{1}e$$

$$^{2}_{1}H + ^{1}_{1}H \rightarrow ^{3}_{2}He + \gamma$$

$$^{3}_{2}He + ^{3}_{2}He \rightarrow ^{4}_{2}He + ^{1}_{1}H + ^{1}_{1}H$$

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Plasma
a form of matter in which all the atoms are completely ionised – sometimes called the fourth state of matter

Thermonuclear bomb
a two-stage nuclear weapon with an initial fission stage, which then triggers a much larger fusion explosion

Inside the core of the Sun, these fusion reactions take place at very high temperatures and enormous pressures. The Sun's core is made of a very hot (15 million kelvin), dense **plasma** at a very high pressure. It is the combination of the very high temperature and extremely high pressure that allows the two hydrogen nuclei (protons) to overcome the extremely strong electrostatic repulsion as they undergo the various processes of nuclear fusion to eventually become helium-4.

Nuclear fusion weapons: the hydrogen bomb

The extreme conditions necessary for the fusion of hydrogen (very high temperatures and pressures) in a hydrogen bomb are created by the explosion of a small fission bomb, which initiates the fusion fuel, creating a super-hot plasma. This means a fusion (or hydrogen) bomb is actually a two-stage nuclear weapon – an initial fission stage, which then triggers a much larger fusion explosion (Figure 4B–7). Lithium-6 deuteride is used as the fusion fuel; it is transformed to tritium early in the fusion process. Such nuclear weapons are known as **thermonuclear bombs**, because the initial fission explosion creates the extreme temperature and pressure combination necessary to ensure that the electrostatic repulsion between the positive hydrogen nuclei is overcome and an uncontrolled fusion explosion commences that only stops when the fusion fuel runs out.

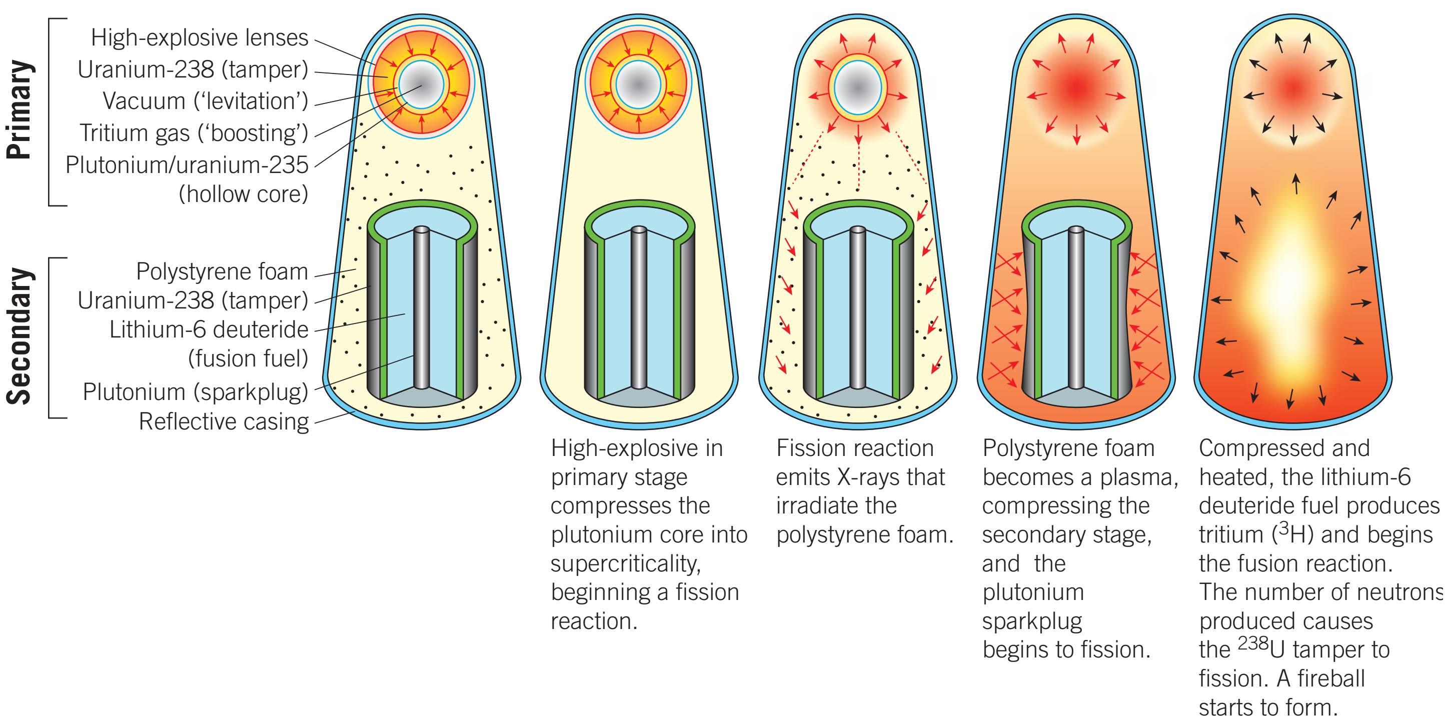

Figure 4B–7 Basic design of a hydrogen fusion bomb and the sequence of operation

Theoretically, thermonuclear bombs can be built to any size. The process could be continued with energy from the secondary fusion stage igniting a third fusion stage and so on.

4A NUCLEAR ENERGY AND ENERGY–MASS EQUIVALENCE LINK

In contrast to thermonuclear bombs, pure fission nuclear weapons are limited in their yield because only so much fission fuel can be amassed in one place before the danger of it accidentally becoming supercritical becomes too great.

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Fusion reactors

The practicalities associated with controlled nuclear fusion – to create miniature 'suns' on Earth and unlock controlled nuclear fusion with its promises of almost unlimited, clean, carbon-free energy with no long half-life radioactive by-products – are proving extremely difficult.

Designing the 'uncontrollable' hydrogen–helium fusion bomb was relatively straightforward compared to designing a controllable nuclear fusion reaction in the laboratory that can be scaled up to producing 1000 MW nuclear fusion reactors.

The physics of controlled nuclear fusion is deceptively simple. Although different isotopes of light elements can be paired to achieve fusion, the deuterium–tritium (DT) reaction below has been identified as the most efficient for Earth-based nuclear fusion devices:

$$^{2}_{1}H + ^{3}_{1}H \rightarrow ^{4}_{2}He + ^{1}_{0}n$$

Deuterium ($^{2}_{1}H$) can be distilled from all forms of water. It is a widely available, harmless and virtually inexhaustible resource. In every cubic metre of seawater, for example, there are 33 of deuterium. Deuterium is routinely produced for many scientific and industrial applications.

Tritium ($^{3}_{1}H$) is a radioactive isotope of hydrogen with a half-life, $t_{\frac{1}{2}}$, of 12.3 years that occurs only in trace quantities in nature. It can be produced during the fusion reaction through contact with lithium. Tritium is 'bred' when neutrons escaping the plasma interact with lithium contained in the blanket wall inside the nuclear fusion device.

Lithium is an easily extractable land-based resource that should provide sufficient stock to operate fusion power plants for more than 1000 years. Lithium can be extracted from ocean water, where reserves are practically unlimited.

A nuclear fusion reaction is about 12 million times more energetic than a chemical reaction such as the burning of coal, oil or gas. While a 1000 MW coal-fired power plant requires 2.7 million tonnes of coal per year, a fusion plant of the kind envisioned for the second half of this century will only require 250 kg of fuel per year: half of it deuterium, half of it tritium.

The technological problems of fusing deuterium–tritium on Earth are challenging. As we do not have the extremely high pressures available in the Sun, the temperatures have to be much higher than the Sun's 15×10^{6} K. The deuterium–tritium fusion requires very high temperature. The temperatures inside the Earth-based fusion reactor must reach at least 150×10^{6} K – or ten times the temperature at the core of the Sun – in order for the gas in the vacuum chamber to reach the plasma state and for the fusion reaction to occur. As the plasma is too hot to come into contact with any material it must be contained in an extremely strong toroidal (donut-shaped) magnetic field. A tokamak is a device that does this.

Figure 4B–8 shows the design for the ITER currently under construction in France. ITER is designed to produce a ten-fold return on energy – 500 MW of fusion power from 50 MW of input heating power. The intention is to have a working nuclear fusion reactor by 2035.

It has been estimated that the world has spent over $12 trillion on a nuclear arms race to ensure 'peace', while only an estimated $200 billion has been spent on controlled nuclear fusion research with its potential to generate almost unlimited, clean, carbon-free energy with no harmful long half-life radioactive by-products.

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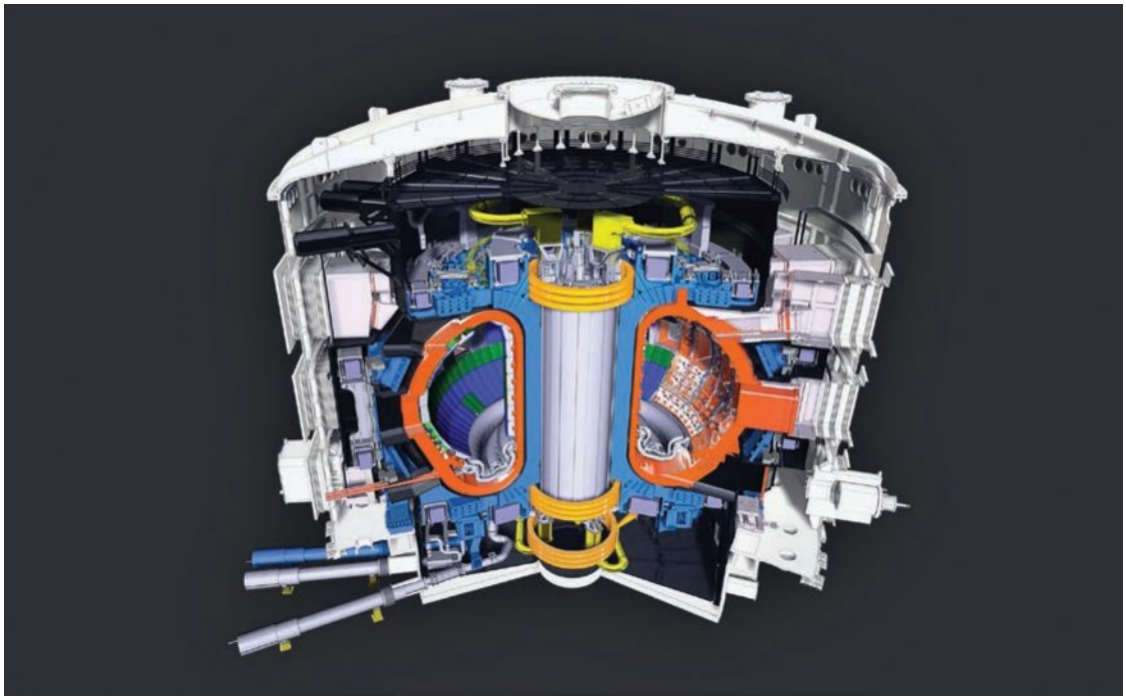

Figure 4B–8 The design for the ITER currently under construction in France. If successful it could generate almost unlimited, clean, carbon-free energy with no harmful long half-life radioactive by-products.

Binding energy curves

You can understand the physics of fusion and fission by carefully analysing the binding energy curve (Figure 4B–9). The binding energy itself is explained in the graph.

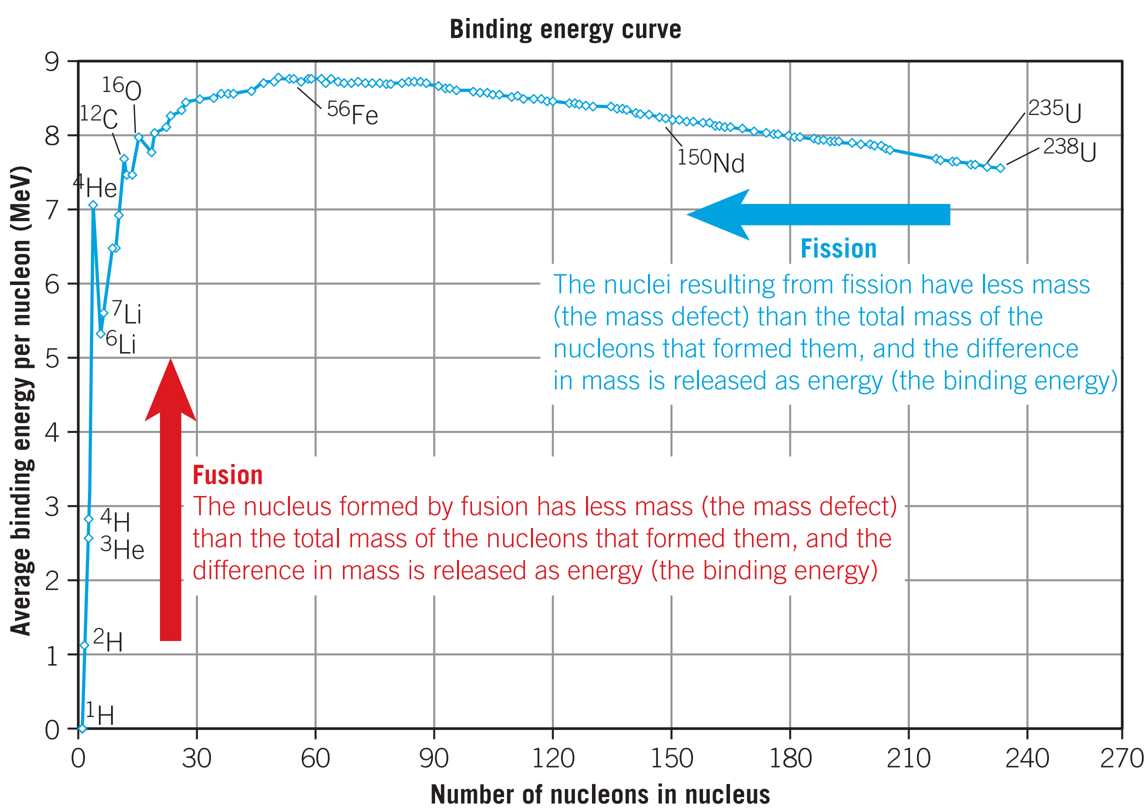

Figure 4B–9 The binding energy curve shows that light elements (low number of nucleons) undergoing fusion (joining together) release energy and heavier elements (high number of nucleons) undergoing fission (splitting into two) release energy. The difference in mass, the mass defect and the binding energy are defined and calculated in the rest of this section.

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The nucleus of an atom is made up of neutrons and protons and there are large electrostatic forces of repulsion between the positive charges of the protons. It takes an energy, called the **binding energy**, to hold nucleons together as a nucleus.

Iron has a mass number of 56 and is the most stable of all the elements. We say that iron has a high binding energy per nucleon.

Binding energy the amount of energy required to split a nucleus into its individual nucleons

Mass defect change in mass of a nucleus created by fusion, or change in mass of the nuclei created in fission

Binding energy and mass defect in fusion

In fusion, the mass of the nucleus that is created is slightly less than the total mass of the original nuclei. The change in mass or **mass defect** is due to the binding energy that is released during fusion. On the binding energy curve (Figure 4B–9), you can see that increasing the number of nucleons in a nucleus up to iron-56 causes the average binding energy per nucleon to increase, releasing energy and forming a more stable nucleus.

Worked example 4B–1 Energy of nuclear fusion

Fusion

The deuterium–tritium nuclear fusion reaction used in the ITER creates helium-4 in the following reaction:

$$^{2}_{1}H + ^{3}_{1}H \rightarrow ^{4}_{2}He + ^{1}_{0}n + \text{energy}$$

Note that the energy on the right-hand side of the equation is the kinetic energy of the helium-4 and the neutron – the neutron has no binding energy. The average binding energy (ABE) per nucleon for deuterium, tritium and helium-4 is given in the table below. Copy and complete the table.

	Deuterium	Tritium	Helium-4
ABE (MeV)	1.12	2.83	7.07
TBE (MeV)			

a Calculate the total binding energy (TBE) for each nucleus.

b Calculate the energy released in the deuterium–tritium nuclear fusion reaction that creates helium-4.

Solution

a Multiply the number of nucleons in each nucleus by the ABE to determine the TBE.

For example, deuterium has two nucleons, so TBE = 2 × 1.12 = 2.24 MeV. Tritium has three nucleons and helium-4 has four. Calculating the values gives:

	Deuterium	Tritium	Helium-4
ABE (MeV)	1.12	2.83	7.07
TBE (MeV)	2.24	8.49	28.28

b The energy released in the deuterium–tritium nuclear fusion reaction is the difference in binding energy between the final product of helium-4 and the reactants deuterium and tritium. Using the TBE values from part **a** gives:

$$E = 28.28 - (2.24 + 8.49)$$
$$= 17.55 \text{ MeV}$$

So, 17.55 MeV of energy is released in each fusion reaction, which is the kinetic energy of the helium-4 and the neutron.

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Binding energy and mass defect in fission

In fission, an unstable nucleus splits into smaller more stable nuclei with a smaller total mass. From the binding energy curve, you can see this difference in mass, the mass defect, between the parent nucleus and the daughter nuclei is due to the binding energy per nucleon increasing as the number of nucleons in each nucleus increases to iron-56. This increase in binding energy per nucleon is released as energy during fission forming more stable nuclei.

Worked example 4B–2 Energy of nuclear fission

Fission

Calculate the energy released in the following fission reaction, in MeV:

$$^{235}_{92}\text{U} + ^{1}_{0}\text{n} \rightarrow ^{93}_{37}\text{Rb} + ^{141}_{55}\text{Cs} + 2\,^{1}_{0}\text{n}$$

Nuclide/particle	$^{1}_{0}\text{n}$	$^{93}_{37}\text{Rb}$	$^{141}_{55}\text{Cs}$	$^{235}_{92}\text{U}$
Mass ($\times 10^{-27}$ kg)	1.675	154.248	233.927	390.173

Solution

The energy released in the reaction is due to an increase in binding energy, which you get from the mass defect and the relationship $E = \Delta mc^2$. Calculate the mass, m, for each side of the reaction using the data table.

Total mass before the reaction: $^{235}_{92}\text{U} + ^{1}_{0}\text{n}$

$$m_{\text{before}} = (390.173 + 1.675)(10^{-27})$$
$$= 391.848 \times 10^{-27}\ \text{kg}$$

Total mass after the reaction: $^{93}_{37}\text{Rb} + ^{141}_{55}\text{Cs} + 2\,^{1}_{0}\text{n}$

$$m_{\text{after}} = (154.248 + 233.927 + (2 \times 1.675))(10^{-27})$$
$$= 391.525 \times 10^{-27}\ \text{kg}$$

The mass defect (difference between the before and after mass) is given by:

$$m_{\text{defect}} = m_{\text{after}} - m_{\text{before}}$$
$$= (391.848 - 391.525)(\times 10^{-27})$$
$$= 0.323 \times 10^{-27}$$
$$= 3.23 \times 10^{-28}\ \text{kg}$$

Energy released is energy equivalent to the mass defect by $E = \Delta mc^2$. Therefore:

$$E = m_{\text{defect}} \times c^2$$
$$= (3.23 \times 10^{-28})(3.00 \times 10^{8})^2$$
$$= 2.91 \times 10^{-11}\ \text{J}$$

Converting J to eV with the relationship 1.00 J = 6.242×10^{18} eV gives:

$$E = (2.91 \times 10^{-11})(6.242 \times 10^{18})$$
$$= 1.81 \times 10^{8}$$
$$= 181\ \text{MeV}$$

Therefore, 181 MeV of energy is released in each fission reaction, but on a mass basis the fusion reaction releases more per kg of reactants.

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Check-in questions – Set 2

1 What is the nuclear process that powers the Sun called?
2 a What is a thermonuclear bomb?
  b What is the main fuel for a thermonuclear bomb?
3 What is a tokamak and why is it used for experimental nuclear fusion reactors?

WORKSHEET 4B–1 COMPARING FUSION AND FISSION

4B SKILLS

VIDEO 4B–2 SKILLS: CALCULATING THE POWER OUTPUT OF STELLAR NUCLEAR FUSION

Calculating the power output of stellar nuclear fusion
A typical exam question involving mass difference and fusion may, for example, require you to calculate the power output of a star. The question will give relevant data including the rate at which the mass-energy conversion is happening (mass difference per second). You will need to know the difference between energy E (measured in joules, J) and power P (measured in watts, W or J s^{-1}) which are related by the formula $E = \frac{P}{t}$.

The Sun converts 600 million tonnes of hydrogen per second into helium with a mass difference of 4.20 million tonnes per second due to nuclear fusion.

Calculate the power output of the Sun. Use $c = 3.00 \times 10^8$ m s^{-1}.

Solution

$$\text{mass difference} = (4.20 \times 10^6)(1000)$$
$$= 4.20 \times 10^9 \text{ kg}$$

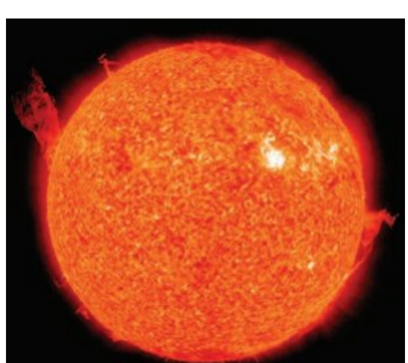
Using $E = \Delta mc^2$ gives:

$$E = (4.20 \times 10^9)(3.00 \times 10^8)^2$$
$$= 3.78 \times 10^{26} \text{ J}$$

This is the energy output every second from the Sun as the mass difference is given as 4.20 million tonnes per second.

To find the power of the Sun, you need to use the formula power $= \frac{\text{energy}}{\text{time}}$:

$$P = \frac{E}{t}$$
$$= \frac{3.78 \times 10^{26}}{1.00}$$
$$= 3.78 \times 10^{26} \text{ W}$$



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Section 4B questions

Multiple-choice questions

1 What is the mass of the products of a nuclear fusion reaction compared to the mass of the original nuclei before fusion?

A less
B same
C more
D sometimes less and sometimes more

2 What is the mass of the products of a nuclear fission reaction compared to the mass of the original nuclei before fission?

A less
B same
C more
D sometimes less and sometimes more

3 What is a positive aspect of nuclear fission?

A the ability to create nuclear weapons
B the ability to release tremendous amounts of energy
C the ability to produce clean nuclear energy with no long-term radioactive waste
D there are no currently known positive aspects of nuclear fission

4 The release of energy in nuclear fission is consistent with the fact that uranium

A has less mass per nucleon than the fragments created.
B has more mass per nucleon than the fragments created.
C has the same mass per nucleon as the fragments created.
D None of the above.

5 The binding energy curve plots the

A average binding energy per proton vs number of protons in the nucleus.
B average binding energy per nucleon vs number of nucleons in the nucleus.
C average binding energy per neutron vs number of neutrons in the nucleus.
D average binding energy per electron vs number of electrons in the nucleus.

Short-answer questions

6 Why are nuclear fission weapons far more powerful than TNT, for the same mass of explosive material?

7 Why are nuclear fusion weapons far more powerful than nuclear fission weapons, for the same mass of explosive material?

8 a One of the long-term effects from a nuclear explosion is radioactive fallout. If all 3.0×10^{26} radioactive fission nuclei were spread evenly among the human population (8 billion), how many radioactive nuclei would each human breathe in?

b Why is this not a realistic calculation?

9 What are the problems involved in making controlled sustainable fusion on Earth?

10 How is the binding energy of a nucleus related to the mass difference of its nucleons?

11 Nuclear fusion in the Sun is given by the equation:

$$^{3}_{2}\text{He} + {}^{3}_{2}\text{He} \rightarrow {}^{4}_{2}\text{He} + {}^{1}_{1}\text{H} + {}^{1}_{1}\text{H}$$

The binding energy for helium-3 is 7.7178 MeV and for helium-4 is 28.2957. Calculate the equivalent energy in MeV, and joules, released by this fusion reaction.

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4C Nuclear energy for Australia

Study Design:
Investigate the viability of nuclear energy as an energy source for Australia

ENGAGE

Natural nuclear reactors

In the 1970s, physicists measuring samples of uranium ore in Gabon, West Africa, found evidence of a natural chain reaction that occurred about 1800 million years ago!

Figure 4C–1 Uranium ore, such as this sample from an Australian mine, normally contains the isotopes uranium-235 and uranium-238 in the ratio of 1:140.

Uranium ore that is dug up today normally contains the isotopes uranium-235 and uranium-238 in the ratio of 1:140; this percentage is fixed by the relative half-lives of the two isotopes. The Gabon sample, however, contained unusually low proportions of uranium-235, especially where the ore was rich in uranium. Further investigation revealed that there were traces of other rare elements in the ore body, in proportions typical of those found in artificial nuclear reactors. Physicists think that 1800 million years ago, when the proportion of uranium-235 was possibly as high as 3%, there was enough fissile uranium in the rock for a natural chain reaction to begin. It is believed that water trapped in the surrounding sandstone may have acted as a moderator. The reactors probably switched on and off at regular intervals. The nuclear fission began, moderated by water, and continued until all available water boiled away as a result of nuclear heat. The reactions could not begin again until new water entered the reactor. This water would be replenished periodically. As a result, the Gabon natural nuclear reactors were extremely stable. There was not a single meltdown; the reactors operated in a stable fashion for up to one million years. Eventually, so much of the fissionable uranium-235 had been used that the Gabon natural nuclear reactors shut themselves down. Evidence of 17 such natural nuclear reactors were eventually found in Gabon. Unfortunately, subsequent intensive uranium mining has destroyed 16 of these natural nuclear reactors.

There is a tendency in public opinion to think that nuclear energy and ionising radiation on Earth are entirely human-made, but this research highlights these processes at work in nature.

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EXPLAIN

Historical and contemporary aspects of Australian attitudes to nuclear energy

The prospect of using nuclear energy as an energy source in Australia has been a divisive topic of public debate since the 1950s. There have been many aspects to the debate – some involving an understanding of the physics of nuclear energy and its implications for humanity and the environment, and others relying on less-informed views.

The issues include the secret British atomic bomb testing on Australian soil and the forceful removal of Aboriginal and Torres Strait Islander peoples from their land; the French nuclear bomb tests in the Pacific; uranium mining in Kakadu National Park; Greenpeace occupying the Lucas Heights Nuclear reactor when protesting about the plans to build a new reactor on the site in Sydney; the purchasing of nuclear submarines by the Australian Government, and the minimal CO_2 impact of nuclear power stations on the environment in our pursuit of reaching climate change targets.

Maralinga

In the 1950s, the Australian Government secretly authorised British atom bomb tests in Australia. Between 1955 and 1963, seven series of atomic tests were undertaken on the Aboriginal land of the Anangu people. Many of the Maralinga Tjarutja, the traditional Aboriginal owners of the land, were forcibly removed from their traditional lands.

This forced relocation destroyed the traditional lifestyle of many Aboriginal families.

Survivors recall seeing the fleeing Aboriginal people being picked up in military trucks or forced on long walks through the desert without water, on routes that avoided exposure to the contaminated lands.

It is believed about 1200 Aboriginal people were exposed to radiation during the testing. The radioactive fallout – called 'puyu' (black mist) by Aboriginal people – caused sore eyes, skin rashes, diarrhoea, vomiting, fever and the early death of entire families. The explosions caused blindness. Long-term illnesses such as cancer and lung disease were found in the 1980s, a time when some Elders grew restless and walked back into their Country.

Figure 4C–2 Left: British nuclear test Operation Buffalo at Maralinga in 1956. Right: Conducting a nuclear test at Maralinga where the soldiers unknowingly become part of the experiment.

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In addition to the major tests, the British carried out 550 minor trials between 1953 and 1963. These experiments were subcritical tests involving the testing of nuclear weapon components, but were not nuclear explosions. They involved experiments with plutonium, uranium, polonium and beryllium to study dispersal patterns of radioactive materials with the prevailing winds.

The United Kingdom Atomic Weapons Research Establishment conducted a minor clean-up of the site in 1964, followed by a major clean-up in 1967. An area of 2 km^2 around the firing range site was ploughed, and all the contaminated equipment and material was buried in 22 pits. These were capped with a sarcophagus (tomb) of 650 tonnes of concrete to prevent any radioactive material or radiation escaping. The British Government stated that 20 kg of the 22 kg of plutonium exploded at the site had been collected and was completely contained in the capped pits. The Australian Government then released the British Government from all further liabilities concerning the Maralinga site.

In 1984, approximately 3000 km^2 of land around Maralinga was scheduled to be returned to the Maralinga Tjarutja, the traditional Aboriginal owners of the land. As a precaution, scientists from the Australian Radiation Laboratory (ARL) were asked to check the radiation levels at the site. They were astonished to find that the level of radioactivity was 10 times higher than predicted and much more widely dispersed than had been claimed by the British Government. The scientists measured radioactivity levels over 400 $kBq\,m^2$ at distances 2.5 km from the testing site. The ARL scientists estimated that there were more than 3 million particles contaminated with plutonium, ranging in size from a few tens of micrometres in diameter to objects bigger than a cricket ball. The ARL scientists concluded that, contrary to the British assurances, most of the 22 kg of plutonium used in the tests was in fact dispersed in the lands of the Maralinga Tjarutja, in an area that extended more than 150 km from the British testing sites. Although plutonium is a short-range alpha particle emitter, it is easily inhaled with the dust during windy periods in the desert area and is therefore extremely dangerous. In addition, plutonium has a half-life of 24 100 years, meaning it will be almost a quarter of a million years before its activity is safe enough to make the contaminated lands habitable again.

In 1985, The Royal Commission into British Nuclear Tests in Australia found that attempts to ensure the safety of Aboriginal and Torres Strait Islander peoples were riddled by ‘ignorance, incompetence and cynicism’. The boundaries of the test fields were inadequately patrolled and the British dismissed concerns for Aboriginal and Torres Strait Islander peoples’ safety with the heartless comment that ‘a dying race couldn’t influence the defence of Western civilisation’.

Extensive research into this shameful chapter in Australia’s history is still being undertaken today and a recent report into high-level plutonium waste on the site indicates that some areas on the site are still not safe for human habitation.

OPAL

Australia’s Open Pool Australian Lightwater (OPAL) reactor is a state-of-the-art 20 MW multi-purpose reactor that uses 20% enriched uranium to create neutron beams for fundamental materials research as well as producing numerous radioisotopes for medical diagnosis and treatment, industry, agriculture and scientific research. It is situated in Lucas Heights, 31 km south-west of Sydney and is part of the Australian Nuclear Science and Technology Organisation.

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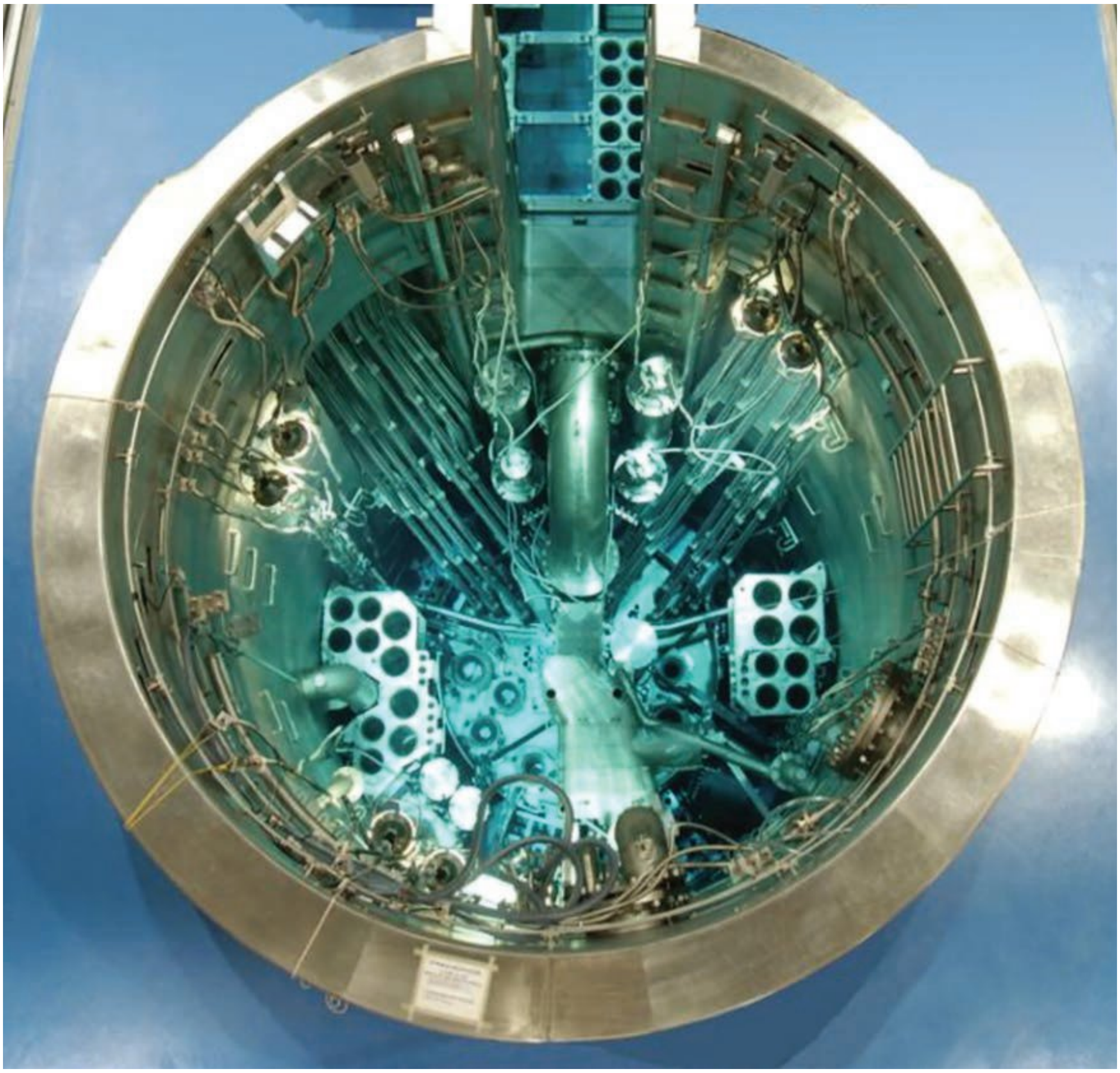

Figure 4C–3 Australia's OPAL Nuclear Research Reactor produces radioisotopes for medical diagnosis and treatment as well as neutron beams for industrial and research purposes.

The heart of the reactor is a compact core of 16 uranium-235 fuel assemblies arranged in a 4 × 4 array, with five control rods controlling the reactor power and facilitating shutdown. OPAL uses low-enriched uranium (20%) fuel.

OPAL's reactor core is cooled by water and is surrounded by a zirconium alloy 'reflector' vessel that contains heavy water (D_2O). The reflector vessel is positioned at the bottom of a 13-metre deep pool of normal (light) water (H_2O). The open pool design makes it easy to see and manipulate items inside the reactor pool.

The depth of the water acts as an effective radiation shield. The heavy water maintains the nuclear reaction in the core by 'reflecting' neutrons back towards the core.

Every Australian is likely to benefit from nuclear medicine and on average will have at least two nuclear medicine procedures in their lifetime. About 75–80% of all of the radioisotopes used in these nuclear medicine procedures in Australia come from the OPAL nuclear research reactor.

More than 50 countries use nuclear energy in about 220 research reactors. In addition to research, these reactors produce medical and industrial isotopes.

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Nuclear submarines

In 2021, the Australian Government ordered at least eight new nuclear submarines at an estimated cost of $120 billion. A key feature of the intended submarines is that they are fuelled 'for life' and are capable of being submerged for periods extending up to 6 months. These will carry 500 MW nuclear reactors on board but will carry conventional weapons – not nuclear weapons like their 'cousin' submarines in the United States and United Kingdom, that carry 24 nuclear missiles with a total destructive capacity more than 1000 times the destructive explosive power of the bombs dropped on Hiroshima and Nagasaki.

Nuclear energy for Australia

Australia has never used nuclear energy for generating electrical power, although Australia has a third of the world's uranium deposits and is the world's third largest producer of uranium for nuclear power stations. It has usually been argued that Australia's significant coal and gas reserves have not necessitated the use of nuclear power.

This contrasts sharply with France, which has 56 functioning nuclear reactors generating more than 70% of the country's electricity. France is the world's largest net exporter of electricity due to its very low cost of generation using nuclear power, and gains over €3 billion per year from this. A 2015 energy policy had aimed to reduce the country's share of nuclear generation to 50% by 2025. This target has now been postponed. The country's energy minister said that the target was unrealistic, that it would increase the country's CO_2 emissions, endanger security of supply and put jobs at risk.

When greenhouse gas emissions from Australia's current coal, oil and gas exports (3.6% of global total) are added to domestic emissions (1.4% of global total), Australia's contribution to the global climate pollution footprint is about 5%. That's equivalent to the total greenhouse gas emissions of Russia, the world's fifth largest CO_2 emitter.

Some of the reasons for Australia's high levels of emissions include the fact that in 2022 approximately 71% of electricity was generated from fossil fuels (51% of the electricity was generated from coal, 18% from gas and 2% from oil). A warm climate also results in high use of energy-hungry air-conditioning units.

In 2021 Australians used 189 billion kilowatt hours (kWh) of electric energy per year. Per capita, this was an average of 7416 kW h. Wind turbines, solar energy and hydro-electricity contributed 29% of our electricity needs.

Australia's uranium recent prevent at least 395 million tonnes of CO_2 per year being pumped into Earth's atmosphere, relative to the use of black coal. Australia's total low-cost uranium reserves could prevent nearly 40 000 million tonnes of CO_2 emissions if these reserves were used instead of fossil fuel for electricity generation.

A single nuclear power plant of 1000 MW capacity can offset the emission of some 7–8 million tonnes of CO_2 each year if this is used instead of black coal generation. A nuclear power plant will also reduce the emission of sulfur dioxide, nitrous oxide and particulates, thereby contributing significantly to improved air quality.

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Nuclear energy versus renewables

So what are the arguments for and against the use of nuclear electricity in Australia? Is the push for renewable energy feasible, viable and stronger than that of nuclear energy? Read the thoughts below and decide.

Figure 4C–4 Nuclear versus renewables – deciding Australia's future energy directions

James Lovelock, a scientist and climate change environmentalist, had this to say in 2004.

Nuclear power is the only green solution
Sir James Lovelock
The Independent, 24 May 2004

… I am a Green and I entreat my friends in the movement to drop their wrongheaded objection to nuclear energy. Even if they were right about its dangers, and they are not, its worldwide use as our main source of energy would pose an insignificant threat compared with the dangers of intolerable and lethal heat waves and sea levels rising to drown every costal city in the world. … Civilisation is in imminent danger and has to use nuclear – the one safe, available, energy source – now or suffer the pain soon to be inflicted by our outraged planet.

The Mineral Councils of Australia had this to say in 2019.

Untapped potential and the case for nuclear energy

Climate change is real and as global energy demand increases, so does the need to decarbonise our power supplies.

Nuclear energy provides around 10 per cent of the world's electricity demand with zero emissions. The power provided by nuclear energy is low cost and can meet the needs of industrial and household consumers 24/7. And billions of citizens in 31 countries already benefit from low cost zero emissions nuclear power.

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Yet Australia, with the world's largest deposits of uranium, continues to prohibit the use of nuclear power. The House of Representatives Standing Committee on Environment and Energy's Inquiry into the prerequisites for nuclear energy in Australia offers a chance to consider the absurdity of this position.

The Minerals Council of Australia strongly supports nuclear power in Australia and continues to promote the case for nuclear energy to support an informed and mature debate on this important issue.

In contrast, the Climate Council of Australia (a peak independent body communicating aspects of climate change) recently made the following points about using nuclear power for electricity generation in Australia.

Nuclear power stations are expensive and take too long to build

Climate Council: Nuclear power stations are not appropriate for Australia – and probably never will be

CSIRO says by far the lowest cost way of producing electricity is with solar and wind even when factoring in storage. In contrast, the costs of building and operating nuclear power stations in Australia remain prohibitively high. Further, analysis conducted by the nuclear industry itself shows nuclear power stations take an average of 9.4 years to build – compared to 1–3 years for a major wind or solar project. Australia needs to replace its ageing coal-fired power stations as quickly as possible, and should be slashing its emissions by 75% this decade. As shown in the Australian Energy Market Operator's Integrated System Plan, by far the cheapest and quickest way to do this is to ramp up renewable energy paired with storage like pumped hydro, and batteries.

Nuclear power poses significant community, environmental, health and economic risks. Radiation from major nuclear disasters, such as Chernobyl in 1986 and Fukushima in 2011, have impacted hundreds of thousands of people and contaminated vast areas that take decades to clean up. Even when a nuclear power station operates as intended it creates a long-term and prohibitively expensive legacy of site remediation, fuel processing and radioactive waste storage. They are also water hungry – requiring massive quantities of water for ongoing operations.

Nuclear power is not renewable. Uranium is a finite resource just like coal, oil and gas. While the operation of a nuclear reactor does not create greenhouse gas emissions, all other parts of producing nuclear power are polluting from mining, to construction, decommissioning and waste management.

Australia is one of the sunniest and windiest countries on Earth, with enough renewable energy to power resources to power our country 500 times over. Building large-scale wind and solar projects is the cheapest way of producing electricity here, even when paired with storage. It is also low risk, renewable and non-polluting. The bottom line is – nuclear power is the slowest, most expensive, most dangerous and least flexible form of new power generation for Australia. It makes no sense. So let's stop wasting time, and get on with building more renewables.

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VIDEO 4C–1 SKILLS: CRITICAL THINKING IN PHYSICS

4C SKILLS

Critical thinking in physics

In critical thinking it is important to:

a make sure you understand the crucial concepts and the links between the various ideas
b determine the relevance and the importance of the arguments and ideas presented
c appraise arguments and identify any inconsistencies and errors in reasoning
d note if there are vested interests in organisations presenting certain points of view
e reflect on how your own assumptions, beliefs and values impact on your evaluation.

In this section you are considering the viability of nuclear energy as an energy source for Australia.

What are the crucial concepts? For example: energy use, production processes and environmental consequences using coal, hydro, solar wind and nuclear as energy sources for generating electricity.

How are they linked?

What are the arguments presented for and against nuclear energy as an energy source for Australia?

Can you identify inconsistencies and errors in reasoning in the arguments presented?

What are the benefits to be gained by, for example, the Minerals Council of Australia or the Climate Council of Australia?

What are your own biases and how do they influence your evaluation?

WORKSHEET 4C–1 NUCLEAR ENERGY FOR AUSTRALIA

Check-in questions – Set 1

1 a What did the British Government test at Maralinga in South Australia in the 1950s and 1960s?
  b What was the impact on the Maralinga Tjarutja, the traditional Aboriginal owners of the land?
2 What is Australia's OPAL reactor used for?
3 a What is the efficiency of a nuclear reactor boiler that produces 1000 MW electrical energy from a 2800 MW thermal energy.
  b Where does the extra thermal energy of 1800 MW go?

Section 4C questions

Multiple-choice questions

1 Putting radioactive plutonium-239, an alpha particle emitter, in concrete capped pits means that the plutonium is
  A no longer radioactive.
  B now safely stored forever.
  C still radioactive but the alpha particles cannot penetrate the concrete cap.
  D still radioactive and some of the alpha particles will penetrate the concrete cap but not enough to cause concern.

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2 On average, every Australian will use nuclear medical radioisotopes produced by the OPAL nuclear reactor
   A hardly ever in their lifetime.
   B less than once in their lifetime.
   C at least twice in their lifetime.
   D at least seven times in their lifetime.

3 Australia has
   A a fifth of the world's uranium deposits.
   B a quarter of the world's uranium deposits.
   C a third of the world's uranium deposits.
   D two-thirds of the world's uranium deposits.

4 The Mineral Councils of Australia suggests that Australia's electrical energy needs could best be supplied by
   A clean coal.
   B nuclear fusion power stations.
   C nuclear fission power stations.
   D renewable sources like solar and wind.

5 The Climate Council of Australia suggests that Australia's electrical energy needs could best be supplied by
   A clean coal.
   B nuclear fusion power stations.
   C nuclear fission power stations.
   D renewable sources like solar and wind.

Short-answer questions

6 a How much of the 22 kg of plutonium used by the British for nuclear testing at Maralinga was claimed to be buried in capped pits when the British cleaned up the site in 1967?
   b What did the ARL determine when the Maralinga site was inspected in 1984?
   c What is the main implication of the ARL findings for the traditional Aboriginal owners of Maralinga?

7 Plutonium is a short-range alpha particle emitter. Why is it hazardous to have more than 3 million particles contaminated with plutonium (ranging in size from a few tens of micrometres in diameter to objects bigger than a cricket ball) in the land at Maralinga?

8 Why do Australians need the OPAL nuclear reactor for medical purposes?

9 Give the main reason why some people say that nuclear energy is considered better than coal for generating electricity in Australia.

10 What does the Climate Council of Australia suggest is better than either coal or nuclear energy for creating electricity in Australia?

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Chapter 4 review

Summary

Create your own set of summary notes for this chapter on paper or in a digital document. A model summary is provided in the Teacher Resources, which can be used to compare with yours.

Checklist

In the Interactive Textbook, the success criteria are linked from the review questions and will be automatically ticked when answers are correct. Alternatively, print or photocopy this page and tick the boxes when you have answered the corresponding questions correctly.

Success criteria – I am now able to:		Linked questions
4A.1	Explain, qualitatively, nuclear energy as energy resulting from the conversion of mass to energy	4☐, 9☐, 11☐, 12☐, 18☐, 19☐, 21☐, 22☐
4A.2	Explain fission chain reactions	8☐, 17☐
4A.3	Discuss the effect of mass and shape on criticality in fission chain reactions	2☐, 3☐, 13☐, 15☐, 16☐
4A.4	Discuss the role of neutron absorption and moderators in fission chain reactions	5☐, 14☐, 21☐
4B.1	Compare and understand the processes of nuclear fusion and nuclear fission	1☐, 6☐, 7☐, 23☐, 27☐, 28☐
4B.2	Explain, using a binding energy curve, why fusion and fission are both nuclear reactions that release energy	24☐, 25☐, 26☐
4C.1	Investigate and analyse the viability of nuclear energy as an energy source for Australia	10☐, 20☐, 29☐, 30☐
4C.2	Discuss the advantages and disadvantages of nuclear energy for Australia	29☐, 30☐

Multiple-choice questions

1 Which one of the following statements best explains the process of fusion?
- **A** the joining of light nuclei to create a more stable nucleus like helium
- **B** the joining of light nuclei to create a more stable nucleus like uranium
- **C** the splitting of a heavy nucleus like uranium into two medium-sized nuclei
- **D** the creation of transuranic nuclei by bombarding uranium-238 with neutrons

2 What is a subcritical mass?
- **A** an amount of nuclear material with a neutron capable of inducing fission rate <1
- **B** an amount of nuclear material with a neutron capable of inducing fission rate $=1$
- **C** an amount of nuclear material with a neutron capable of inducing fission rate >1
- **D** an amount of nuclear material that is ready to explode as a bomb

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3 What is the chain reaction condition required for a nuclear fission bomb?
- **A** a subcritical mass and a neutron capable of inducing fission rate = 0
- **B** a subcritical mass and a neutron capable of inducing fission rate <1
- **C** a critical mass and a neutron capable of inducing fission rate = 1
- **D** a supercritical mass and a neutron capable of inducing fission rate >1

4 In nuclear power reactors, the fuel rods contain
- **A** pure uranium-235.
- **B** pure plutonium-235.
- **C** enriched uranium-235.
- **D** enriched plutonium-235.

5 The function of a moderator in a nuclear power reactor is to
- **A** absorb neutrons.
- **B** reflect neutrons.
- **C** speed up neutrons.
- **D** slow down neutrons.

6 What was the main reason that the uranium-235 fission gun barrel type bomb was not tested before it was used on Hiroshima?
- **A** It was believed it should work.
- **B** There was only enough uranium-235 for one bomb.
- **C** There was not a suitable testing site available for the test.
- **D** Uranium-235 bombs had been successfully used against Germany previously.

7 Why was the spherical plutonium-239 bomb tested before a similarly constructed bomb was dropped on Nagasaki?
- **A** Scientists wanted to know if an implosion design type of bomb would actually work.
- **B** There was more than enough plutonium-239 to construct five more bombs.
- **C** Scientists wanted to see if it produced enough radioactive by-products.
- **D** The United States wanted Japan to know they had a powerful new weapon.

8 One of the advantages of using enriched uranium to generate electricity in nuclear power stations is
- **A** no waste heat is created in a nuclear power station.
- **B** no dangerous radioactive by-products are created.
- **C** no carbon dioxide is released by uranium undergoing fission.
- **D** the spent fuel rods can not be recycled into creating nuclear weapons.

9 In what main form does the released energy from a nuclear fission reaction in a nuclear power plant appear?
- **A** thermal energy
- **B** light
- **C** gamma rays
- **D** electromagnetic radiation

10 Why does the Climate Council of Australia believe renewables are the best option for generating Australia's electricity?
- **A** because Australia is running out of coal
- **B** because Australia should be seen as leaders in green energy
- **C** because Australia is better off selling its uranium to the world
- **D** because Australia is one of the sunniest and windiest countries on Earth

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Short-answer questions

11 Comment on whether Einstein's equation, $E = mc^2$, can be used to explain how coal burns, how uranium fissions in a nuclear power plant and how the Sun shines because of the nuclear fusion of hydrogen. (3 marks)

12 Uranium ore that is mined from the ground contains uranium-235 and uranium-238.

- **a** Which of these isotopes normally represents 0.7% of the ore? (1 mark)
- **b** Which of these isotopes normally represents 99.3% of the ore? (1 mark)
- **c** Which of these isotopes is the more fissile when bombarded with slow neutrons. (1 mark)
- **d** Explain why a chain reaction does not normally occur in a uranium ore. (1 mark)

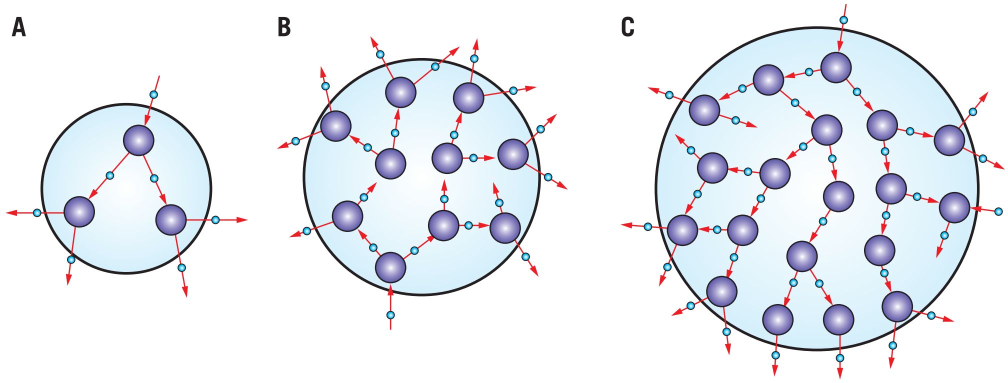
13 Why is uranium ore enriched to approximately 4% to be used in the fuel rods of the reactor core in some nuclear power stations? (2 marks)

14 The core of a nuclear reactor contains fuel rods, a moderator and control rods.

- **a** Explain the function of each component. (3 marks)
- **b** Give examples of typical materials used for each of these components. (3 marks)

15
- **a** Which has the greater surface area: a whole apple or the same apple that has been sliced in half? (1 mark)
- **b** Which will lose more neutrons to the surrounding environment, a spherical sample of uranium-235 or the same spherical sample that has been cut into two equal hemispherical pieces? (1 mark)
- **c** How is this related to the concept behind the 'Little Boy' uranium-235 bomb dropped on Hiroshima? (2 marks)

16 The diagram below shows three different size spheres of uranium-235 that is undergoing fission.



- **a** State the most likely state of criticality for A, B and C. (3 marks)
- **b** State the number of neutrons capable of inducing fission within the sphere. (3 marks)

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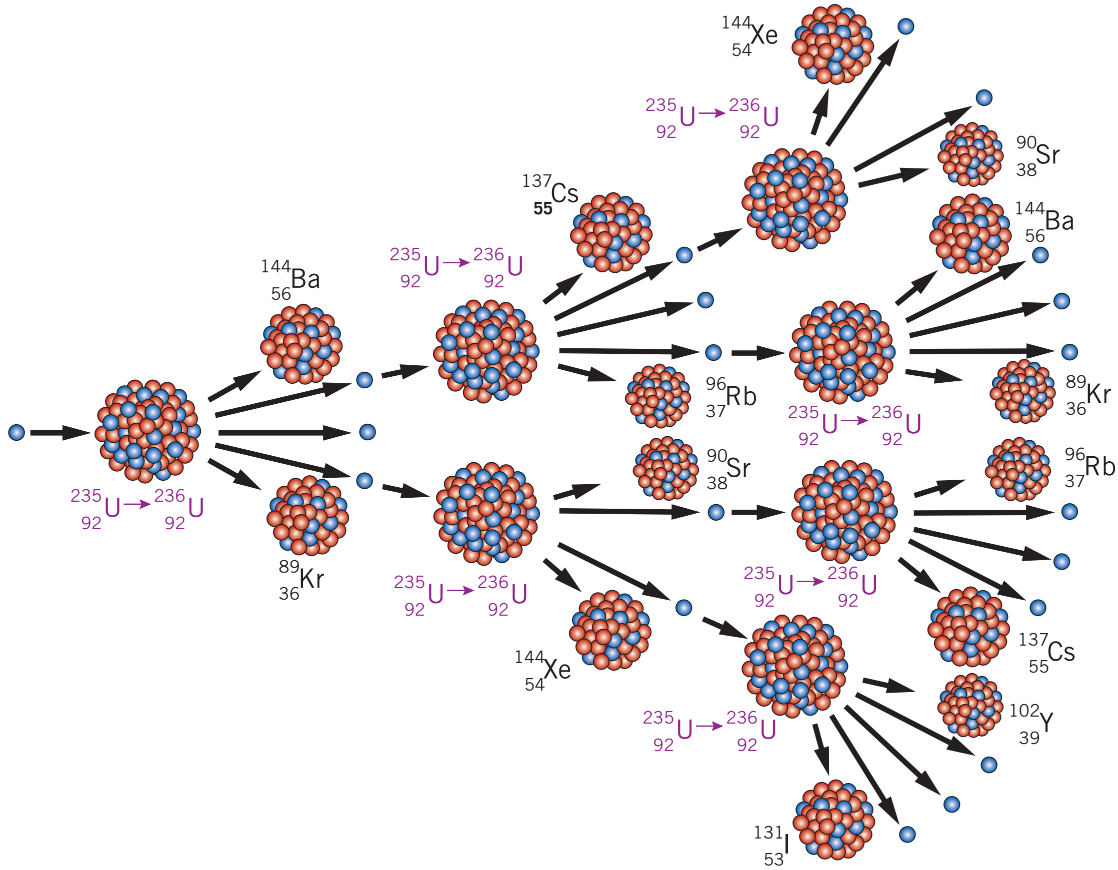
17 The diagram shows the initial stages (three generations) of an uncontrolled chain reaction.



a Write down the names of all the different isotope fragments produced by just three generations of fission. (8 marks)

b Each fissioning on average produces 200 MeV. How many total fissions have occurred, and how much energy has been released, after just three generations of fission? (2 marks)

c How much energy would be released if there was enough fissile uranium-235 so that 81 generations of fission could occur? Assume only two of the neutrons released by each fission create new fission (i.e. 81 generations of doubling).
Give your answer in MeV, J (1 MeV = 1.60×10^{-13} J) and the equivalent kilotonnes of TNT (1.0 tonne TNT = 4.18×10^9 J). (3 marks)

18 Plutonium-239 is a fissile material. When a plutonium-239 nucleus absorbs a neutron, it can undergo fission in many different ways. The nuclear equation below shows one possible fission reaction:

$$^{239}_{94}Pu + ^{1}_{0}n \rightarrow ^{145}_{56}Ba + ^{93}_{36}Kr + 2\,^{1}_{0}n + \text{energy}$$

Use the following data for the nuclear masses (kg):

Neutron	Plutonium-239	Barium-145	Krypton-93
1.67495×10^{-27}	3.96960×10^{-25}	2.40660×10^{-25}	1.54318×10^{-25}

a What is the decrease in mass (in kg) for this fission reaction? (2 marks)

b Calculate the amount of energy (in MeV) that is released during the fission of one plutonium-239 nucleus. (1 eV = 1.60×10^{-19} J) (2 marks)

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19 During a 20 Mt nuclear explosion, approximately 8.4×10^{16} J of energy is released. What amount of mass was changed into energy for this explosion? (2 marks)

20 Approximately 96% of the uranium in the fuel rods of nuclear reactors is uranium-238. When struck by a neutron, a uranium-238 nucleus can absorb the neutron.

- **a** In what way does this change the uranium-238 nuclei? (2 marks)
- **b** Why does this lead to problems in disposing of the nuclear waste? (2 marks)
- **c** Can the spent fuel rod by used to create nuclear weapons? (1 mark)

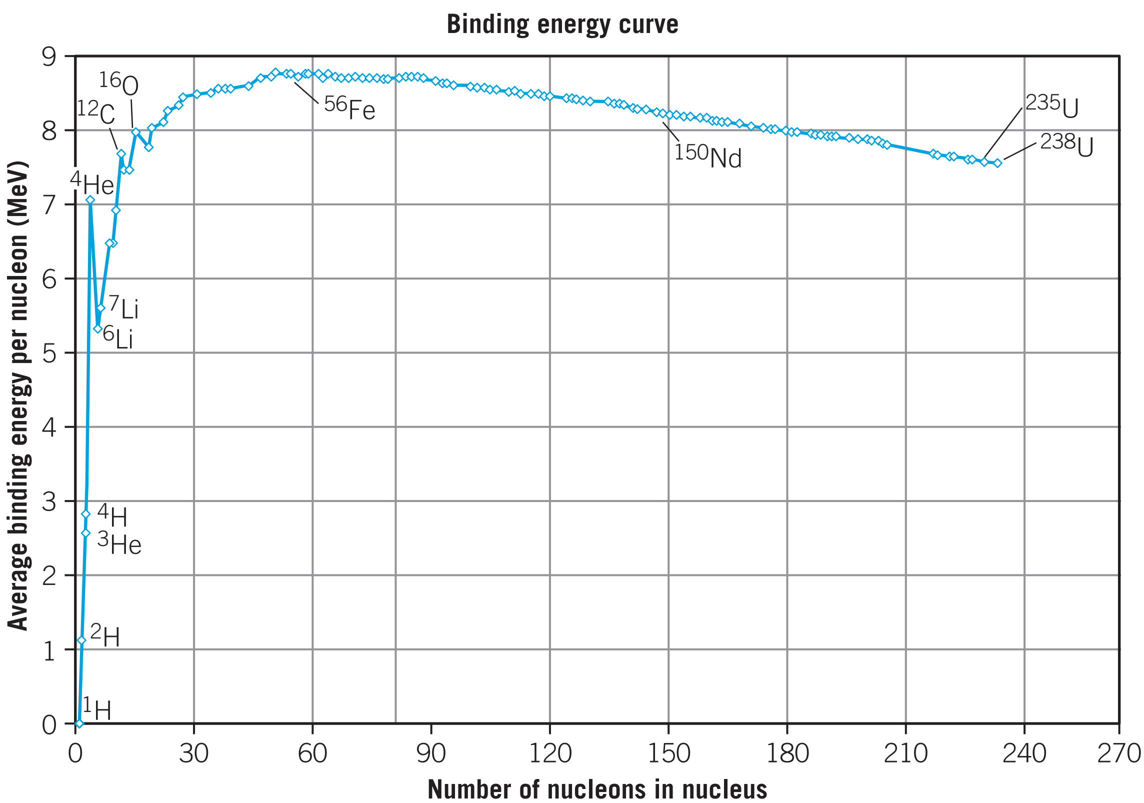
21 How can a nuclear reactor be shut down quickly in an emergency and how does this work?

22 Demonstrate, by using the appropriate calculations, that 99.9 per cent of all the energy released by a nuclear weapon is released in the last 10 generations of nuclear-splitting. (2 marks)

23 Why are neutrons good at initiating nuclear reactions such as the fissioning of a uranium-235 nucleus? (2 marks)

Use the following information to answer Questions 24–26.

The average binding energy per nucleon versus the number of nucleons in the nucleus is shown below in the binding energy curve.



24 Explain why light elements like isotopes of hydrogen release energy when they fuse into helium. (2 marks)

25 **a** From the binding energy curve, estimate the average binding energy per nucleon for deuterium (^{2}H), tritium (^{3}H) and helium (^{4}He). (3 marks)

b Show that the energy released for the following fusion reaction is approximately 17.5 MeV. (2 marks)

$$^{2}_{1}H + ^{3}_{1}H \rightarrow ^{4}_{2}He + ^{1}_{0}n + \text{energy}$$

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26 Explain why heavy elements like uranium-235 release energy when they undergo fission. (2 marks)

27 **a** What were the two major isotopes used for making fission bombs? (2 marks)

b What was the approximate equivalent TNT yield of the fission bombs dropped on Japan? (1 mark)

28 Thermonuclear bombs are also known as hydrogen bombs.

a What is the basic principle in making a thermonuclear bomb? (2 marks)

b Why are they also known as hydrogen bombs? (1 mark)

c By what approximate factor are thermonuclear bombs more explosive than fission bombs? (1 mark)

29 Why is it important for Australians to have their own 20 MW nuclear reactor known as OPAL for creating radioisotopes? (3 marks)

30 Read the following seven dot points from the organisation Nuclear for Net Zero.

Critically analyse each of the dot points put forward and see whether or not you think they provide good reasons for Australia to adopt nuclear energy as a viable energy source.

- The solution to climate change is not living with less energy. The solution is embracing better technology, which must include nuclear energy.
- Nuclear power was banned in Australia in 1998 under federal legislation. At the time, anti-nuclear sentiment was strong and demand for nuclear energy was low in a country spoilt by energy from cheap, abundant fossil fuels.
- Nuclear energy is used all over the world. It's safe, reliable, produces zero emissions and, importantly, an abundance of energy every hour of every day regardless of weather.
- With nuclear energy, Australia could bring back domestic manufacturing and other high-energy industries, reduce dependency on foreign countries for essential goods and supplies, and stop outsourcing our emissions in an attempt to bring down our own.
- With nuclear energy, Australia could convert to electric land transport without creating undue strain on electricity production and transmission.
- With nuclear energy, Australia could develop a domestic world-leading nuclear technology sector with creation of high-skilled jobs for our best scientists at home.
- And with nuclear energy, Australia could reach net zero emissions by 2050, without shutting down agriculture or banning meat or closing the aviation industry and without energy poverty.

Source: https://nuclearfornetzero.org

Use the critical thinking skills in your answer.

a Make sure you understand the crucial concepts and the links between the various ideas.

b Determine the relevance and the importance of the arguments and ideas presented.

c Appraise arguments and identify any inconsistencies and errors in reasoning.

d Note if there are vested interests in organisations presenting certain points of view.

e Reflect on how your own assumptions, beliefs and values impact on your evaluation. (7 marks)

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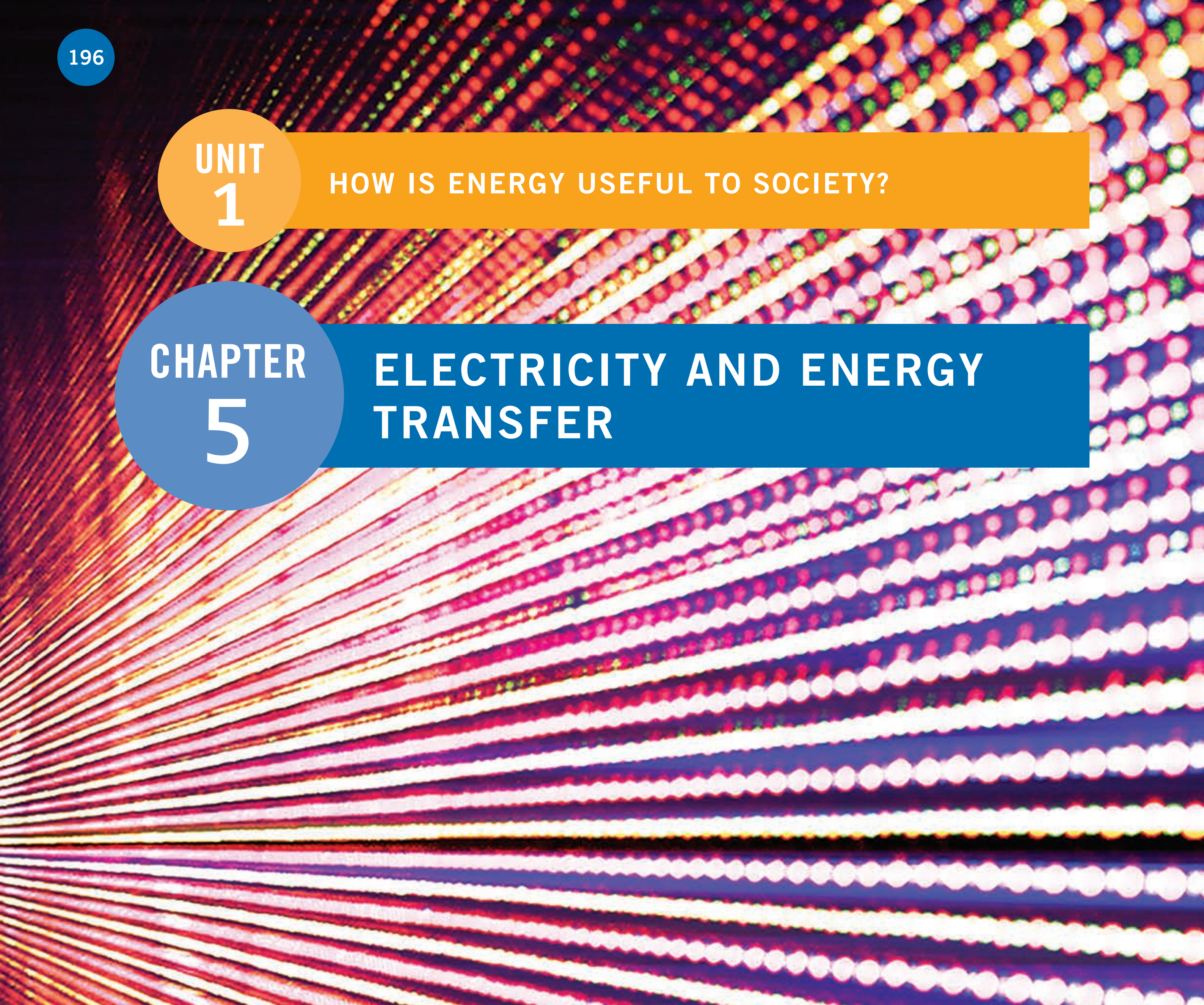

UNIT 1 HOW IS ENERGY USEFUL TO SOCIETY?

CHAPTER 5 ELECTRICITY AND ENERGY TRANSFER

Introduction

In our twenty-first century lives, electricity is used every day and will be our main source of energy in the future. We recharge our smartphones, run our computers, catch trams, fly drones, brush our teeth with electric toothbrushes – all from circuits that include either batteries or mains power supplies. The mechanisms of this electricity is largely hidden from us, yet our lives would be very different without it. Only occasionally do we actually see the effects of electricity, when a thunderstorm sends lightning jagging across the sky (and our dogs howling or hiding under the bed).

In this chapter your understanding of electricity begins with an examination of electric charge and current, energy and potential difference, series and parallel circuits and electric power. You will consider models of charge, current, energy (potential difference) and power used to explore the underlying principles and some applications of electric circuits. Measurements of these quantities in circuits allow us to collect and analyse data, determine mathematical relationships, and calculate and predict the effects of currents in circuits.

These are the basic concepts used to design everything electrical from a torch to a powerful electric vehicle (EV). Techniques to control electrical output based on changes in temperature or light levels and household electricity are explored in Chapter 6.

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Curriculum

Area of Study 3 Outcome 3
How can electricity be used to transfer energy?

Study Design	Learning objectives – at the end of this chapter I will be able to:
Concepts used to model electricity • Apply concepts of charge (Q), electric current (I), potential difference (V), energy (E) and power (P), in electric circuits • Analyse and evaluate different analogies used to describe electric current and potential difference • Investigate and analyse theoretically and practically electric circuits using the relationships: $I = \frac{Q}{t}, V = \frac{E}{Q}, P = \frac{E}{t} = VI$ • Justify the use of selected meters (ammeter, voltmeter, multimeter) in circuits	**5A Charge (Q) and current (I)** **5A.1** Model a metal as having a sea of electrons free to move **5A.2** Describe current in a metal in terms of drift velocity of negatively charged electrons **5A.3** Use analogies to model charge and current in a circuit **5A.4** Use circuit symbols to draw a circuit diagram from a given picture, practical simple circuit or description in words **5A.5** Use an ammeter to measure current in a simple circuit; construct a circuit and a suitable circuit diagram to show the use of an ammeter **5A.6** Apply the formula $I = \frac{Q}{t}$ for calculations involving current, charge and time
• Apply concepts of charge (Q), electric current (I), potential difference (V), energy (E) and power (P), in electric circuits • Analyse and evaluate different analogies used to describe electric current and potential difference • Investigate and analyse theoretically and practically electric circuits using the relationships: $I = \frac{Q}{t}, V = \frac{E}{Q}, P = \frac{E}{t} = VI$ • Justify the use of selected meters (ammeter, voltmeter, multimeter) in circuits	**5B Electrical energy and potential difference** **5B.1** Recall that separating positive and negative charges creates a potential difference, V, and requires an input of energy, E **5B.2** Apply the formulas $V = \frac{E}{Q}$ and $E = VIt$ to calculate the energy supplied to a charge flowing in a circuit **5B.3** Use analogies to model potential difference and current in a circuit **5B.4** Use a voltmeter to measure potential difference in a simple circuit; construct a circuit and draw a suitable circuit diagram to show the role of an ammeter **5B.5** Distinguish between the positioning of an ammeter (in series) and a voltmeter (in parallel) in a simple circuit

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Study Design	Learning objectives – at the end of this chapter I will be able to:
Circuit electricity • Model resistance in series and parallel circuits using: ▸ current versus potential difference (*I*–*V*) graphs ▸ resistance as the potential difference to current ratio, including R = constant for ohmic devices ▸ equivalent resistance in arrangements in – series: $R_{equivalent} = R_1 + R_2 + \ldots + R_n$ – parallel: $\frac{1}{R_{equivalent}} = \frac{1}{R_1} + \frac{1}{R_2} + \ldots + \frac{1}{R_n}$ • Calculate and analyse the equivalent resistance of circuits comprising parallel and series resistance • Analyse circuits comprising voltage dividers	**5C Modelling resistance in series circuits** **5C.1** Construct a simple circuit to measure current and potential difference across an ohmic resistance; change potential difference and record data in a table of *I* vs *V*; plot or create *I* vs *V* graph **5C.2** Recall that resistance is the ratio of potential difference to current, including R = constant for ohmic devices **5C.3** Recognise that the current flows continuously through resistors in a series circuit, without reducing; current is constant at all points in a series circuit **5C.4** Recall that the potential difference drops across each resistance in a series circuit, as energy is converted to other forms: $V_{supply} = V_1 + V_2 + \ldots + V_n$ **5C.5** Recognise and calculate equivalent resistance in a series circuit as the sum of each resistance: $R_{equivalent} = R_1 + R_2 + \ldots + R_n$ **5C.6** Calculate the potential difference output V_{out} of a potential divider, given the ratio of resistances and the supply voltage
• Model resistance in series and parallel circuits using: ▸ current versus potential difference (*I*–*V*) graphs ▸ resistance as the potential difference to current ratio, including R = constant for ohmic devices ▸ equivalent resistance in arrangements in – series: $R_{equivalent} = R_1 + R_2 + \ldots + R_n$ – parallel: $\frac{1}{R_{equivalent}} = \frac{1}{R_1} + \frac{1}{R_2} + \ldots + \frac{1}{R_n}$ • Calculate and analyse the equivalent resistance of circuits comprising parallel and series resistance	**5D Modelling resistance in parallel circuits** **5D.1** Recognise a parallel circuit as one with junctions, where the current takes more than one path around the circuit **5D.2** Recall that the current flows continuously through resistors without reducing, but splits at the junctions in a parallel circuit and reunites to return to the main branch through the battery: total current supplied by the battery is $I_{supply} = I_1 + I_2 + \ldots + I_n$ **5D.3** Recognise that the potential difference across each branch of a parallel circuit is the same, as energy is converted to other forms **5D.4** Recall and calculate that equivalent resistance in a parallel circuit is $\frac{1}{R_{equivalent}} = \frac{1}{R_1} + \frac{1}{R_2} + \ldots + \frac{1}{R_n}$ **5D.5** Use *I*–*V* graphs of individual components to predict the equivalent resistance of those components in series and in parallel

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Study Design	Learning objectives – at the end of this chapter I will be able to:
Concepts used to model electricity • Apply concepts of charge (Q), electric current (I), potential difference (V), energy (E) and power (P), in electric circuits • Investigate and analyse theoretically and practically electric circuits using the relationships: $I = \frac{Q}{t}$, $V = \frac{E}{Q}$, $P = \frac{E}{t} = VI$ **Circuit electricity** • Compare power transfers in series and parallel circuits • Explain why the circuits in homes are mostly parallel circuits	**5E** **Electric power** **5E.1** Calculate power as the rate of energy transfer $P = \frac{E}{t}$ in a simple circuit **5E.2** Calculate power from $P = VI$ supplied and consumed in a simple circuit; use alternative formulas $P = \frac{V^2}{R} = I^2R$ **5E.3** Calculate the power supplied to loads in series and in parallel **5E.4** Explain the advantages and disadvantages of series and parallel circuits, in particular relating to household circuits

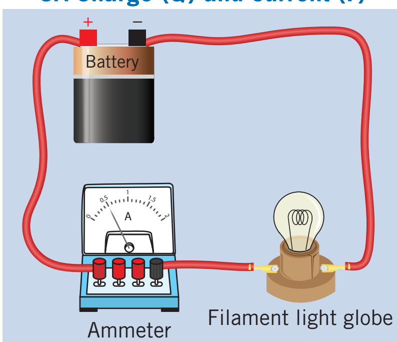
Glossary

Ammeter
Ampere, amp (A)
Battery
Charge
Coulomb (C)
Current
Electric cell
Electric circuit
Electric generator
Electrical conductor
Electrical potential energy
Electron
Equivalent resistance
Insulator
Ion
Joule (J)
Load
Ohmic
Ohm's law
Parallel
Potential difference
Potential (voltage) divider
Power
Resistance
Resistor
Semiconductor
Series
Volt (V)
Voltmeter
Watt (W)

Concept map

Concepts of charge and current are key to understanding electric circuits

5A Charge (Q) and current (I)



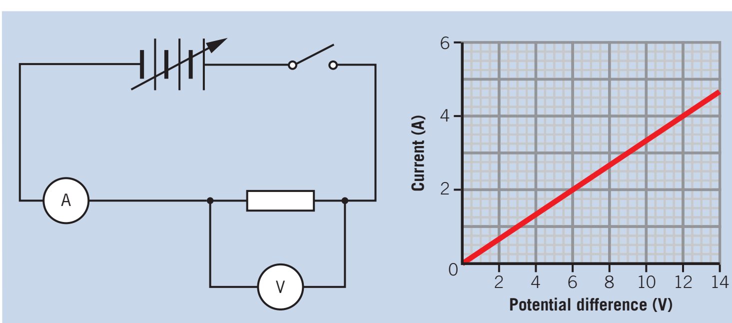
Batteries may provide energy to an electric current, to operate devices such as an EV (electric

5B Electrical energy and potential difference

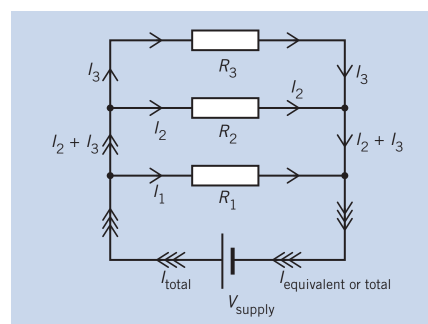
The characteristic i–V graph gives useful information about the performance of a component in a circuit

Parallel circuits allow each component to be controlled independently

5C Modelling resistance in series circuits



5D Modelling resistance in parallel circuits



When greater power is supplied, energy can be transformed more rapidly

5E Electric power

See the Interactive Textbook for an interactive version of this concept map interlinked with all concept maps for the course.

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5A Charge (Q) and current (I)

Study Design:
- Apply concepts of charge (Q), electric current (I), potential difference (V), energy (E) and power (P), in electric circuits
- Analyse and evaluate different analogies used to describe electric current and potential difference
- Investigate and analyse theoretically and practically electric circuits using the relationships: $I = \frac{Q}{t}$, $V = \frac{E}{Q}$, $P = \frac{E}{t} = VI$
- Justify the use of selected meters (ammeter, voltmeter, multimeter) in circuits

Glossary:
Ammeter
Ampere, amp (A)
Battery
Charge
Coulomb (C)
Current
Electric circuit
Electrical conductor
Electron
Insulator
Ion
Load
Semiconductor
Series

ENGAGE

How do we know what is inside an atom, or even that atoms exist?

Like all concepts in science, the idea of an atom and what is inside it can be tested by experiment, and when the results of an experiment suggest that the concepts are less than perfect (as often happens) then it's time to revisit those understandings and reinvent the theory.

You, this book, the air you breathe and everything around you are made of atoms. Atoms are often called 'the building blocks of matter'. The solids, liquids and gases that surround us are made up of an enormous number of these tiny particles. For a long time, it was believed that atoms could not be split apart into smaller particles. The word 'atom' comes from a Greek word meaning 'indivisible'.

Scientists now know that this view of atoms is not correct. Ongoing experiments have shown that atoms have an internal structure and that there are tiny particles inside them. Although it is impossible to see inside an atom, it is possible to work out the main features (Figure 5A–2). Knowing about the structure of an atom helps us to understand electricity.

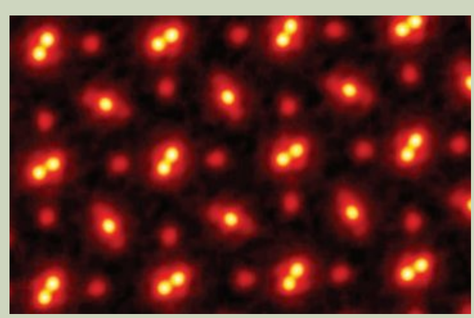

Figure 5A–1 This image of atoms in a crystal is the highest-resolution image of atoms captured at that time. It was taken by David Muller at Cornell University and his colleagues in 2021.

Figure 5A–1 shows the highest-resolution image of atoms that has so far been captured (2021), breaking a record set in 2018. David Muller at Cornell University in Ithaca, New York, and his colleagues captured this image using a praseodymium orthoscandate crystal. Their technique uses an electron microscope and a special crystal. This image is double the resolution of their previous best, and three times as clear those obtained using different techniques.

Although we cannot 'see' atoms or what is inside them, we can test models experimentally and use the results to develop new technology as well as new theories.

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3A NUCLEAR STABILITY: FORCES IN THE NUCLEUS LINK

Charge
a property of matter that causes electric effects. Like charges repel, opposite charges attract.

Electron
the lightest stable subatomic particle known. It carries a negative charge of 1.60×10^{-19} coulomb, which is considered the basic unit of electric charge.

EXPLAIN

A useful model of the atom

As you saw in Chapter 3, an atom can be modelled as a central nucleus composed of protons (positively charged) and neutrons (no **charge**). In studying nuclear physics you learnt that protons and neutrons in the nucleus of an atom are very tightly bound together, so any changes to the nucleus involve very large amounts of energy.

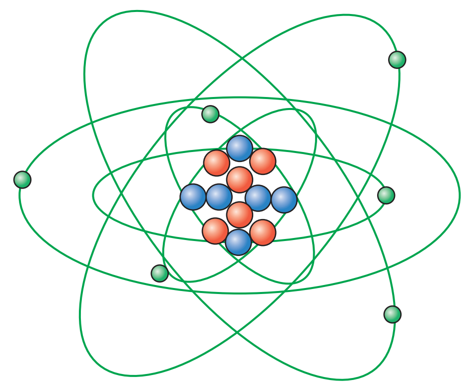

Figure 5A–2 A useful model (not to scale)of the atom showing a nucleus with protons (red), neutrons (blue) and orbiting electrons (green)

3A NUCLEAR STABILITY: FORCES IN THE NUCLEUS LINK

Orbiting the nucleus are **electrons** (negatively charged), as shown in Figure 5A–2. Each electron is so tiny that its position at any point in time is difficult to measure. The outer electrons are involved in chemical bonds (studied in chemistry). They can sometimes be removed from atoms by friction (experienced on dry days as an electrostatic spark), or by light of sufficient energy (photoelectric effect). In metals, the outer electrons behave as a 'sea' or 'cloud' of electrons not bound to any particular nucleus but free to move through the metal, which is called an **electrical conductor**. In this chapter you will analyse the behaviour of currents of electrons in electric circuits.

UNIT 4 LINK

Electrical conductor
a material that allows electric charge to flow readily

NOTE

Many more subatomic particles have been discovered, leading to the development of the Standard Model. This explains matter and nuclear and electromagnetic forces but the theory is beyond the scope of this course. Concepts such as quarks, leptons and bosons, including the recently detected Higgs particle, form the Standard Model. While it's the best we currently have, this model cannot yet explain gravitational force nor dark matter or dark energy.

Check-in questions – Set 1

1 Name the two heaviest particles of an atomic nucleus and state the charge of each.
2 Name the small, negatively charged component of an atom.
3 Complete the following sentence.
Positive charge repels ____________ charge and attracts ____________ charge. It is said that 'like charges ____________ and opposite (or unlike) charges ____________'

Charge and current

A simple **electric circuit** consists of a source or supply of electrical energy (e.g. a **battery**) and a **load** that converts electrical energy to another form of energy. They are connected by conductors, usually metal wires, that complete the circuit to make a continuous loop. The battery is connected at the battery terminals.

In Figure 5A–3, the source is a battery, and the load is a heating coil, but it could be any component that converts electrical energy to a different form. This load, the electrical heating element, converts most of the electrical energy to thermal energy.

In our model of the metal wires, the outer electrons of the metal atom can move around, like molecules in a liquid (Figure 5A–4 top). They are called free electrons. The positive **ions** are fixed in the metal lattice. Without the battery, the electrons are constantly moving randomly between ions in the lattice (Figure 5A–4 bottom).

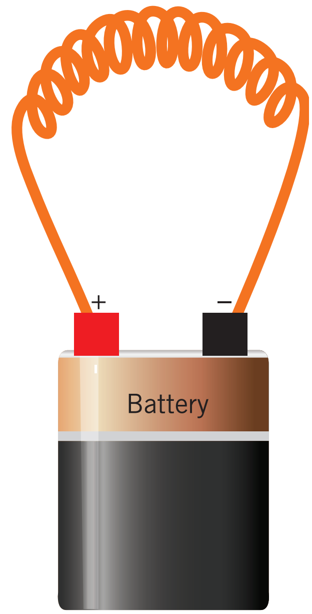

Figure 5A–3 A simple circuit consisting of a battery and a heating coil of high-resistance metal wire. An electric kettle or coffee machine has a circuit similar to this but uses AC electric current from the mains and a switch. An old-fashioned filament globe is also made of high-resistance wire.

VIDEO 5A–1 UNDERSTANDING ELECTRICITY

Electric circuit the pathway of electrical conductors that allows a continuous loop (or 'complete circuit') for electrons to flow through. A circuit with an open switch, or in some other way incomplete, is known as an 'open' circuit.

Battery a source or supply of electrical energy usually formed from a number of electric cells connected in series

Load the component(s) in a circuit where electrical energy is transformed into other forms of energy, e.g. thermal, light, kinetic energy

Ion an atom or molecule that carries net positive or negative charge

LINK CHAPTER 2

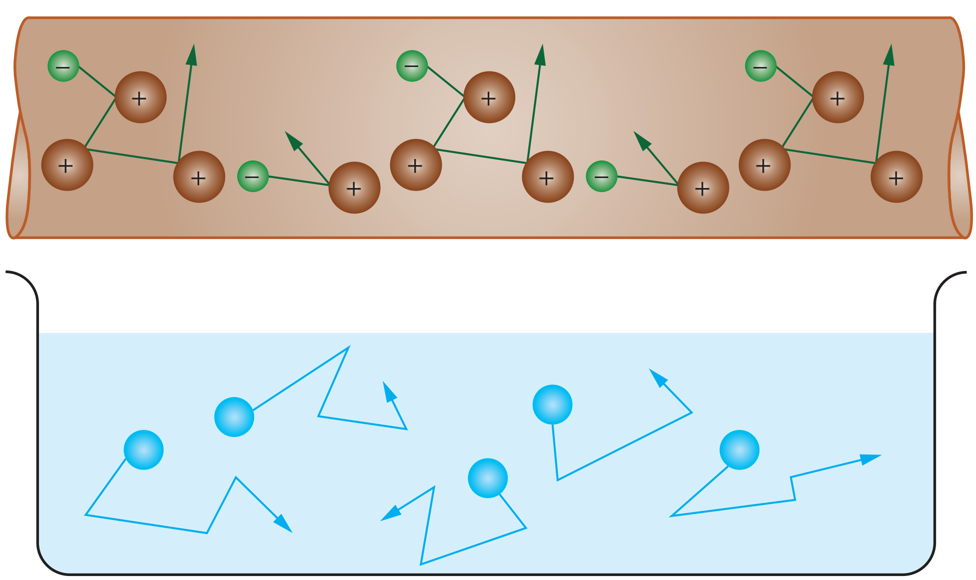

Figure 5A–4 Free electrons in a wire (top) move randomly like water molecules in a liquid colliding with each other and with other water molecules not shown here (bottom). The brown spheres represent atoms of the wire, with positive changes due to having lost one or more electrons.

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Current
the net flow of electric charge, measured in amperes (A), where 1 A = 1 C s^{-1}.

When a battery is connected to each end of the wire, the free electrons drift towards the positive side of the battery, creating a flow or **current** of electrons (recall that opposite charges attract). Refer to Figure 5A–5. As soon as the end of the wire touches the second terminal, there is a complete circuit and current will flow through the wire to the opposite terminal, and through the battery as well. If the circuit is not a complete loop, no current will flow and it may be called an open circuit.

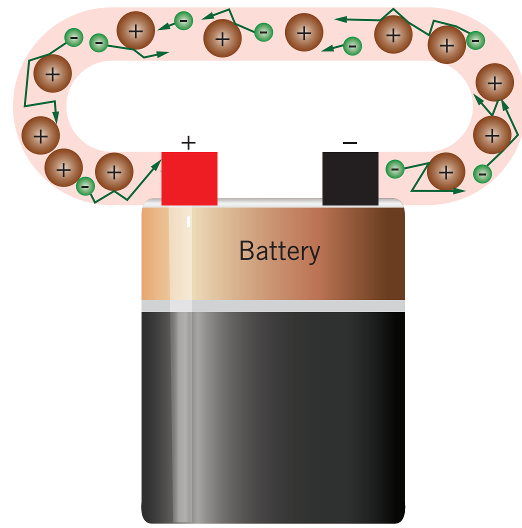

Figure 5A–5 Electrons drift towards the positive side of the battery, creating a current. This diagram shows a 'short circuit'. The wire will soon get very hot, as a large current flows and electrical energy is converted to thermal energy in the wire. The battery also rapidly runs flat. Try to avoid creating short circuits!

This drift of electrons is quite slow, about 0.1 mm s^{-1}, because electrons collide with each other and with the positive ions in the metal lattice. However, the drift begins in all parts of the wire as soon as the connection is made; it is said that 'the circuit is completed and a current flows'. The circuit is a complete closed path as the electrons also travel through the battery, then continue on around the circuit again. The filament immediately begins to heat up as soon as the wires are connected to the battery.

Conventional current

Electrons were not discovered until 1897, around 70 years after electric current which by convention was regarded as flowing from positive to negative. This means that when we refer to 'current', we mean the conventional current, which is in the opposite direction to the electron flow. In physics, the direction of 'current' is usually taken as the direction a positive charge would move and is opposite to the direction that electrons (negative charge) actually move in a metal wire (electron current). The effect the current has (i.e. the energy the current transfers to the load) is the same whether it's positive (+) or negative (–) charges that move, but it is easiest to remember that 'current flows from the positive terminal of a battery to the negative terminal'. From now on, when we refer to 'current', we mean conventional current, as if the moving charges are positive. Any material in which charges are free to flow is a conductor. Metals contain free electrons, so are good conductors.

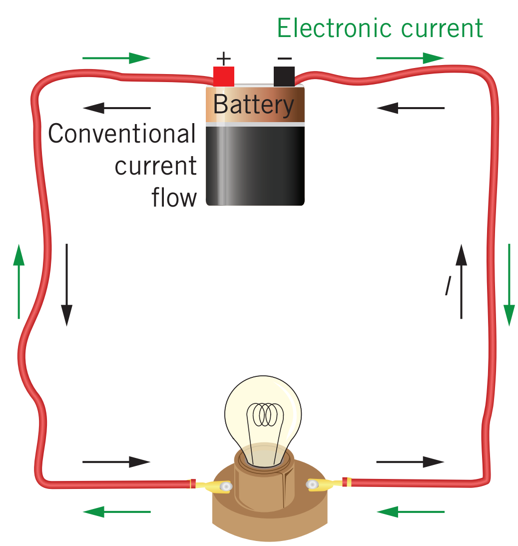

Figure 5A–6 Electron current and conventional current, *I*, flow around a simple circuit containing a battery and a resistive element, in this case an incandescent light globe that converts electrical energy to light (and quite a lot to thermal energy).

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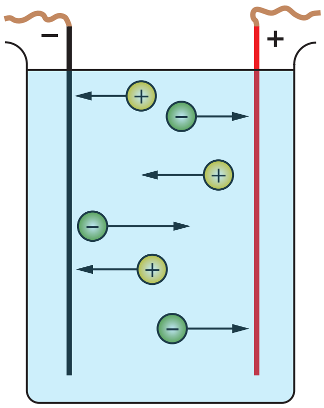
In certain circumstances, some gases and liquids also act as conductors. In these cases, there are usually positively and negatively charged ions, both free to move. When a battery is connected, the positive charges move to the negative terminal and the negative charges drift the opposite way, to the positive terminal.



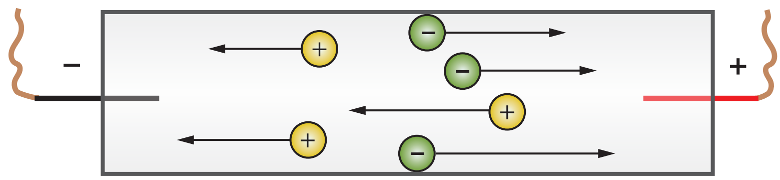


Figure 5A–7 When a battery is connected to a liquid (left) or a gas (right) in which ions are free to move, the positive charges move to the negative terminal and the negative charges go the opposite way, to the positive terminal. The 'current' is, by definition, taken to be in the direction the positive charges move.

Insulator
a material that does not conduct electricity; has few or no free charges

Semiconductor
a material that conducts electricity only partially, or only under certain conditions

There are also many materials that have few or no free electrons and do not conduct electricity. These are known as **insulators**. Some materials conduct partially or under particular conditions and these are known as **semiconductors**.

LINK **6A** USEFUL ELECTRONIC COMPONENTS

Figure 5A–8 Wood-burning stoves are unpopular with neighbours in the city, due to the smoke and ultrafine particles they produce. Some of these particles are so small (less than 2.5 μm) they can penetrate human lungs and enter the bloodstream, causing health problems. An electrostatic precipitator (ESP) has been developed which can sit on top of the chimney. It uses a high-voltage electrode to charge the particles in the flue gas and trap them inside an oppositely charged filter. ESPs have been used in industry for many years but are now being adapted for household use.

Check-in questions – Set 2

1. What is it that moves when a current flows in a metal wire and how fast do they move?
2. List three conductors (materials that can conduct electric current) and three insulators (materials that do not conduct electric current). What is the most likely difference between the conductors and insulators at an atomic level?

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An analogy of electric current

It is often useful to describe (or 'model') something you don't know about, using its similarities to something familiar. There are conceptual models, which represent a system people don't understand by relating them to concepts the do understand. There are mathematical models which describe a system using mathematical equations; and there are physical models, such as small- or large-scale representations of an object.

Figure 5A–9 A bicycle wheel gains kinetic energy from the rider via pedals and the chain

Of course, there will be similarities and differences in the model compared to the real thing. However, as long as you understand its limits, the model, or 'analogy', can be useful to help you understand and even make predictions that can then be tested in the laboratory or even in real life.

Bicycle chain analogy

You can think of a simple electric circuit like the chain on a bicycle. Imagine the free electrons are the links in the chain. As soon as the pedals are turned (the battery is connected), every link in the chain begins to move. The wheel axle will start turning instantly, even though it takes some time for an individual link to travel to the axle cog.

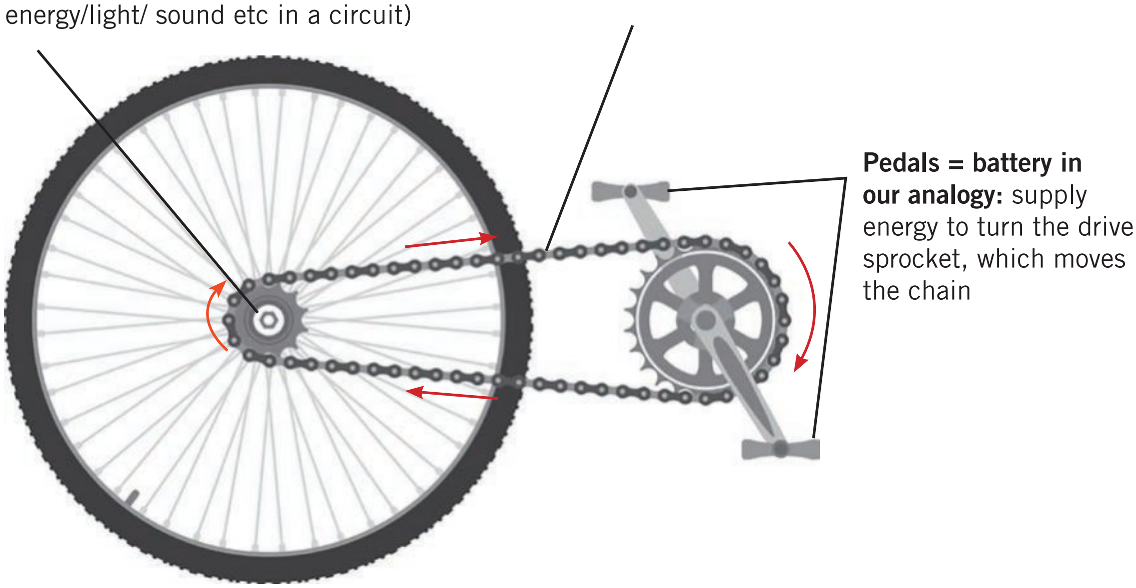

Figure 5A–10 A bicycle chain analogy for an electric circuit

If any part of a circuit is disconnected, the current stops. This is like when a link in the chain on a bicycle breaks, there is no transfer of energy from the pedals to the axle cog.

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When you deliberately start and stop a current, you usually use a switch of some sort to disconnect or 'open' the circuit.

Figure 5A–11 An open circuit (left) is as though the bicycle chain broke and came apart (right), so the links (electrons) can no longer move around the circuit.

Of course, the bicycle chain model has a lot of differences from the real situation, as well as these useful similarities. Electrons are a lot smaller than the chain links and electrons are free to move in three dimensions, not locked into a chain. Also, the electrical energy carried by each electron is not the same as the kinetic energy of the chain links. Think of it more as a form of potential energy, like a person carrying a muesli bar to use for energy later.

LINK **5B** ELECTRICAL ENERGY AND POTENTIAL DIFFERENCE

Many analogies can be used to model electric circuits. They are useful, but of course none of them are truly like the real circuit.

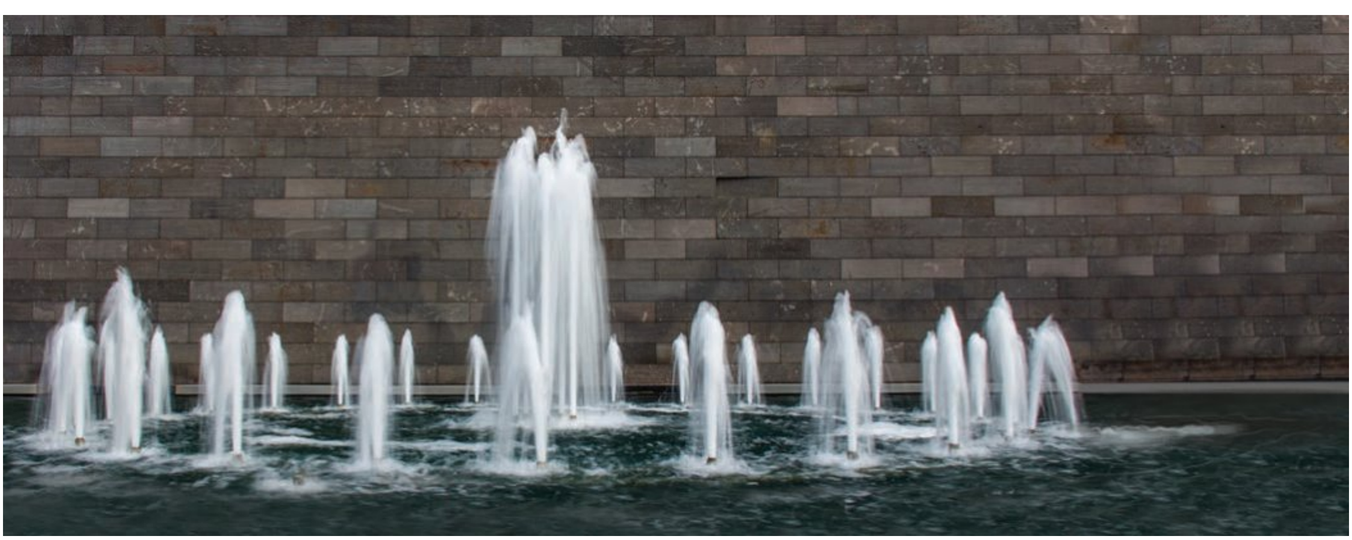

Figure 5A–12 Another analogy: just as the pump in a fountain can cause a flow of water into the air, a cell or battery can cause a movement of charge through a conductor. The two situations are not exactly alike, since an electrical circuit must be complete so the electrons can return to the battery, while water does not need to return to the pump but could flow freely out of the fountain, as long as there is sufficient water in the pool so the pump doesn't run dry.

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Using diagrams to represent circuits

Electric circuits can be simple or complex, but they all consist of the same basic components and follow the same principles in their operation. To understand a circuit and analyse how it works, you need to identify its component parts and see how they work together to make the circuit operate. To simplify this, an agreed set of symbols is used in circuit diagrams. These symbols are used instead of pictures, which could show similar components but not be easily recognised. Symbols are also more compact and quicker to draw.

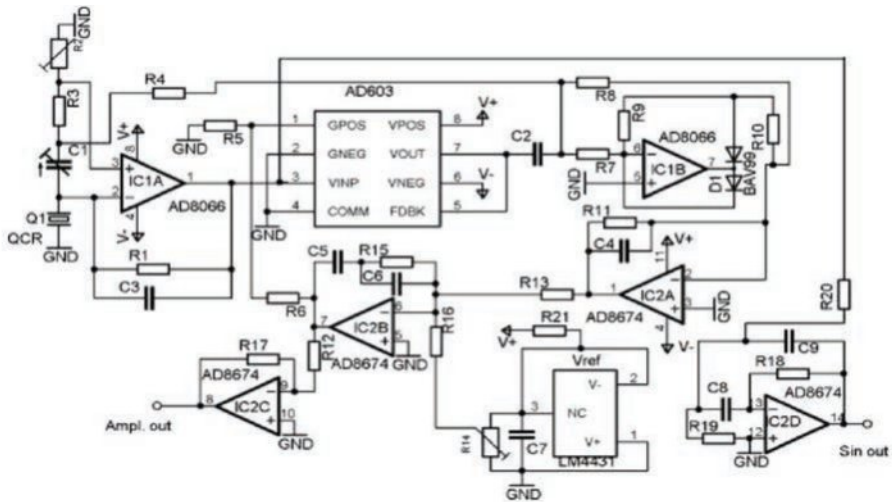


Figure 5A–13 Circuit diagrams follow a universal language, to represent circuit components according to their function and connections in the circuit rather than what they look like. Components may be updated or substituted, as long as they perform the same function.

Table 5A–1 Circuit symbols for use in circuit diagrams

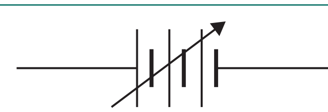
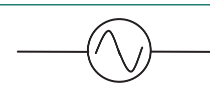
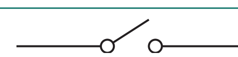
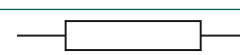
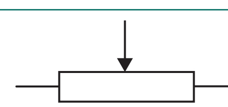
Component	Symbol
Cell	
Battery, DC power supply	
Variable DC power supply	
AC power supply	
Simple switch (single pole, single throw)	
Resistor	
Resistor, variable resistor, potentiometer, potential divider or voltage divider	
Variable resistor	
Filament globe	

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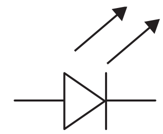
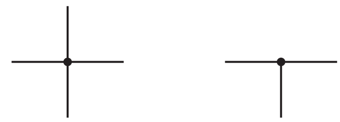
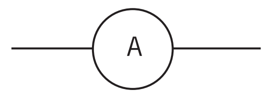
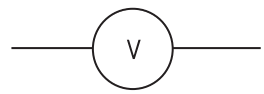
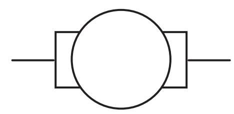
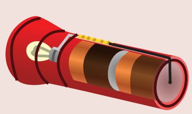
Table 5A–1 *Continued*

Component	Symbol
LED	
Connected leads	
Ammeter	
Voltmeter	
Motor	

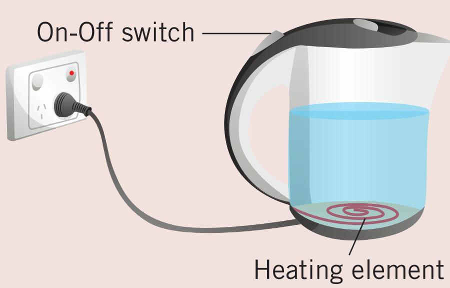
Worked example 5A–1 Circuits

Construct a circuit diagram for each of the pictured circuits.

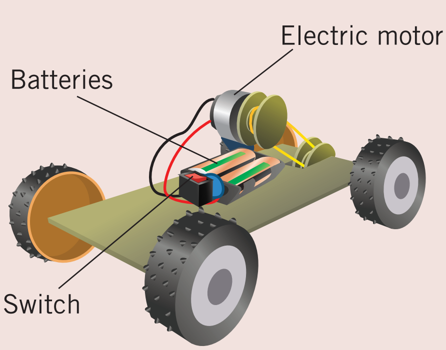
a Torch



b Electric kettle

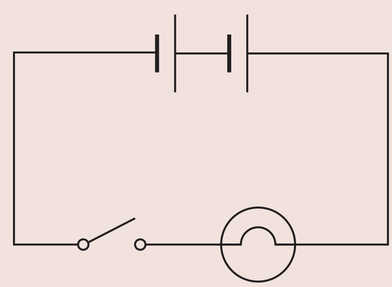


c Home-made toy car

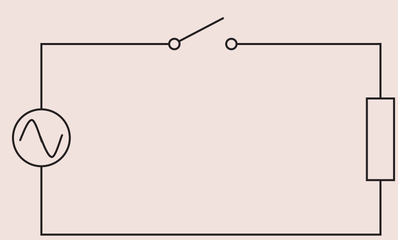


Solution

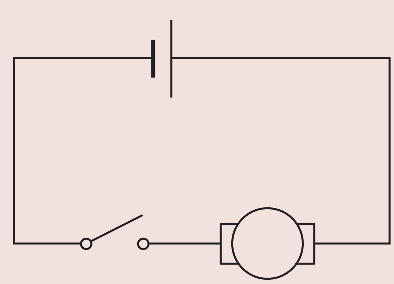
a



b



c



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Check-in questions – Set 3

1 Draw the circuit symbols for the following components.
   a incandescent filament globe
   b electric motor
2 Neatly draw a circuit diagram for a circuit in which a toy motor has an LED indicator light that switches on when the motor does. Include a battery and a switch.

Measuring current

The energy supplied by a battery causes a movement of charge (i.e. an electric current) around a conducting circuit. The greater the energy supplied by the battery, the greater the current in the circuit, as more electrons flow.

5C MODELLING RESISTANCE IN SERIES CIRCUITS LINK

To measure current, an **ammeter** (from 'amp-meter') is placed in the circuit, so that the current to be measured runs through it. This position is called in **series**. You can think of it as a series of links in a chain, where one component follows another all the way around the circuit with no branches or side-tracks. The unit for current is the **ampere or amp, (A)**, for short. One amp is quite a large value of current, so milliamps (mA or 10^{-3} A) are more often used in laboratory practical work.

To remember 'in series', think about a television series where one episode follows another.

Ammeter an instrument used to measure the electric current in a circuit in amperes (A)

Series when circuit components are connected one after another in a continuous loop so that the same current passes through each component

Ampere, amp (A) the SI unit for electric current, a fundamental quantity

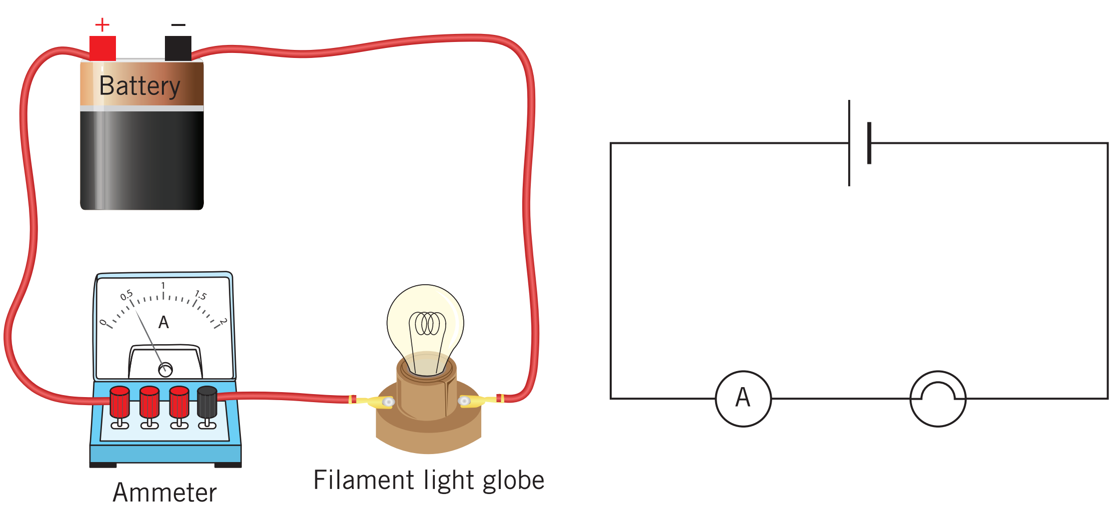

Figure 5A–14 An ammeter measures current in the circuit when placed in series, so all the current flowing must pass through it. The circuit is shown in picture format (left) and as a circuit diagram (right). The circuit diagram will be understood by any scientist regardless of what type of battery, cell or ammeter they have access to.

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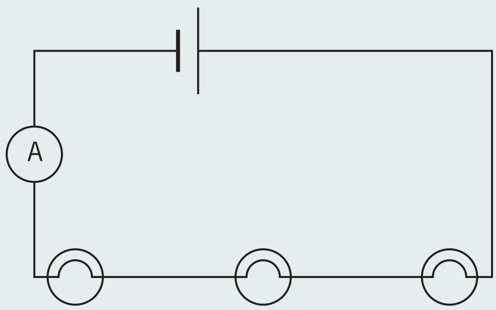
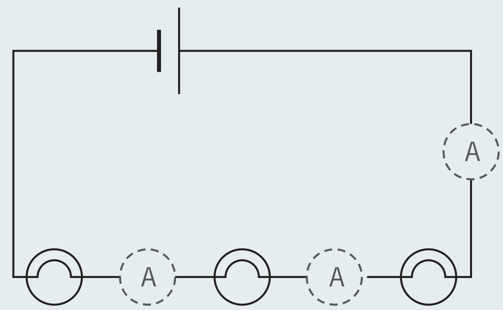
ACTIVITY 5A–1 USING AN AMMETER TO MEASURE CURRENT

Construct a simple circuit, including an ammeter to measure current, and draw the circuit diagram. Move the ammeter to each possible point in the circuit and record the current reading.

For example, construct the circuit shown below left and then record the ammeter readings. Repeat with the ammeter in the positions marked on below right.



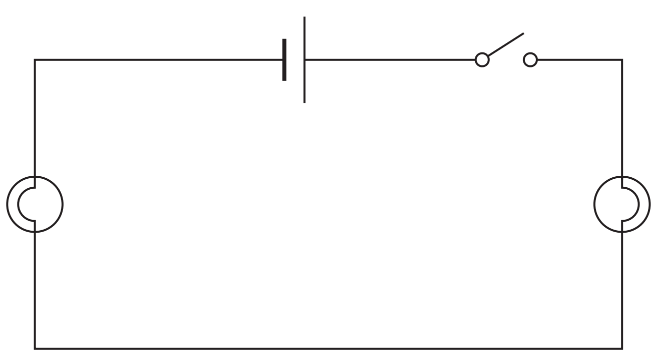


In a simple circuit like the ones above, wherever the ammeter is placed it will measure the *same* current. This shows that the electrons flow at the same rate *the whole way around* the circuit. If this surprises you, read ahead to Section 5B to see what gets 'used up'. Hint: it isn't the current!

LINK **5B** ELECTRICAL ENERGY AND POTENTIAL DIFFERENCE

Check-in questions – Set 4

1 Why is an ammeter always placed *in series* in a circuit? Hint: what does it measure?
2 Why do ammeters often have more than one red terminal?
3 Place the ammeter in this circuit so it measures the current. Redraw the circuit diagram to show your solution. Compare your diagram with those of other students. What do you notice? What can you predict about the magnitude of the current in the ammeter, regardless of where placed in the circuit?



Calculating charge from current

In order to measure charge, a suitable unit is needed. One possibility is to use, as the basic unit, the amount of charge carried by an electron or a proton. However, this charge is so tiny that it would be inconvenient for measuring the charges encountered in the laboratory or in everyday life.

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Coulomb (C) the SI unit for charge. 1 C is equivalent to the combined charge of 6.25×10^8 protons (or electrons) or the amount of charge that passes a point when a current of 1A flows for a time of 1 s.

In fact, electrons are so tiny (9.1×10^{-31} kg) and have such a small (negative) charge that the unit of charge, the coulomb (C) can be thought of as a large parcel of electrons. The **coulomb** is defined from the amount of current that flows. The unit of current is the ampere (A):

$$1 \text{ A (1 ampere)} = 1 \text{ C s}^{-1} \text{ (1 coulomb per second)}$$

Or, looking at it the other way around, 1 coulomb = the amount of charge passing a point when 1 amp flows for 1 second.

Scientists have agreed to use the coulomb, C, as the unit of charge. This is quite a large value of charge, so a microcoulomb (μC, 10^{-6} C) is often used. Remember, there are 1 million μC in 1 C.

How many electrons are needed to make up one coulomb of charge? To answer this, you need to know the size of the charge on an individual electron. This quantity of charge is known as the elementary or electronic charge, as it has long been regarded as the smallest charge that can be found in nature. Some experiments have indicated that smaller charges may exist, but the term 'elementary charge' is still used to refer to the charge on an electron. While the electron carries negative charge, protons carry positive charge of the same magnitude.

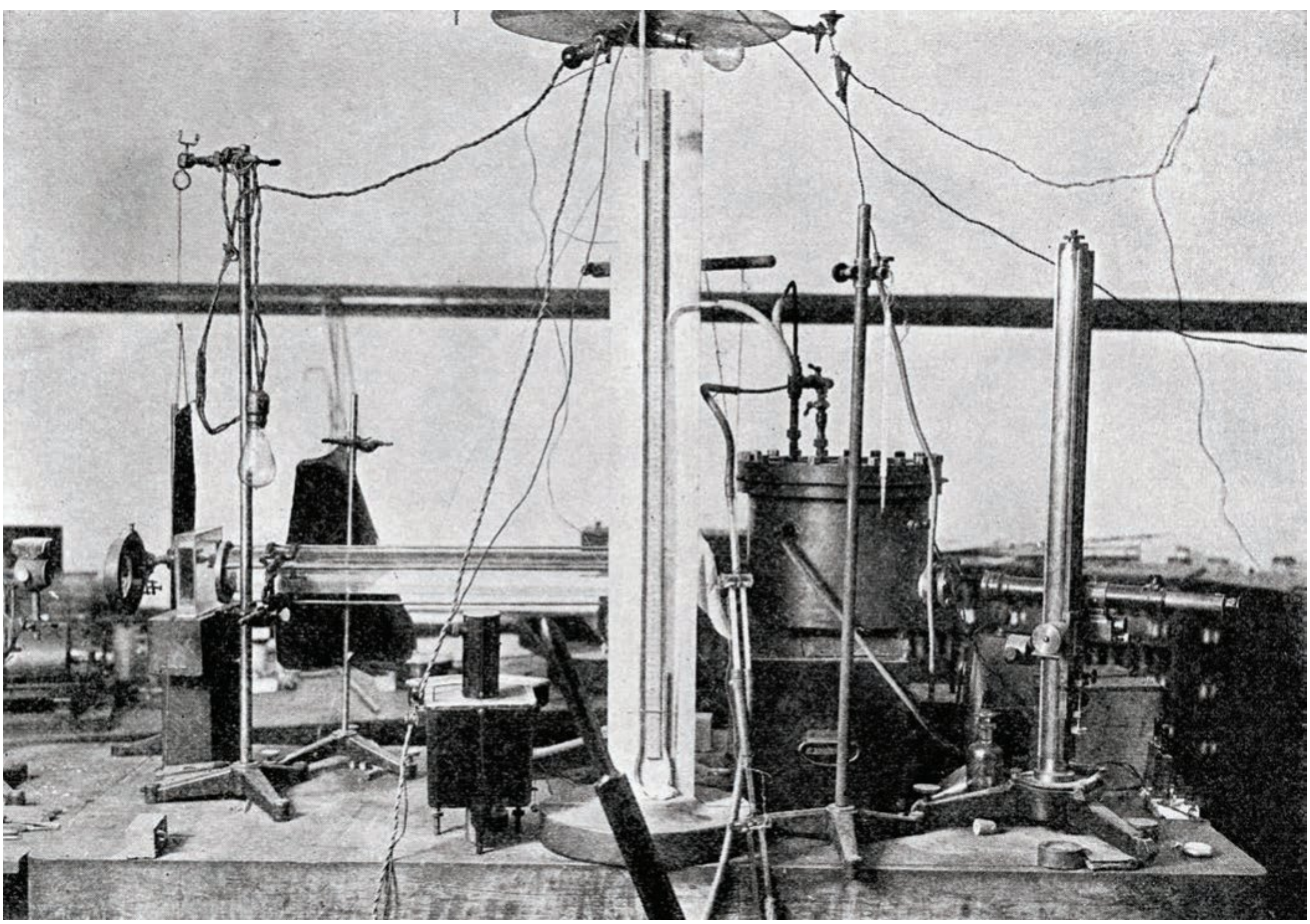

Figure 5A–15 This photograph taken in Chicago in 1917, shows the apparatus used by Robert Millikan to measure the charge on the electron. He did this by observing the motion of tiny charged drops of oil in an electrified field between two metal plates housed in the black metal tank, centre right. Millikan (1868–1953) was awarded the Nobel Prize in Physics in 1923 for accurately determining the charge on the electron, *e*, which is the smallest quantity of charge that exists in nature.

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The elementary charge, e, equals 1.6×10^{-19} C. If there are n elementary charges in 1 C, then:

$$n \times 1.6 \times 10^{-19} = 1 \text{ C}$$

Therefore:

$$n = \frac{1}{1.6 \times 10^{-19}}$$
$$= 6.25 \times 10^{18}$$

The actual number of electrons in 1 coulomb is 6.25×10^{18}. This is a very large number!

If the current in a circuit is known, the total charge leaving the battery in a given time interval can be calculated. The electric current at any point in the circuit is usually given the symbol I. An equation can be written as follows:

Formula 5A–1 Current

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

Where:

I = Electrical current (A)

Q = Charge (C) passing a point over time

t = Time (s)

This can be rewritten:

$$Q = It$$

Worked example 5A–2 Electrical charge from current

a Calculate the charge in coulombs that passes the positive terminal of the battery in 1 second when there is a current of 0.2 A in the circuit.

b How many electrons is this equivalent to?

Solution

a Using the formula $Q = It$ with $I = 0.2$ A and $t = 1$ s, you can calculate the charge passing the positive terminal as:

$$Q = It$$
$$= 0.2 \times 1$$
$$= 0.2 \text{ C}$$

So, 0.2 C of charge passes the positive terminal each second.

b The number of electrons in 1 C is 6.25×10^{18}. If 0.2 C of charge passes by the positive terminal, this is equivalent to:

$$0.2 \times 6.25 \times 10^{18} = 1.25 \times 10^{18} \text{ electrons}$$

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WORKSHEET 5A–1 CHARGE (Q) AND CURRENT (I)

Check-in questions – Set 5

1 What is a flow of electric charge called? What unit is it measured in?
2 How many coulombs flow through a given point in 1 second if the current is 3 A?
3 Calculate the current that flows through a circuit if 24 C of charge pass the positive terminal of the battery in 10 s. How many electrons per second is this?

VIDEO 5A–2 SKILLS: BUILDING CIRCUITS FROM CIRCUIT DIAGRAMS

5C MODELLING RESISTANCE IN SERIES CIRCUITS LINK

5A SKILLS

Building circuits from circuit diagrams

Your teacher will help you develop practical skills to build circuits from their diagrams. It is important to use a logical order. Lay out the components in order on the bench, starting from the battery or power source, and follow the circuit diagram in order. Then connect them in order one by one, using insulated metal wires with crocodile clips or banana plugs. Begin at the positive terminal of the battery or power source and work around the complete loop, connecting into one side of the component and then from the other side to the next component until you reach the negative terminal. Check the diagram regularly to avoid mistakes, especially before you turn on the power. Watch closely for the expected effects as you switch on, and if something unexpected occurs, switch off quickly and re-check the circuit. If nothing happens when you expect something to occur, check that you have made good contact – metal to metal – at all the connections and that no wires have loose connections to their clips.

Section 5A questions

Multiple-choice questions

1 Which of the following charges could not exist in nature?
 A 3.2×10^{-19} C
 B 8.0×10^{-19} C
 C 6.0×10^{-18} C
 D 1.6×10^{-19} C

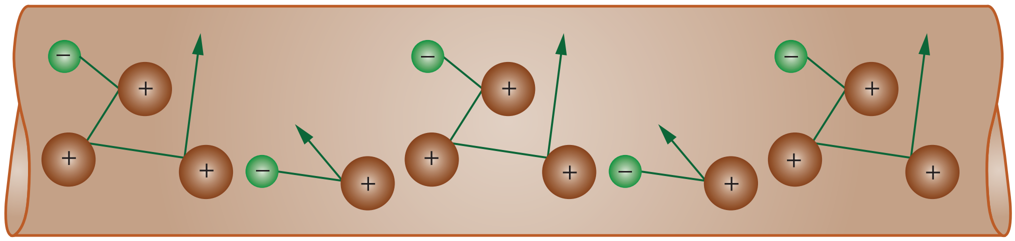
2 Which one of the following materials is an electrical conductor?
 A polythene
 B rubber
 C nylon
 D copper

3 Which of the following materials is an electrical insulator?
 A iron
 B saltwater
 C plastic
 D aluminium

4 Which of the following best explains what makes up current in a metal wire?
 A a flow of positive charges
 B a flow of negative charges
 C a flow of metal ions
 D a flow of energy without any moving matter

Short-answer questions

5 The following diagram shows a model of an electric current flowing in a wire.



Is the direction is the conventional current flow left or right? Explain your choice.

6 Copy and complete the following table of components of an atom, giving the correct masses and charges from the list below.

positive negative neutral 9.11×10^{-31} kg proton 1.67×10^{-27} kg

	Mass	Charge
Electron		
Neutron	1.69×10^{-27} kg	

7 Match the function to the component in a circuit.

Circuit component	Function
1 Wire	**A** To supply electrical energy
2 Battery	**B** To convert electrical energy to a different form of energy
3 Load	**C** To make an electrical connection between components

8 Devise an analogy for electric current that compares electrons to canoeists or kayakers drifting down a river that is flowing gently.

a Explain three similarities between this situation and a real electric circuit.

b Explain three differences between this situation and a real electric circuit.

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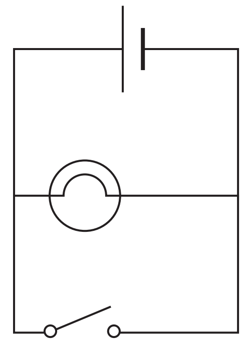
9 Explain the problem with the following circuit, which is meant to show a hand-held torch.



10 Calculate the number of electrons in the following charges.

a 1 C

b 5 C

c 100 C

11 A charge of 100 C flows past a point in a circuit in 25 s. Calculate the current through the circuit.

12 An electric heater draws a current of 5 A. Calculate the total charge that flows through the heater in 1 min.

13 An ammeter shows a current of 1 A through an appliance.

a Calculate the amount of charge that flows through the appliance in 5 min.

b How many electrons pass through the appliance in that time?

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5B Electrical energy and potential difference

Study Design:

- Apply concepts of charge (Q), electric current (I), potential difference (V), energy (E) and power (P), in electric circuits
- Analyse and evaluate different analogies used to describe electric current and potential difference
- Investigate and analyse theoretically and practically electric circuits using the relationships: $I = \frac{Q}{t}, V = \frac{E}{Q}, P = \frac{E}{t} = VI$
- Justify the use of selected meters (ammeter, voltmeter, multimeter) in circuits

Glossary:
Electric cell
Electric generator
Electrical potential energy
Joule (J)
Parallel
Potential difference
Volt (V)
Voltmeter

ENGAGE

News flash: piezoelectric materials measure the force of an insect bite

There are some materials (some types of quartz crystal, tourmaline, rochelle salt and nano materials ZnO and $BaTi_3$ to mention a few) that separate charge to produce a potential difference when they are squeezed or compressed under pressure. If there is a complete circuit between the ends of this piezoelectric crystal, a current will flow. While no useful battery or generator has yet been developed using piezoelectric materials, they are widely used in microphones and have been put to good use as sensors in a range of experiments. In 2021, German researcher Peter Rühr reported the results of an experiment to measure the strength of the jaws of hundreds of insects collected from Australia, China, Europe and Panama between 2018 and 2021. Rühr used a tiny metal device containing a piezoelectric crystal that, when compressed, converts mechanical energy into potential difference; if there is a complete circuit, a current will flow.

Each cricket, wasp, termite, stag beetle, bee and ant had the sensor placed between the tips of its mouthparts (called mandibles). When the insect chomped down, the tiny crystal compressed and created a current that could be measured, with the size of the current indicating the force of the bite.

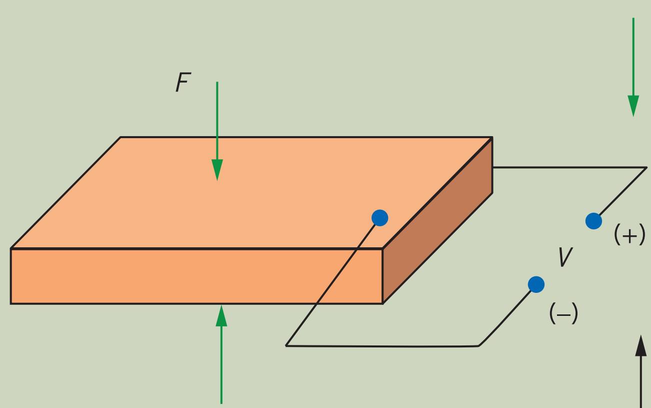

Figure 5B–1 A slice of piezoelectric crystal, when compressed, converts mechanical energy into potential difference and, if there is a complete circuit, a current will flow.

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The researcher compared hundreds of insects. The one with the strongest bite was not a predator, but the raspy cricket, an Australian insect that bites into living wood to dig out nests. Another Australian species claimed the prize for the weakest bite, a wasp (*Netelia*) whose bite force was roughly 1200 times smaller than the raspy cricket.

Figure 5B–2 Potential difference created by compressing a piezoelectric crystal sensor has been used to measure the bite force of 650 insects from around the world. The strongest bite was from a raspy cricket (*Chauliogryllacris acaropenates*) and the weakest from a wasp (species *Netelia*, shown here), both native to Australia.

EXPLAIN

Creating potential difference: energy and charge

Friction is one way to separate charges and create electrical potential energy. Early experiments with electricity used this technique; for example, in a Van de Graaff generator. A moving rubber or plastic belt scrapes against a strip of metal, removing electrons from the metal and leaving the whole metal dome positively charged. You may also see this effect when a spark flies as you step out of a car, take off a jumper made of synthetic fibres or even open the paper packet of a bandaid.

Figure 5B–3 The phenomenon of lightning is extremely complex and a topic for study at PhD level and beyond. Difficulties measuring *in situ* and in reproducing the conditions that create lightning in thunderclouds make it challenging to research. A simplified understanding is that the friction between molecules in a thunder cloud, as moist warm air currents rise rapidly while cooler air falls, causes loosely bound outer electrons to be separated from their atomic nuclei and attached to other molecules. This creates an electrical potential difference within the cloud.

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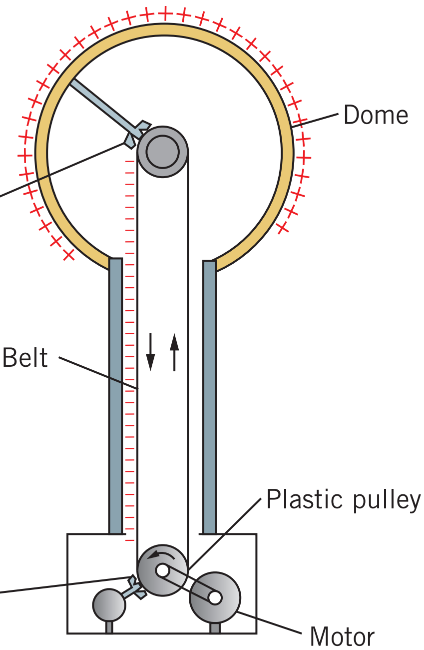

Figure 5B–4 Van de Graaff generators are common in school laboratories. The insulating belt scrapes against the brushes, and removes electrons from the metal dome (and anything connected to it), then delivers them to an earthed brush in the base of the generator. The dome becomes positively charged.

Van de Graaff generators were originally turned by hand, but now the belt is usually driven by an electric motor. Clearly this motor requires electrical energy to run, so where does this come from? Our energy needs are increasingly being met by electrical energy from solar panels, wind turbines and hydro power as well as the more traditional fossil fuel-burning technologies of coal, gas and oil.

Electric cell
a device that stores chemical energy, and can produce an electric current when a circuit is created between the two terminals of the cell

Charge separation

The process that transfers electrons from one substance to another, leaving one negatively charged and the other positively charged, is called charge separation. Charges can be separated in several ways; for example, by an **electric cell** (or a collection of cells known as a battery); by an **electric generator** run by diesel, wind, hydro or tidal energy; by a solar cell; and even by some animals such as electric eels. In each case, electrical energy is produced by separating the charges using a different form of energy:

- in the battery: chemical energy → electrical energy
- in a hydro generator: kinetic energy of water → electrical energy
- in a diesel generator: chemical energy → kinetic energy → electrical energy
- in a coal-fired power station: chemical energy → kinetic and thermal energy of steam → electrical energy
- in a solar cell: radiant energy → electrical energy

LINK UNIT 3

Electric generator
a device that converts kinetic energy into electrical energy; usually a coil rotating in a magnetic field.

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ACTIVITY 5B–1 ANIMALS USING ELECTRICITY

Some animals can use electrical energy and detect electric potentials in ways that humans can't. The platypus has a sixth sense that uses electrical energy to search for food under water when it has eyes, ears and nostrils closed.

The human nervous system also uses electric pulses, although we lack the sensitivity of the platypus to detect electric fields outside our body. The most we usually notice is the hairs standing up on our arms when lightning in a thunderstorm is nearby.

Search for information on electroreception in the platypus and write a 150-word summary, with at least one diagram.

Batteries

In a battery, a chemical reaction keeps one terminal positively charged and the other negatively charged. You will recall from earlier in this section that when the terminals are connected to a conducting circuit, electrons flow freely through the circuit from one terminal to the other, causing a current, which can be measured using an ammeter. Recall that current conventionally flows from the + towards the – side of the battery. Now, the *amount of energy each coulomb of charge carries* from the battery (and transfers to the load components in the circuit) depends on the **electrical potential energy** of the separated charges at the battery terminals.

Electrical potential energy potential energy due to the concentration of charge in part of an electric circuit

Figure 5B–5 From the 1940s, an Eveready 4 $\frac{1}{2}$ volt battery for electrical instruments, toys, telegraph sets and other battery-operated devices. The multiple terminals allow for varying the output voltage from 1.5, 3.0 and 4.5 V, or using subsections of the cells such as one cell for 1.5 V and two cells for 3.0 V.

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Figure 5B–6 Batteries supply different amounts of electrical energy. For household use a potential difference of 1.5 V up to 6 or 12 V is sufficient. The battery that drives an electric vehicle is between 300 and 500 V, with energy storage capacity of 150–400 kW h.

LINK CHAPTER 6

Figure 5B–7 The Tesla Model 3 has a battery pack under the floor and direct drive electric motors. The low centre of mass contributes to stability, especially when cornering.

The electrical potential energy the charges gain as they pass through the battery is converted to other forms of energy in the load (and sometimes to thermal energy in the wires and battery too). By the time the charges return to the battery, they have zero electrical potential energy left and need to gain more from the battery to continue flowing. The **potential difference** is a measure of the electrical potential energy each coulomb of charge carries from the battery.

Potential difference
the difference in electric potential between two points in a circuit; measured by a voltmeter when connected across a circuit component. A battery creates a potential difference across a circuit, which causes current to flow.

Volt (V)
the SI unit of measurement for potential difference

Joule (J)
the SI unit of measurement for energy

Formula 5B–1 Potential difference

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

Where:

V = Potential difference (V)

E = Electrical potential energy (J)

Q = Amount of charge that passes through the battery (C)

Sometimes this formula is written as $E = QV$. You can see that if more charge, Q, flows (if the current is larger) *or* if a battery of greater potential difference, V (more **volts**) is used, then there will be more energy, E, taken from the battery and delivered to the circuit components. The energy is measured in **joules**.

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NOTE

The potential difference, V, is sometimes called voltage, after its units. In this text the energy per coulomb is refered to as 'potential difference' not 'voltage', but keep in mind that it is the same thing. Potential difference is also sometimes referred to as 'electromotive force' or EMF. This is not a real force. It is more useful to think of circuits in terms of energy transfer, rather than forces.

Worked example 5B–1 Potential difference in a battery

a Calculate the energy supplied to an electric drill when 2000 C of charge pass through it. The potential difference across the battery terminals was measured to be 18 V.

b Calculate the energy supplied to a charge of 2000 C in the same drill if the battery is replaced with a 9 V one.

Solution

a Rearrange Formula 5B–1, $V = \frac{E}{Q}$, to make E the subject:

$$E = QV$$

From the question, $V = 18$ V and $Q = 2000$ C.

Substitute into the formula:

$$\begin{aligned} E &= 2000 \times 18 \\ &= 36\,000 \text{ J} \\ &= 36 \text{ kJ} \end{aligned}$$

Therefore, the energy supplied is 36 kJ.

b For a 9 V battery (which is half of 18 V), we expect half the energy will be transferred. Checking with the formula gives:

$$\begin{aligned} E &= QV \\ &= 2000 \times 9 \\ &= 18\,000 \text{ J} \\ &= 18 \text{ kJ} \end{aligned}$$

Check-in questions – Set 1

1 Make a table that shows the symbol and SI units for electrical potential difference, electrical energy and electric charge.

2 How much electrical energy (in joules) does a 9 V battery supply to each coulomb of charge that passes through it?

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Modelling electrical energy

Where does the energy come from to move charges around the circuit? Batteries are a familiar source of electrical energy and are one way to chemically separate positive and negative charges, which then have a tendency to recombine. Batteries have electrical potential energy in the same way that a kayaker at the top of a waterfall (or a set of rapids) has gravitational potential energy. If there is a path between the high and low potential, then the current will flow, in the same way that kayakers drop down through the rapids.

Kayaking a gravitational analogy for electric current and potential difference

Let's use a model that compares electric current to kayakers to help understand the relationship between potential difference and current.

Current, ***I*****:** The more kayakers that travel down the river, the greater the current since more kayakers pass a given point per second.

Potential difference, ***V*****:** The greater the drop from the top of the rapids or waterfall to the bottom, the greater the potential difference; the kayakers will have more energy to get through any obstacles such as rapids or whirlpools.

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Figure 5B–8 One kayaker drops down a small height (left) and another kayakers dops down a large waterfall (right)

The total energy of all the kayakers depends on both how many kayakers pass the waterfall and how much potential difference each one drops through:

$$\text{Total energy} = \text{charge} \times \text{potential difference}$$

or

$$E = V \times Q$$

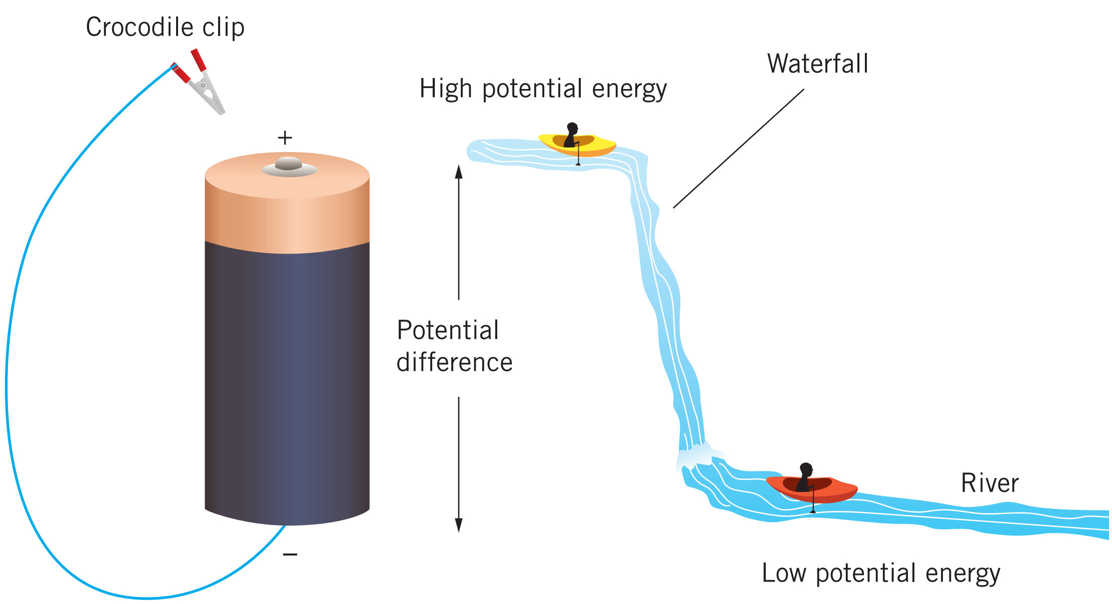

Figure 5B–9 The potential energy of a kayaker depends on the height of the waterfall (right), while the potential energy of a coulomb of electric charge depends on the state of the battery.

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The height of the waterfall above the pool below determines the gravitational potential difference. In the battery it's the number of cells and the chemical make-up of them that determines the electrical potential difference, which is usually given symbol V because it's measured in volts. (You will sometimes see potential difference referred to as voltage, but it's easier to remember that we're dealing with electrical energy if we keep the word 'potential' in the name. A better abbreviation is 'p.d.' or just 'V'.)

Bowling balls: another gravitational analogy

Consider a simple electrical circuit, in which a light globe is connected to a battery (Figure 5B–10). As electric charge flows around the circuit, stored chemical energy is taken from the battery as electrical potential energy, then transformed to other forms of energy, namely thermal energy and light as the charge flows.

LINK 5A CHARGE (Q) AND CURRENT (I)

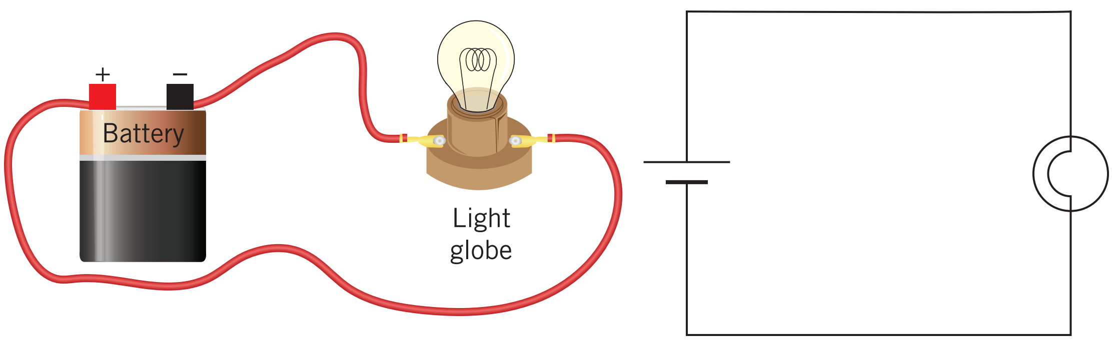

Figure 5B–10 A simple electrical circuit (shown as a drawing and a circuit diagram) transforms electrical energy into light and thermal energy.

One way to picture this process is shown in Figure 5B–11. In this analogy, the person represents the battery. They give gravitational potential energy to a bowling ball by raising it to the top plank. The balls are like coulombs of charge in the electric circuit. As the ball falls through the liquid, the gravitational potential energy is converted to thermal energy. The ball then then returns to the person to begin the next circuit.

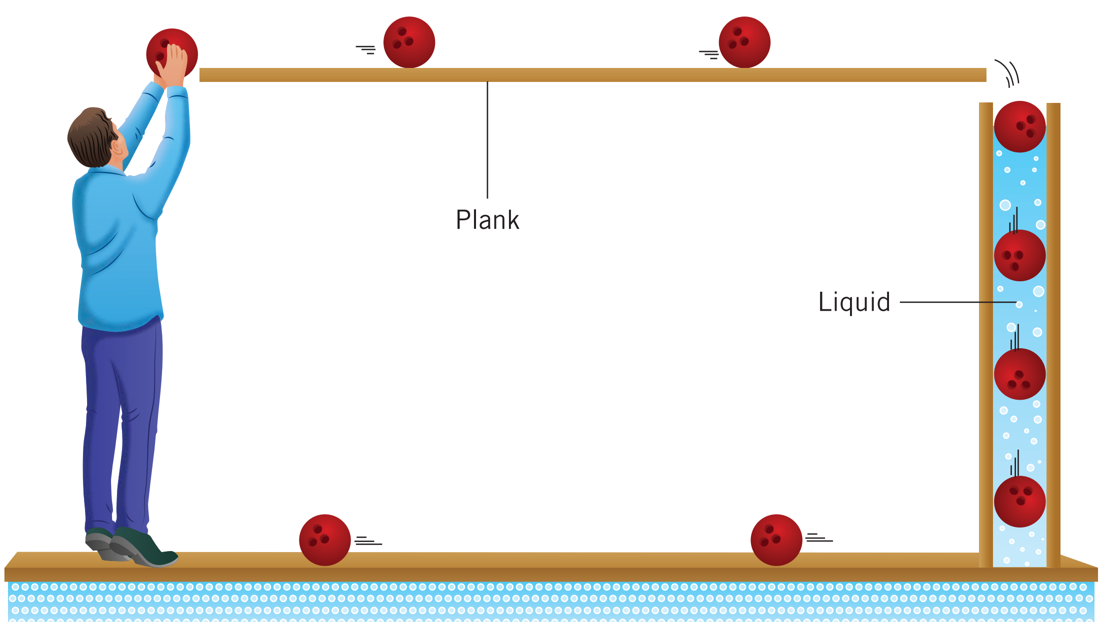

Figure 5B–11 A bowling ball analogy for an electric circuit

There are several points to notice in this analogy of an electrical circuit.

- The person supplies energy to the bowling balls, which transport the energy until they give it up as heat. Each ball acquires the same amount of energy from the 'battery' and gives up that amount of energy to the liquid through friction. The overall result is a conversion of potential (stored) energy to thermal energy. The total amount of energy delivered to the liquid depends on two things: the number of bowling balls that fall through it (the current) and the height they fall from (the potential difference).
- The total number of balls remains constant and, once the height of the top plank is set, a constant number of balls passes any point in the circuit each second.

UNIT 4 LINK

In electrical terms, the battery contains chemical potential energy. This is converted to electrical potential energy of the charge, which is then converted to kinetic energy as the charges move around the circuit and collide with each other and with the atoms of the various parts of the circuit through which they are passing (Figure 5B–12). The energy lost by the electrons in the collisions becomes vibrational energy of the atoms (internal or thermal energy), so the circuit gets hot. If a globe is one of the components of the circuit, the filament inside the globe will give off light when it is hot. Both the current and the potential difference affect the total energy transferred to the globe from the battery.

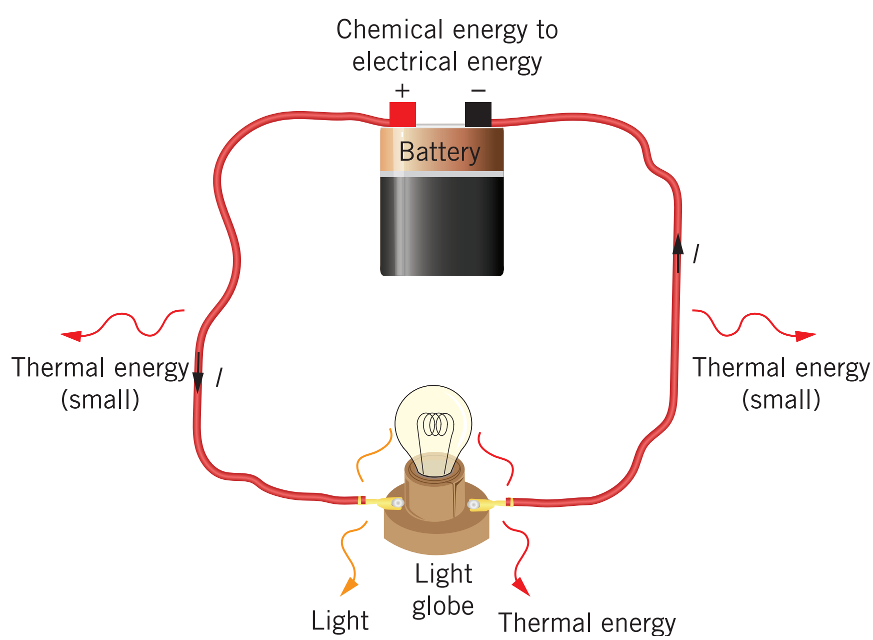

Figure 5B–12 Conversion of electrical energy to thermal and light energy in a simple circuit

These same ideas can be extended to circuits containing more components, as shown in Figure 5B–13, which shows a motor and a light indicating when it is on. The electrons gain electrical energy from the source and transport it to the light globe, where it appears as light (and thermal energy), and to the motor where it becomes kinetic energy (energy of motion). Each component has a potential difference, or potential drop, across it that corresponds to the amount of energy each coulomb of charge loses as it passes through the component. A voltmeter connected across the component as shown will measure the potential difference (Figure 5B–13 right).

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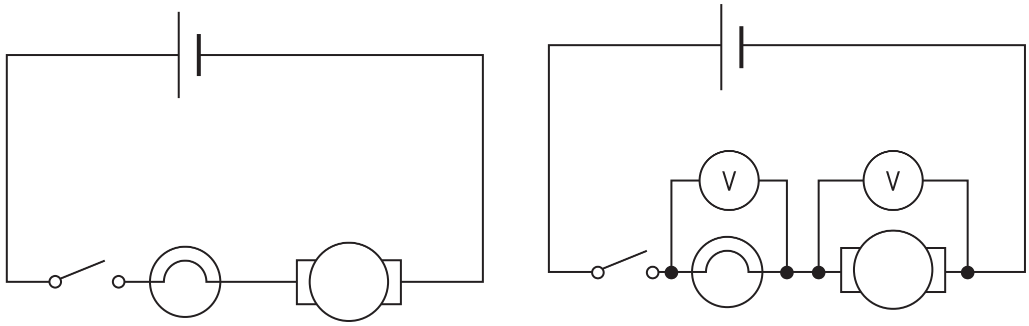

Figure 5B–13 The circuit on the left shows a motor and a light indicating when the switch is closed. Voltmeters in parallel will measure the potential difference (energy per charge) across each component (right).

Bicycle chain analogy revisited

In the analogy comparing a bicycle chain as the electric circuit, we said that the links in the chain represented the coulombs of charge moving around the circuit. The energy obviously must come from the person pushing the pedals, so the amount of energy they put into their pedalling would be the joules of energy available to the chain (coulombs of charge). That is, the potential difference (in volts) is the energy per coloumb. This energy is then transferred to the axle to move the wheels and get the bicycle moving (kinetic energy).

LINK 5A CHARGE (Q) AND CURRENT (I)

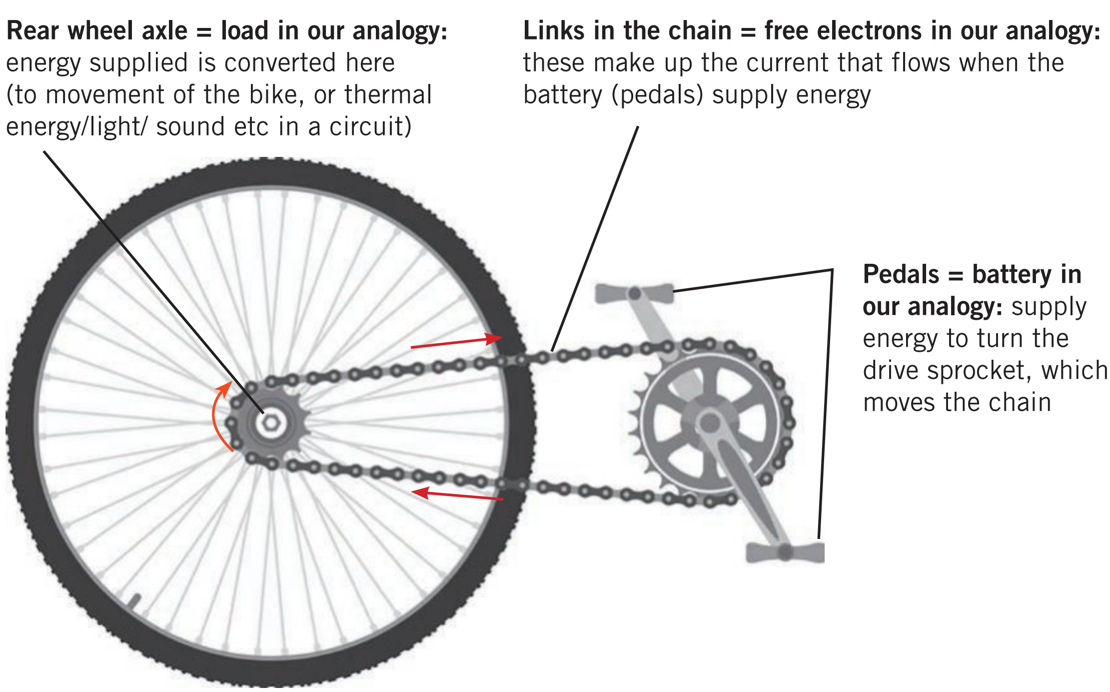

Figure 5B–14 Input: energy from the person pedalling represents the electric potential energy supplied by the battery. Output: kinetic (movement) energy represents light/sound/motion or thermal energy in the load of the circuit, whether that is a globe, an LED, a speaker, a motor, or a heating element.

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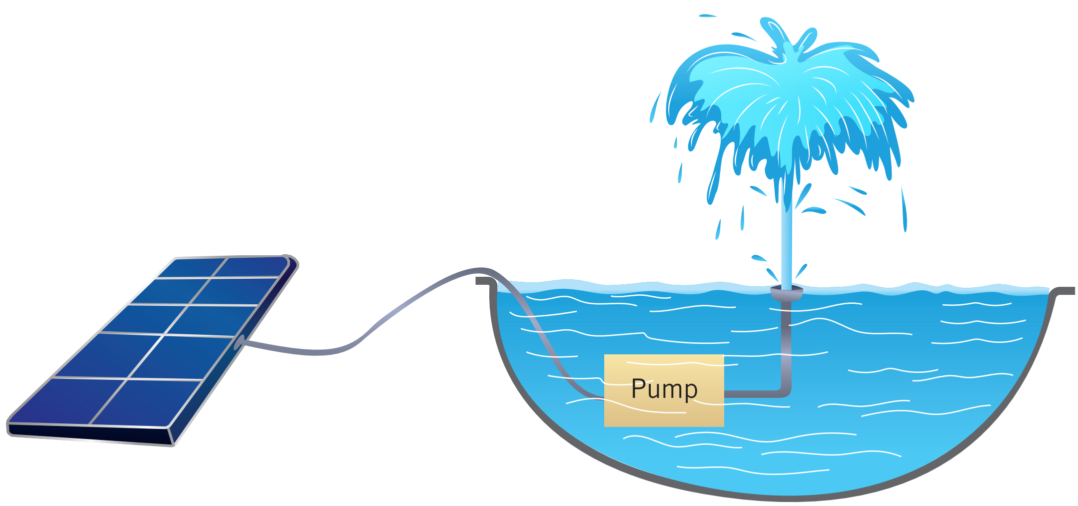
Check-in questions – Set 2

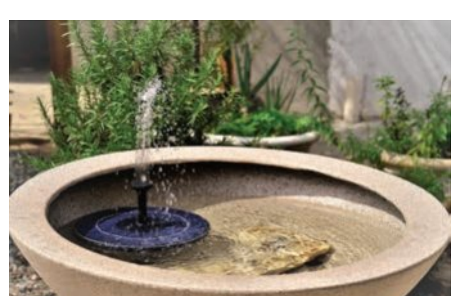
1 In the bowling ball analogy in Figure 5B–11, several variations are possible. Match the variation in the analogy below with the effect in the electric circuit.

Analogy	Electric circuit
1 An extra person joins her friend in lifting the bowling balls up to the top plank.	**A** An extra battery is added (in series) in the circuit, increasing the potential difference provided.
2 The top plank is raised higher off the ground, so more energy is needed to lift the ball up to the plank.	**B** A battery of larger capacity (e.g. from AA to D size) is used but with the same potential difference.
3 More bowling balls are added to the circuit.	**C** More energy is required to pass through the component so the battery will 'run flat' sooner. (The 'resistance' is increased.)
4 The tube of liquid is made thinner, with oil instead of water.	**D** An extra battery is added beside the original one (in parallel), increasing the amount of charge that can flow without increasing the potential difference

2 When the sun is shining, a solar panel provides energy to a pump that makes a small fountain in a bowl of water. Use this as an analogy for potential difference and current in an electric circuit.



What would the pump and solar panel together represent, and what represents the electric current in this model? How is the potential difference increased, and what effect does this have in the circuit?



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AC or DC: what's the difference?

In a direct current (DC) circuit, the polarity of the potential difference stays constant. In other words, the positive terminal is always positive and the negative terminal is always negative, as in the case of a battery. When a battery is connected into a circuit, the charge always flows along the wire in the same direction. This is the type of current studied in Section 5A.

LINK **5A** ELECTRICAL ENERGY AND POTENTIAL DIFFERENCE

Figure 5B–15 Left: Solar panels produce DC, which must be converted to AC by the inverter before it can be used in the house or fed into the electricity grid. Individual panels may instead each have a small 'microinverter' connected to them on the roof, which ensures that if one microinverter fails there isn't too much energy production lost before it is noticed and replaced. Right: caravans generally run on DC, so a solar panel can be set up to recharge the battery without needing an inverter.

In an alternating current (AC), circuit the polarity of the potential difference changes in a regular way, so that the charge first flows in one direction then in the other. The Australian mains electricity supply is AC, changing polarity first one way then back again 50 times per second; that is, with a frequency of 50 hertz.

The choice of AC or DC is determined by the situation in which electricity is needed. Any battery-powered supply will be DC, while the domestic mains supply is AC, because an alternating potential difference is needed for the transformers that form an essential part of the mains supply system.

LINK **UNIT 3**

Figure 5B–16 A laboratory power supply can usually provide both AC and DC. Take care if using these in experiments to connect to the red and black terminals for DC. For most circuits you will not need the AC terminals, which are often yellow.

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Voltmeter
an instrument used to measure potential difference (in V) between two points in a circuit

Parallel
when two components are connected, creating alternative paths around an electric circuit

Measuring potential difference

A **voltmeter** is used to measure the potential difference produced by a battery or generator, or consumed by a circuit component. Like the ammeter, it is named for the units it measures. Voltmeters are always connected in **parallel** with other components in an electric circuit (Figure 5B–17) because their job is to compare the energy carried by each charge entering with the energy per charge leaving the component. It's the 'difference in potential energy' of each coulomb of charge that registers as the number of volts. (If needed, you can refresh your understanding at the start of this section.)

5D MODELLING RESISTANCE IN PARALLEL CIRCUITS LINK

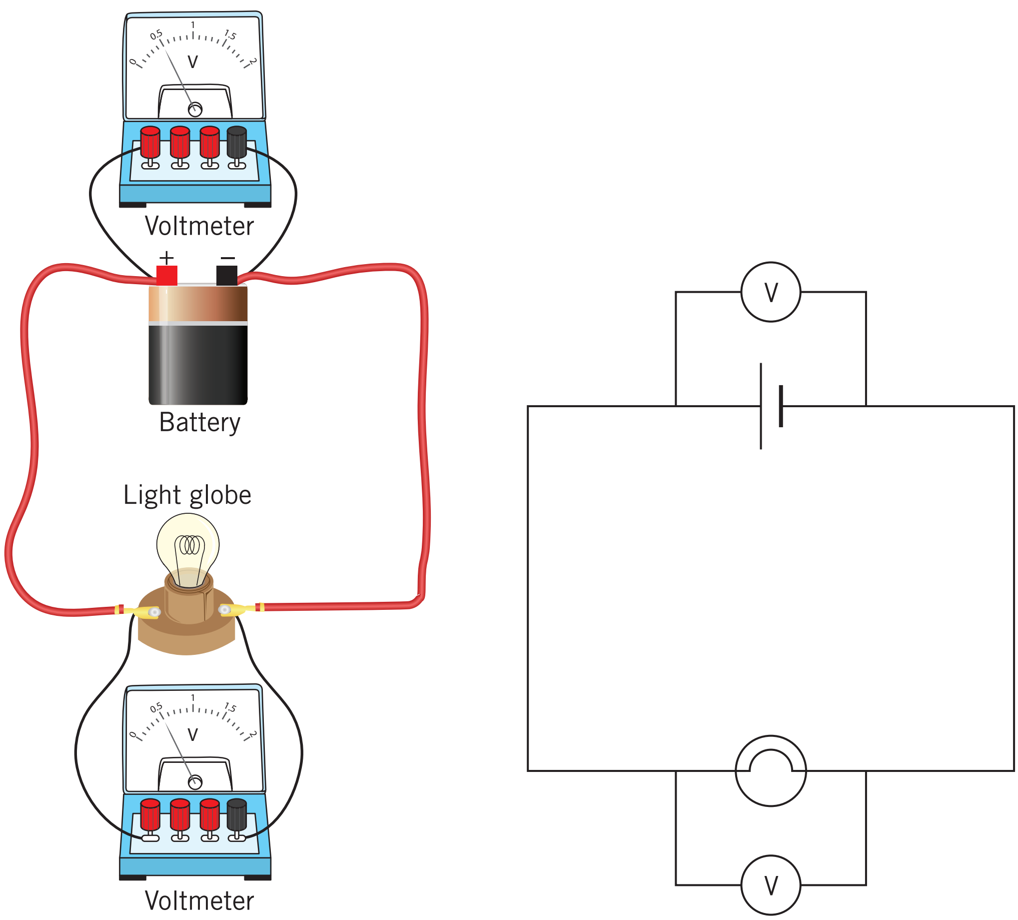

Figure 5B–17 A voltmeter is used to measure the potential difference, the energy transferred by each coulomb of charge, or the energy supplied by the battery to each coulomb of charge. Note that the voltmeter is always connected *across* the component it is measuring (in parallel) to compare the energy before and energy after – the meter shows the potential *difference*. Like ammeters, there is often a particular orientation. Left: a picture of simple circuit with voltmeters across globe and across battery. Right: a circuit diagram of the same circuit using correct symbols. Note that there are many different ways to draw the circuit diagram, but the simplest is usually the best and following the layout of the picture makes it easier.

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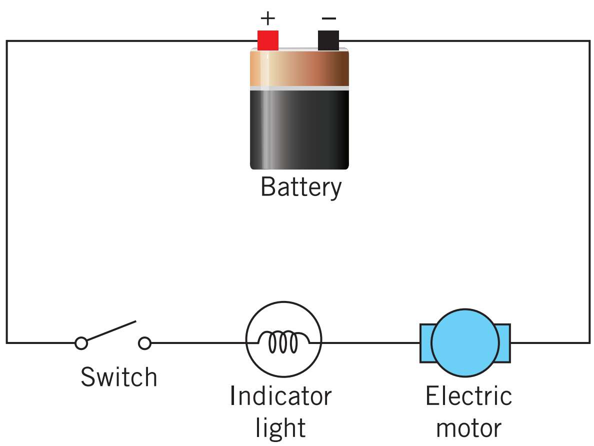
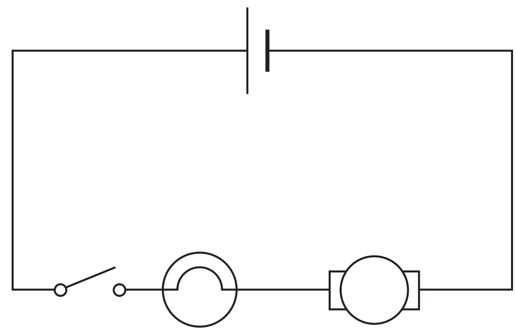
Check-in questions – Set 3

Refer to the following diagrams to answer these questions.





1 Redraw the circuit diagram and show where you would connect the voltmeter to check the potential difference across each of the motor, the indicator light and the battery in this circuit.

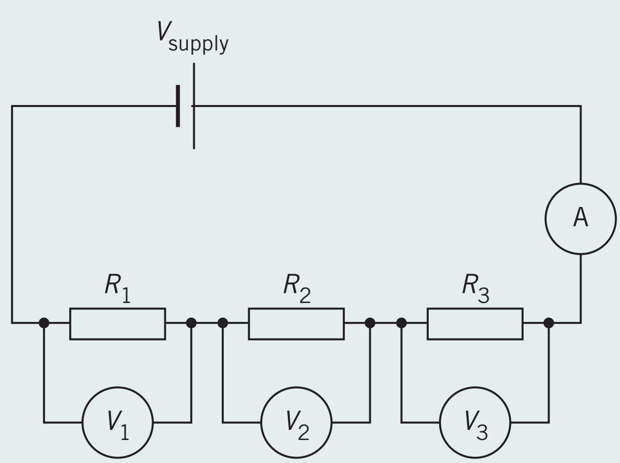
2 Show how you would connect an ammeter to check the current through the motor in this circuit.

3 When the switch is closed both the motor and the indicator light turn on. Describe the energy transfers in each of these components when the switch is closed.

ACTIVITY 5B–2 VOLTMETERS IN A CIRCUIT

Construct a series circuit and use a voltmeter to measure the potential difference *across* each resistance in the circuit and the power source.

1 Set up a series circuit as shown.



2 Use a voltmeter to measure the potential difference across each resistance in the circuit and the power source. Record each reading.

3 Recognise that any differences in V_{supply} compared with the sum of $V_1 + V_2 + V_3$ are probably due to measurement uncertainties and energy converted to thermal energy in the connecting wires.

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Calculations of current, potential difference, charge and energy

5A CHARGE (Q) AND CURRENT (I) LINK

It can be useful to know how much energy a particular component or appliance will need. A useful expression for energy (in joules) can be derived by combining two previous formulas from Section 5A and earlier in this Section 5B.

Recall the formula for current, $I = \frac{Q}{t}$, where I = current (A), Q = charge (C) and t = time (s) and rearrange:

$$Q = It \qquad \text{Equation 1}$$

Recall the formula for potential difference: $V = \frac{E}{Q}$, where V = potential difference (V), E = energy (J) and Q = charge (C) and rearrange:

$$E = QV \qquad \text{Equation 2}$$

Now substitute It for Q (from Equation 1) into Equation 2.

$$E = QV$$
$$= It \times V$$

So, $E = VIt$.

6B ELECTRICITY AT HOME LINK

This is particularly useful for calculating electrical energy because it is simple to use a voltmeter and an ammeter to measure the first two terms, then multiply by the time the appliance is running for. Remember to convert from minutes, hours or days into seconds to get the answer in joules.

Formula 5B–2 Electrical energy

$$E = VIt$$

Where:

E = Electrical energy (J)

V = Potential difference (V)

I = Current (A)

t = Time (s)

Worked example 5B–2 Electrical energy of appliances

a An electric induction cooktop draws a current of 32 A. Calculate the electrical energy used by the cooktop during 10 minutes of cooking.

b The same cooktop is now turned down to low. If the cooktop now uses 360 kJ of energy in 1 minute, calculate the current and the amount of charge flowing through the cooktop during that minute.

Solution

a Use the formula for electrical energy, $E = VIt$.

From the question, $V = 230$ V (because the cooktop is on mains power supply), $I = 32$ A and $t = 10 \times 60 = 600$ s.

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Substitute into the formula:

$$E = 230 \times 32 \times 600$$
$$= 4\,416\,000 \text{ J}$$
$$= 4.416 \text{ MJ}$$

Therefore, in 10 minutes the cooktop uses 4.416 kJ of electrical energy.

b Rearrange the formula for electrical energy to make I the subject:

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

From the question, $V = 230$ V, $E = 360$ kJ and $t = 60$ s. Substitute into the formula:

$$I = \frac{360 \times 10^3}{230 \times 60}$$
$$= 26 \text{ A}$$

Hence, the cooktop on low draws 26 A of current.

In order to find how much charge flows through the cooktop in 1 minute, use the relationship $I = \frac{Q}{t}$, which can be rearranged to give:

$$Q = It$$

Substitute and calculate:

$$Q = 26 \times 60$$
$$= 1560 \text{ C}$$

So, in 1 minute 1560 C of charge passes through the cooktop.

Check-in questions – Set 4

WORKSHEET 5B–1 ELECTRICAL ENERGY AND POTENTIAL DIFFERENCE

1 Explain the application of the formula $E = VIt$ to a real-world situation such as, a torch.
2 Calculate the electrical energy used in a torch circuit during 1 minute, if an ammeter measures the current through the bulb as 0.5 A and a voltmeter measures a potential difference of 5.9 V across the bulb.

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VIDEO 5B–1 SKILLS: CONNECTING A VOLTMETER IN A CIRCUIT

5B SKILLS

Connecting a voltmeter in a circuit to measure potential difference

In practice, it is easiest to build the main loop(s) of the circuit first. Connect a wire to each terminal of the voltmeter. Then attach the wires either side of the component to measure the potential difference. Think about how large you expect the potential difference to be (hint: it will always be smaller than the battery voltage) and choose the voltmeter scale to be larger than that maximum possible. Most analogue voltmeters have two or three red terminals, from which you select the best scale, and a black terminal that should always be connected facing towards the negative terminal of the battery. If the reading is too small to see accurately on an analogue meter, you can always switch down a scale, but choosing a small scale and finding it's a larger potential difference could damage the meter. Multimeters, which are digital, have built-in protection, but you still need to think about what quantity you're measuring. The scales are often labelled with the units: V for potential difference (in volts), A for current (in amps). Multimeters can usually also measure resistance, R, in ohms (Ω) (see Sections 5C and 5D) and even AC (see Chapter 6).

5C MODELLING RESISTANCE IN SERIES CIRCUITS LINK

5D MODELLING RESISTANCE IN PARALLEL CIRCUITS LINK

CHAPTER 6 LINK

Section 5B questions

Multiple-choice questions

Note that in these calculations, a mains supply at 240 V is used for ease of calculation, even though in Australia the supply is now 230 V (+10%, −6%)

1 How much energy is given to each coulomb of charge by the 240 V mains supply?

A 240 J
B 1 J
C 100 J
D 240 V

2 How much energy does each electron receive in the situation in Question 1?

A 240 J
B 1 J
C 6.25×10^{18} J
D 3.84×10^{-17} J

3 How much energy does 20 C of charge deliver to an appliance connected to the 240 V mains supply?

A 20 J
B 240 J
C 240 V
D 4800 J

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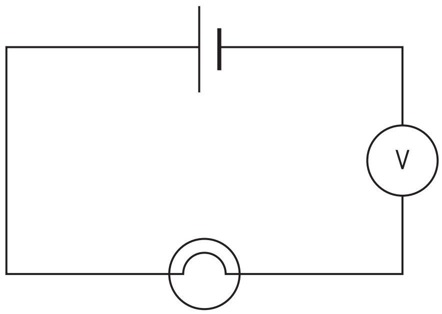
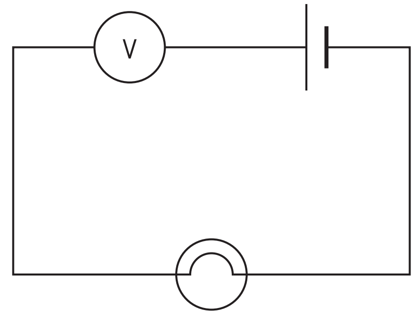
4 Which of the following circuits best shows a correctly positioned voltmeter?

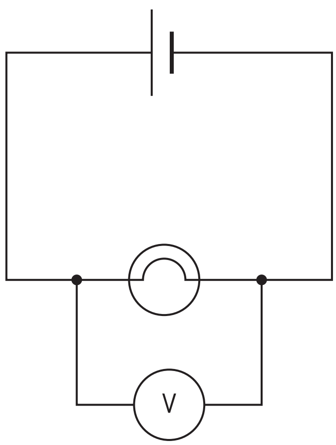
A



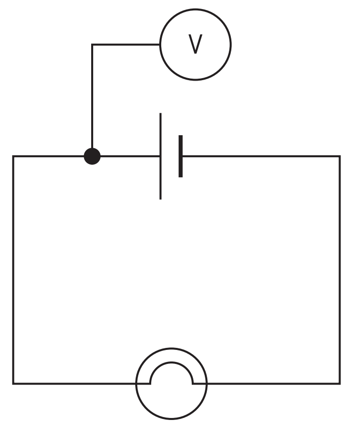
B



C



D



Short-answer questions

5 a How much energy is given to each coulomb of charge as it passes through a 12 V car battery?

b How much energy does each electron receive?

6 What energy is gained by a charge of 15 C when it passes through a generator producing 12 V?

7 Each item below represents one component of an electric circuit according to the bowling ball analogy in Figure 5B–11 for a conventional current circuit. Match the analogy item to the circuit component.

Circuit component	Analogy
1 Battery	**A** Bowling balls
2 Coulombs of charge	**B** Positive side of battery
3 Water	**C** Person lifting the bowling balls
4 High plank	**D** The components of the circuit that convert electrical energy to other forms, such as a light globe (the 'load')

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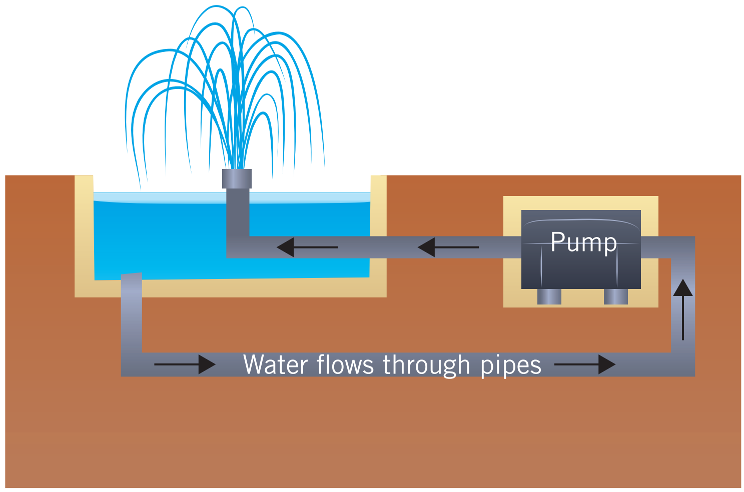
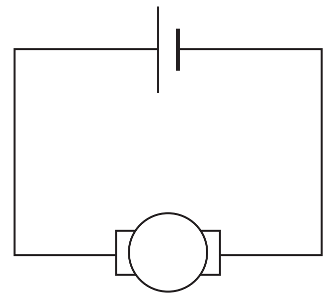
8 A garden water feature could be an analogy for an electric circuit.



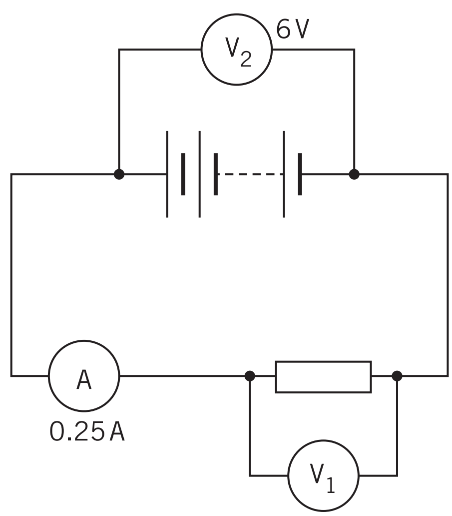


Suggest parts of the fountain that could represent these circuit components in the following circuit and justify your reasoning.

a battery
b current
c motor

9 The position of a voltmeter is always *across* the component whose potential difference is being measured (it is 'in parallel').

a Explain this in terms of the energy changes in the circuit.
b What value will the voltmeter V_1 show in the following circuit?



10 The reading on a voltmeter connected directly across a battery or power pack is often different depending on whether there is current flowing (a complete circuit) or not (an open circuit). Can you suggest why this might be?

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5C Modelling resistance in series circuits

Study Design

- Model resistance in series and parallel circuits using:
  - current versus potential difference (I–V) graphs
  - resistance as the potential difference to current ratio, including R = constant for ohmic devices
  - equivalent resistance in arrangements in
    - series: $R_{\text{equivalent}} = R_1 + R_2 + \ldots + R_n$
    - parallel: $\frac{1}{R_{\text{equivalent}}} = \frac{1}{R_1} + \frac{1}{R_2} + \ldots + \frac{1}{R_n}$
- Calculate and analyse the equivalent resistance of circuits comprising parallel and series resistance
- Analyse circuits comprising voltage dividers

Glossary:

Equivalent resistance
Ohmic resistor
Ohm's law
Potential (voltage) divider
Resistance
Series circuit

ENGAGE

Can electricity be used for transport in Australia?

The transport industry is one of the most carbon intensive in Australia. Nearly 20% of Australia's CO_2 emissions come from transport of various types, so electrifying as much as possible of this is key to meeting our net-zero 2050 goals. Many people now ride bikes with electric motors run from small batteries, which assist while you're pedalling, allowing longer trips with less effort. Cars have progressively become more fuel efficient, and car companies are producing electric vehicles (EVs) and plug-in hybrids that use less petrol. When these vehicles are recharged from renewable sources of electricity, they provide a clean and quiet means of transport.

Figure 5C–1 Electric vehicles capable of travelling 500 km between charges are already available. When not in use, they can be set up to rapidly supply peak load electricity to the grid.

EVs have the added advantage of regenerative braking. As the car slows down, some of the kinetic energy that would normally be transformed to heat in the brake pads is instead transformed into electrical potential energy stored in the battery.

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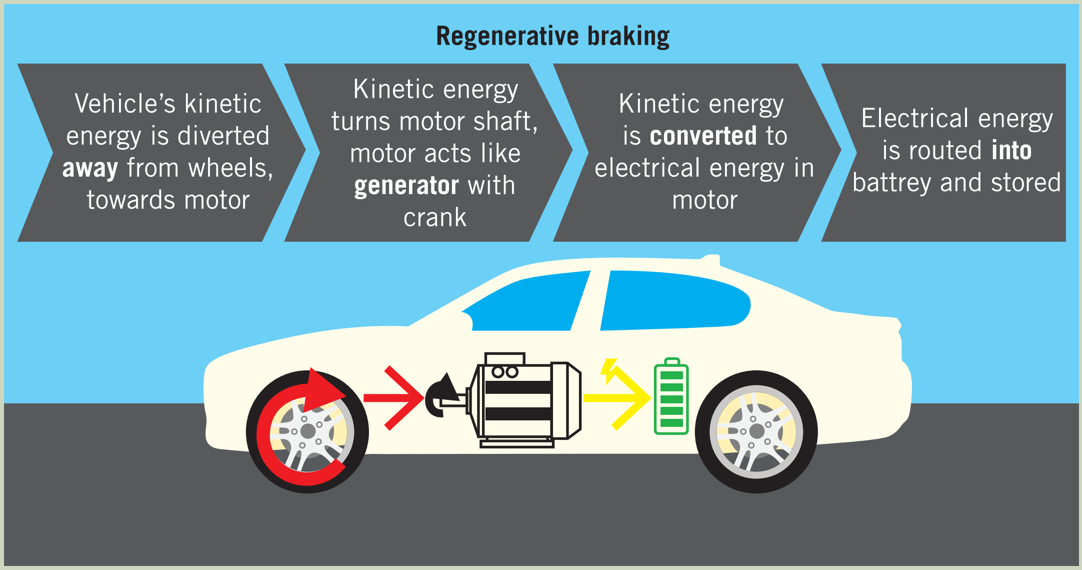

While it does not fully return all the energy expended to accelerate, regenerative braking is efficient enough to increase an EV's overall range when compared to a similar car with conventional braking systems. Overall, regenerative braking is not designed to make a car more efficient; it is designed to make it less inefficient.

In the public transport arena, all of the electricity used to power Melbourne's tram network and its fleet of more than 400 trams is offset by renewable energy from two Victoria solar facilities: the 38 MW Bannerton Solar Park and the 128 MW Numurkah Solar Farm. Melbourne's Yarra Trams is also installing large arrays of solar panels that, while not directly powering the trams, will feed electrical energy into the mains grid. The average single-occupancy Victorian car produces more than 240 grams of CO_2 emissions per person per kilometre travelled, whereas trams produce approximately 20 grams and also reduce traffic congestion.

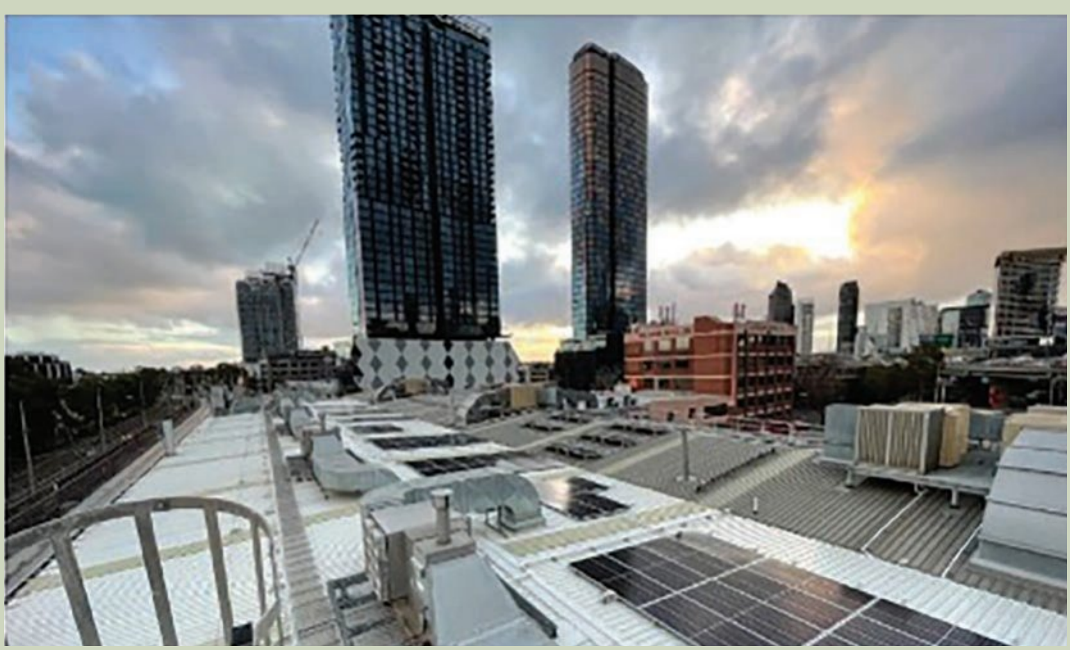

Figure 5C–2 200 solar panels were installed on the Southbank Tram Depot in 2022. Along with new skylights and LED lighting, this is expected to cut CO_2 emissions by more than 1 megatonne per year.

Fully electric battery buses are also on the way, with the possibility of wireless charging stations under the roadway at the terminus. Other vehicles use hydrogen as fuel to burn in a small generator, which then runs the EV. As battery costs rapidly decrease, the economic benefit of EVs compared to large diesel engines for heavy road haulage becomes clearer. By their design, the torque from an electric motor is well suited to heavy loads currently towed by diesel trucks. Aside from fuel savings, EVs also save on servicing costs because there are fewer moving parts, oil changes and so on required.

EXPLAIN

What is electrical resistance?

You have seen that the energy dissipated in a circuit can be understood using concepts of charge, current and potential difference. These quantities are related: as the energy supplied to a circuit increases, the amount of charge that flows increases. Sometimes the relationship between these quantities is simple, and other times it is more complex. Let's start with a simple circuit.

In Figure 5C–3 (left), a light bulb is connected to a power supply. The potential difference supplied can be varied from 0 to 12 V. When the switch is closed, current flows through the bulb.

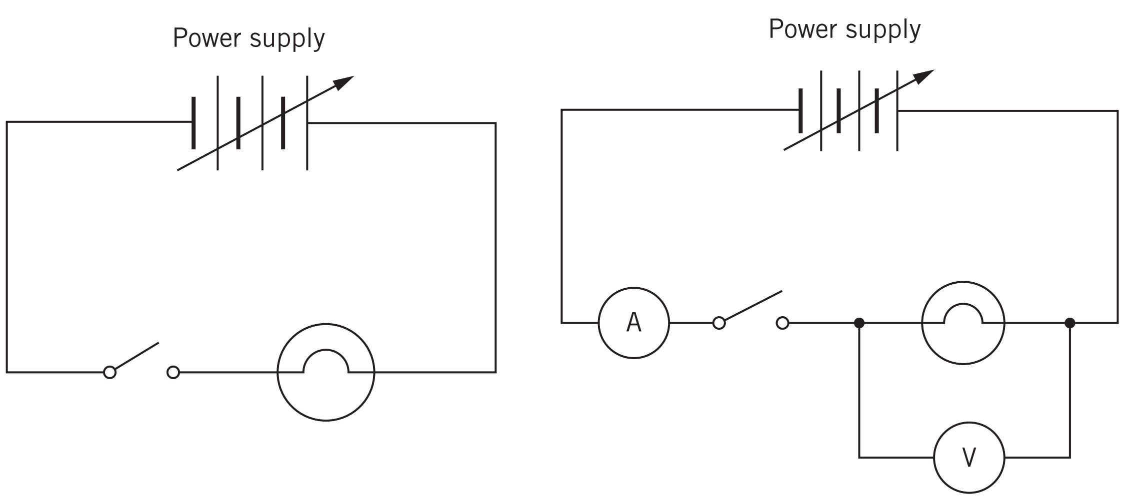

Figure 5C–3 Left: A simple circuit showing a light bulb connected to a variable voltage power supply Right: By connecting an ammeter in series and a voltmeter in parallel as shown, the I–V (current vs potential difference) data for the bulb can be easily obtained and graphed.

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5B ELECTRICAL ENERGY AND POTENTIAL DIFFERENCE LINK

As the potential difference is increased, the current will increase too. The light will get brighter as more energy is supplied (recall from Section 5B that $E = VIt$). But are the two quantities, current and potential difference, related to each other in a simple mathematical way? To find out, a voltmeter and an ammeter must be added to the circuit as shown in Figure 5C–3 (right).

The potential difference can now be increased in steps from 0 to 12 V and the value of current recorded for each step. Plotting a graph of current against potential difference (Figure 5C–4) shows that as the potential difference is increased, the current increases too, but not in a uniform (or steady) way. You can tell this because the graph is not a straight line; the gradient changes. This is because the filament of the bulb gets hotter as more current passes through it, and hotter metals become more resistant to current flow. Think of vibrations of thermal energy of the metal lattice ions getting in the way of the drifting electrons, like a rugby player with the ball trying to dodge while running through the opposition defence. If the defenders move more, it's harder to dodge through without colliding.

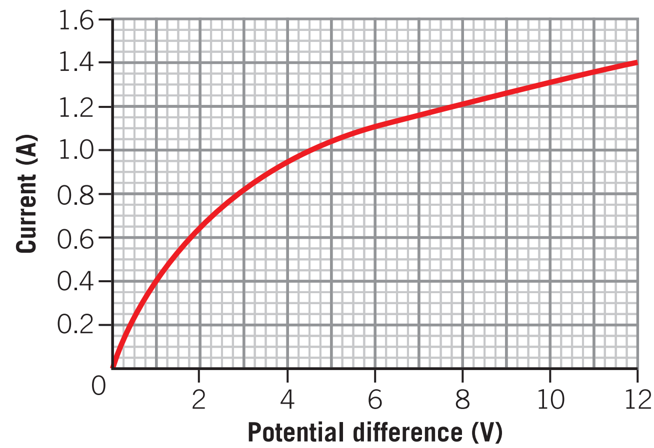
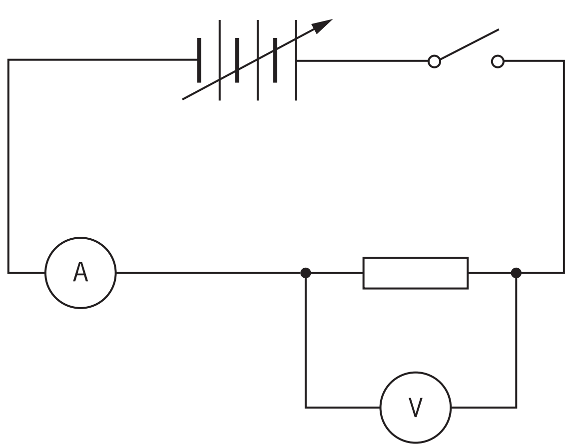


Figure 5C–4 Graph of current vs potential difference obtained from the circuit shown in Figure 5C–3 (right)

If a similar circuit is set up where the heating effect is as small as possible, the I–V graph will be straight. Figure 5C–5 (left) shows an example using a laboratory resistor. The current now increases steadily as the potential difference rises, shown by the graph of I vs V (Figure 5C–5 right).



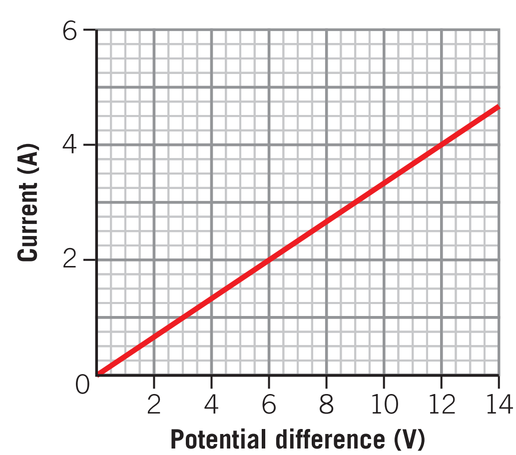


Figure 5C–5 Left: A laboratory resistor connected to a variable voltage power source Right: A resistor shows a straight line I–V graph. The graph is a straight line of constant gradient. This means that the ratio of V to I is constant. Such resistors are said to be 'ohmic'. This resistor has a constant resistance of 3 Ω.

Resistance a measure of how much an object or material impedes the flow of current measured in units of ohms (Ω)

Ohmic resistor a material that gives a straight line I–V graph; i.e. it obeys Ohm's law

The ratio of V to I for a component is called its **resistance**, R. The unit of resistance is the ohm (given the Greek letter 'omega', Ω). It is constant for some components such as an **ohmic resistor** and varies with current and temperature for others, such as a light bulb.

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The relationship between potential difference and current is expressed by the equation below. This is called **Ohm's law** and it is more commonly expressed as:

Ohm's law
for a particular type of material that gives a straight-line characteristic I vs V graph, meaning that $V = IR$ always holds for that material

Formula 5C–1 Ohm's law

$$V = IR \quad \text{or} \quad R = \frac{V}{I}$$

Where:

V = Potential difference (V)

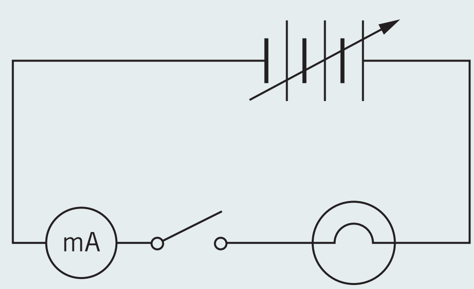
I = Current (A)

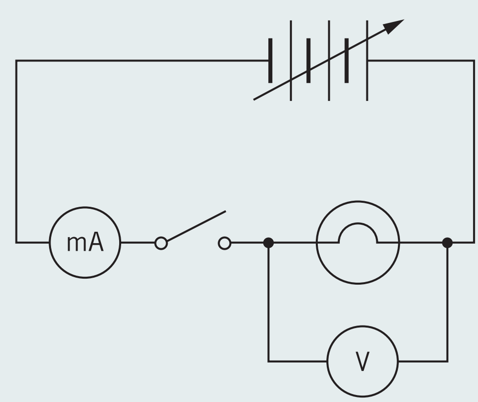
R = Resistance (Ω)

The laboratory resistor in Figure 5C–5 has a constant value for $\frac{V}{I}$, so it has a constant resistance of 3 Ω. Note that this can be calculated from $\frac{1}{\text{gradient}}$ of the I–V graph or $\frac{\text{run}}{\text{rise}}$. The value of $\frac{V}{I}$ for the light bulb changed as the current increased, showing that in this case, the resistance was not constant. When a current of 0.5 A is flowing, the value of $\frac{V}{I}$ is 3 Ω, while at 1.0 A it is 5.0 Ω.

ACTIVITY 5C–1 OHM'S LAW

1 Connect the circuit shown below left. Check with your teacher whether you will need an ammeter or a milliammeter (or use a multimeter on the amps setting).





2 Add a voltmeter (as shown above right).
3 Set up a table to record potential difference, V (in volts) and current, I (in mA).
4 Turn on the power supply and increase the potential difference in steps from 0 to 12 V, recording the value of current recorded for each step.
5 Plot a graph of current against potential difference. Draw a line of best fit.
6 Draw a conclusion about the resistance of the globe, based on the way current through the light bulb changes at different potential difference values.

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Worked example 5C–1 Applying Ohm's law to a car headlight

A car LED headlight is powered by a 12.0 V battery. Find the resistance of the car headlight when there is a current of 5.0 A through it, operating normally.

Solution

Use Ohm's law:

$$V = IR$$

The potential difference is provided by the battery, so $V = 12.0$ V, and the current is given as $I = 5.0$ A.

The resistance, R, is given by:

$$R = \frac{V}{I} = \frac{12.0}{5.0} = 2.4\ \Omega$$

The resistance of the headlight is 2.4 Ω.

NOTE

In practice, when current is large enough to cause heating, this increases the resistance. The ratio $\frac{V}{I}$ gives the resistance at any moment but, depending on the type of headlight, the resistance may not be constant, i.e. it may be non-ohmic.

Worked example 5C–2 Current in a light bulb

An old-fashioned incandescent light bulb has a resistance of 960 Ω when working normally, connected to the 230 V mains power supply. What current does the light bulb typically draw?

Solution

Use Ohm's law:

$$V = IR$$

The potential difference is provided by the mains power supply, so $V = 230$ V, and the resistance is given as $R = 960\ \Omega$.

You want to find the current, I.

$$I = \frac{V}{R} = \frac{230}{960} = 0.24\text{ A}$$

The light bulb draws a current of 0.24 A.

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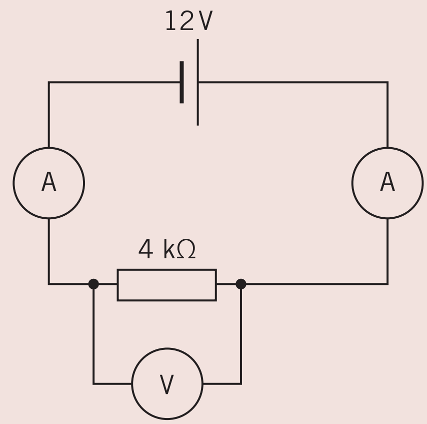
Worked example 5C–3 Meter readings in a circuit

What would each of the meters read in this circuit?



Solution

For a circuit with a single resistor, the entire potential difference from the battery is dissipated in the 4 kΩ resistor. So, the voltmeter will read 12 V.

The current can be calculated using Ohm's law:

$$V = IR$$

The potential difference is $V = 12$ V, and the resistance is $R = 4$ kΩ. Rearrange the formula to find the current, I.

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

$$= \frac{12}{4 \times 10^3}$$

$$= 3 \times 10^{-3} \text{ A}$$

It is a series circuit, so both ammeters will read 3 mA.

NOTE

When an ammeter is used to measure current in a circuit, it is designed to use the least possible energy, so that it doesn't significantly alter the function of the circuit. This means that it has the lowest possible resistance, with a very small to negligible potential difference across it. An 'ideal ammeter' is considered to have zero resistance.

Voltmeters, which are connected in parallel to measure the potential difference across a component, are designed to take very little current into their branch of the circuit. They have very high resistance, for digital voltmeters it is in the order of megaohms (10^6 Ω). An 'ideal voltmeter' is considered to have infinite resistance.

For the purposes of this course, all meters are considered to be ideal.

Check-in questions – Set 1

1 Copy and complete the following table.

Quantity	Symbol	Units
Potential difference		
Current		
Resistance		

2 Calculate the resistance of a component when the potential difference across it is 6.0 V and the current through it is 0.2 A.

3 On the same axes, sketch an I–V graph for:

a a resistance of 0 Ω

b an infinite resistance.

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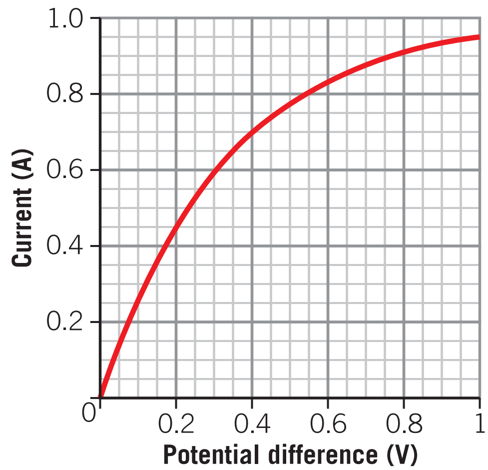
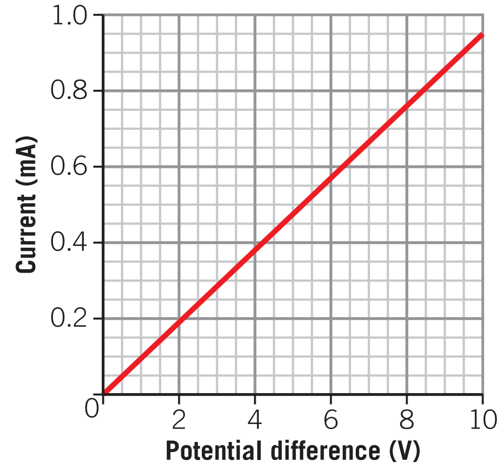
4 For each of the following current–potential difference (I–V) graphs, identify whether it is more likely to be produced by a light bulb or a resistor. Justify your choice.

a



b



Series circuits: current, potential difference and resistance

So far Ohm's law, $V = IR$, has been used to analyse simple circuits with only one load component. Many circuits contain several components, and their total or **equivalent resistance** must be found before the circuit can be analysed fully. Components may be connected in **series**, in parallel or in a combination of the two.

Equivalent resistance the value of a single resistor that could replace a number of individual resistors to give the same effect in the circuit

Series circuit when circuit components are connected one after the other in a continuous loop, so that the same current passes through each component

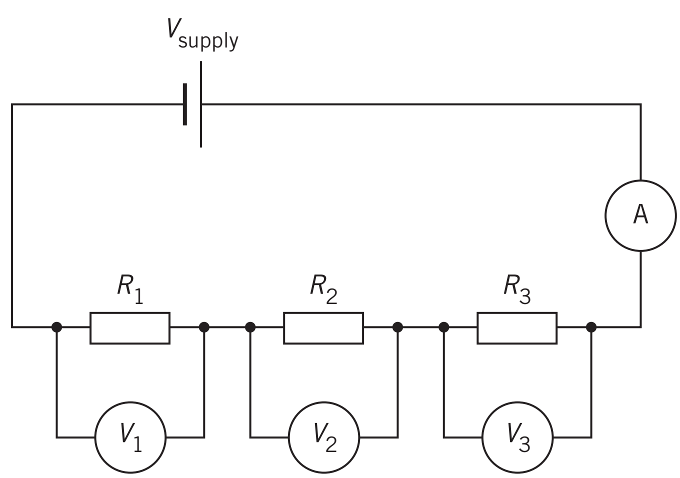


Figure 5C–6 In a series circuit, the same amount of current passes through each of the resistors and back to the battery — there is nowhere else for the electrons to go. The energy supplied by the battery (the potential difference) is shared between the resistors according to the resistance of each of them. The greater the resistance, the greater its share of the potential difference.

5D MODELLING RESISTANCE IN PARALLEL CIRCUITS LINK

Two or more components are said to be in series in a circuit if there is only one path for current to flow. The components are connected in a chain, one after the other.

Note that for series circuits:

- there is only one current path through R_1, R_2 and R_3, so there must be the same current, I, in each. (Electrons do not stop anywhere on their way around the circuit.)
- the sum of the potential differences across R_1, R_2, and R_3 must equal the potential difference that the battery provides: $V_{supply} = V_1 + V_2 + V_3$

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Using Ohm's law repeatedly around this circuit gives $R = \frac{V}{I}$ for each resistor. If you then add these up, you can find the equivalent resistance of the circuit.

$$R_{\text{equivalent}} = \frac{V_1}{I_1} + \frac{V_2}{I_2} + \frac{V_3}{I_3} = R_1 + R_2 + R_3$$

Therefore, for resistors in series, the total equivalent resistance of the combination is the sum of the individual resistances:

Formula 5C–2 Series resistance

$$R_{\text{equivalent}} = R_1 + R_2 + \ldots + R_n$$

Where:

$R_{\text{equivalent}}$ = Equivalent resistance for resistors in series (Ω)

$R_1, R_2, \ldots, R_n$ = Resistance of each resistor (Ω)

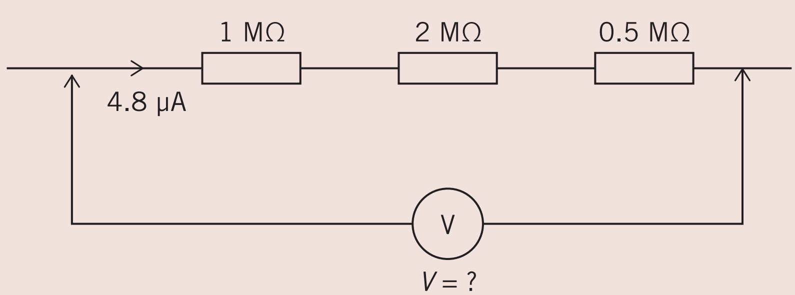
If you connect batteries in series, the total potential difference is the sum of the individual potential differences.

Worked example 5C–4 Ohm's law for series resistance

Three resistors of 1 MΩ, 2 MΩ and 0.5 MΩ are connected in series and carry a current of 4.8 μA. Find the potential difference across the combination.

Solution

First draw a circuit diagram, adding all the information from the question:



Apply the series resistance Formula 5C–2 to calculate the equivalent resistance of the series combination:

$$\begin{aligned} R_{\text{equivalent}} &= R_1 + R_2 + R_3 \\ &= 1 \times 10^6 + 2 \times 10^6 + 0.5 \times 10^6 \\ &= 3.5 \times 10^6\ \Omega \end{aligned}$$

Apply Ohm's law to find the potential difference:

$$\begin{aligned} V_{\text{total}} &= IR_{\text{equivalent}} \\ &= 4.8 \times 10^6 \times 3.5 \times 10^6 \\ &= 16.8\ \text{V} \end{aligned}$$

The potential difference across the series combination is 16.8 V.

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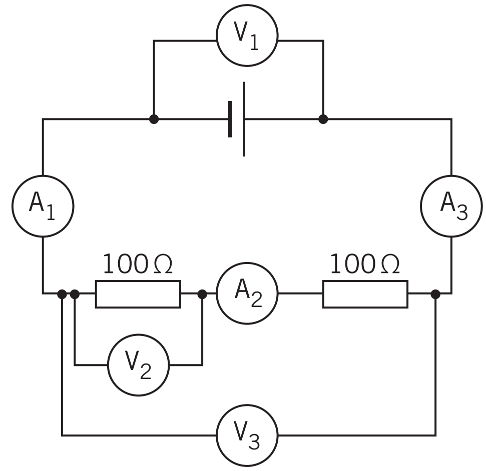
Check-in questions – Set 2

Consider the circuit containing a battery and two resistances in series, shown on the right.



1 Describe the relative sizes of the potential differences measured by the voltmeters V_2 and V_3 in terms of the battery potential difference, V_1. Justify your answer.

2 Describe the relative sizes of the currents measured by the ammeters A_1, A_2 and A_3 in terms of which are smaller, which are larger, and if any are the same. Justify your answer.

Potential (or voltage) dividers: a useful series circuit

Potential (voltage) divider
a series circuit with two or more components; where the voltage is shared (or divided) between the components in the circuit

A simple **potential divider** (or **voltage divider**) consists of two resistors in series. The output potential difference is taken from the point between the two, as shown in Figure 5C–7.

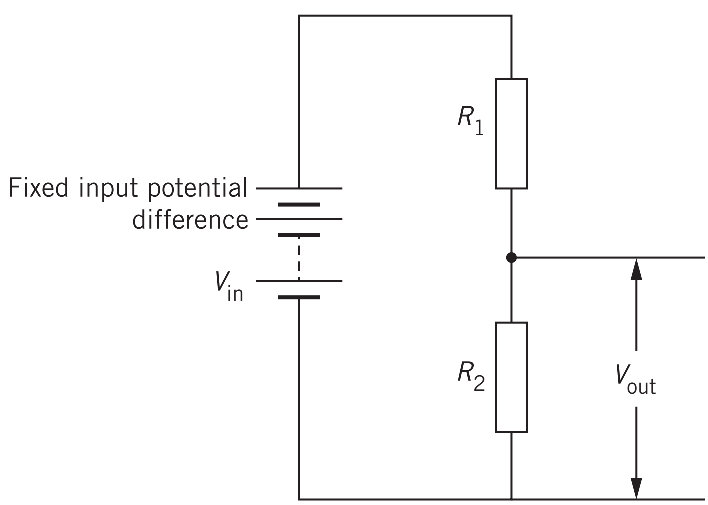


Figure 5C–7 Two resistors in series with a fixed voltage supply can be used to give any amount of output voltage, V_{out}, by varying the sizes of the resistors

By varying the values of each resistor, any number of volts can be supplied at the output from a fixed input. Knowledge of series circuits and Ohm's law are used to calculate the output as follows.

The total equivalent resistance, $R_{equivalent}$, in this circuit is:

$$R_{equivalent} = R_1 + R_2$$

Using Ohm's law ($V = IR$), the current, I, through $R_1 + R_2$ is given by:

$$I = \frac{V}{R_{equivalent}} = \frac{V_{in}}{R_1 + R_2} \qquad \text{Equation 1}$$

Applying Ohm's law to R_2 gives:

$$V_{out} = IR_2 \qquad \text{Equation 2}$$

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Substituting Equation 1 into Equation 2 gives:

$$V_{out} = \frac{V_{in}}{R_1 + R_2} \times R_2$$

Which is usually written as:

Formula 5C–3 Potential divider

$$V_{out} = \left(\frac{R_2}{R_1 + R_2}\right)V_{in} = \left(\frac{R_2}{R_{equivalent}}\right)V_{in} \text{ or } \frac{V_{out}}{V_{in}} = \frac{R_2}{R_{equivalent}}$$

Where R_1 and R_2 are the resistances of the resistors, V_{in} is the potential difference of the supply and V_{out} is the output potential difference across R_2.

This ratio $\frac{R_2}{R_1 + R_2}$ makes sense, as you know that in a series circuit the potential drop across each component depends on the resistance of that component. So, the potential drop across R_2 will be the same proportion of V_{in} as the proportion of R_2 is in the whole circuit $R_1 + R_2$.

Resistors R_1 and R_2 'divide up' the input volts V_{in} in proportion; hence the name for this arrangement: potential divider (sometimes called voltage divider). By using variable resistors, or components that are sensitive to changes in temperature (thermistors) or light level (light-dependent resistors), V_{out} can be controlled to turn on or off refrigeration motors or streetlights at the appropriate temperature or level of darkness. You will explore this in more detail in Chapter 6.

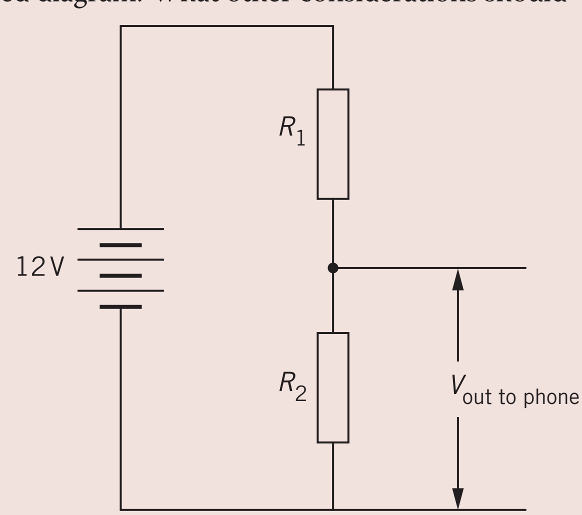
LINK 6A USEFUL ELECTRONIC COMPONENTS

Worked example 5C–5 Using a potential divider

A particular mobile phone requires a potential difference of up to 5 V to charge correctly. The only power supply available is a 12 V battery from a caravan. A physics student thinks of using a potential divider circuit to supply the required 5 V. If one available resistor is 1.0 kΩ, what should the second resistor in the potential divider be and how should they be arranged? The other resistors available are 0.8 kΩ, 1.2 kΩ and 1.4 kΩ. Show your reasoning and a labelled diagram. What other considerations should the student take into account before operating this set-up?

Solution

First draw a diagram including all the information given in the question.



Consider whether the 1 kΩ resistor would be best placed as R_1 or R_2. Since 5 V required is less than half the 12 V available, put the 1 kΩ as R_2 so the larger resistors can be in the top of the potential divider.

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Using Formula 5C–3 we can calculate the required equivalent resistance:

$$\frac{R_2}{R_{\text{equivalent}}} = \frac{V_{\text{out}}}{V_{\text{in}}}$$

$$\frac{1 \times 10^3}{R_{\text{total}}} = \frac{5}{12}$$

$$R_{\text{total}} = \frac{5}{12} \times 10^3$$

$$= 2.4 \times 10^3\ \Omega$$

Now, because R_1 and R_2 are in series:

$$R_{\text{total}} = R_1 + R_2$$

Substitute into the formula:

$$2.4 \times 10^3 = R_1 + 1 \times 10^3$$

So:

$$R_1 = 1.4 \times 10^3$$

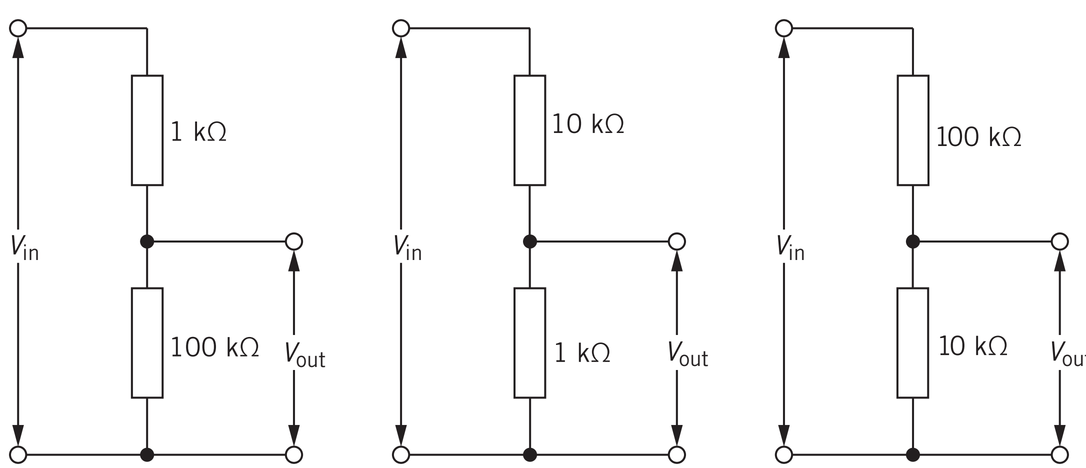
$$= 1.4\ \text{k}\Omega$$

Among the other considerations is the amount of current the phone will draw while recharging: can the battery supply this without overheating, and can the resistors and the connecting wires handle this current without damage? Conversely, would the battery supply more current in this set-up than the phone can handle? More detailed understanding of these and other factors is needed, and experimenting with expensive items is not recommended.

WORKSHEET 5C–1 MODELLING RESISTANCE IN SERIES CIRCUITS

Check-in questions – Set 3

1 If V_{in} is 12 V, calculate V_{out} in each of these potential dividers (1 k = 1000 Ω) Hint: you should be able to see a short cut to using the complete formula each time.



2 Can the output potential difference, V_{out}, of a potential divider ever be larger than the input potential difference, V_{in}? Explain your answer.

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5C SKILLS

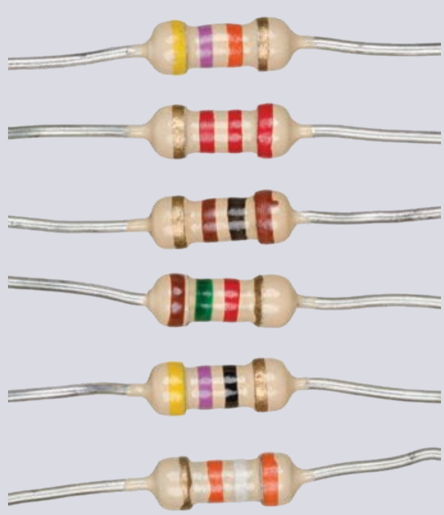
VIDEO 5C–1
SKILLS: RESISTOR CODE

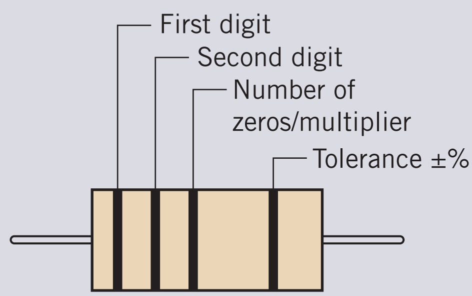
Resistor code

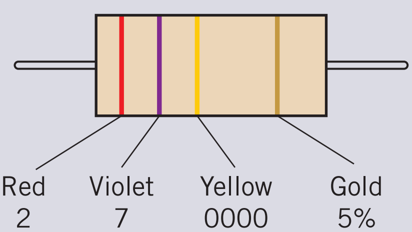
Many electrical components are very small, so it is difficult to print information in words or figures on the component itself. There are a number of internationally accepted codes for such components, which include capacitors, integrated circuits (ICs or chips) and of course resistors. Those codes are an example of cooperation across the international scientific community.

For fixed resistors, a colour code is used to indicate the size and reliability of the resistance. While memorising the code is beyond this course, the concepts involved are useful to students and the structure of the code reveals interesting detail about standard ceramic resistors.

Each digit 0–9 is given a colour. The colours of the first two bands give the two digits of the resistor value, and the third band colour is the power of ten multiplier. The fourth band, if present, shows the tolerance of the measurement given by the first three bands.



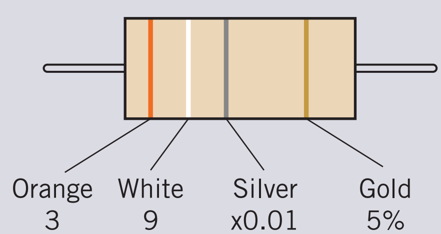




Resistance = 270 kΩ ±5%

0 – Black	6 – Blue
1 – Brown	7 – Violet
2 – Red	8 – Grey
3 – Orange	9 – White
4 – Yellow	x0.1 – gold
5 – Green	x0.01 – Silver

Red is 2% *Silver* is 10%
Gold is 5% *No band* is 20%



Resistance = 0.39 Ω ±5%

You can check the resistance read from the code using a multimeter, but if you want to select a number of resistors, this would be time consuming, whereas comparing the coloured bands is quick and easy.

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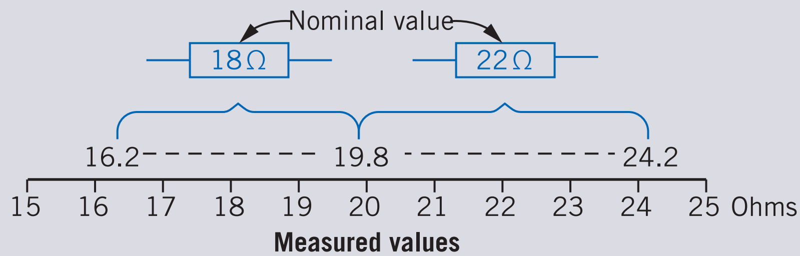
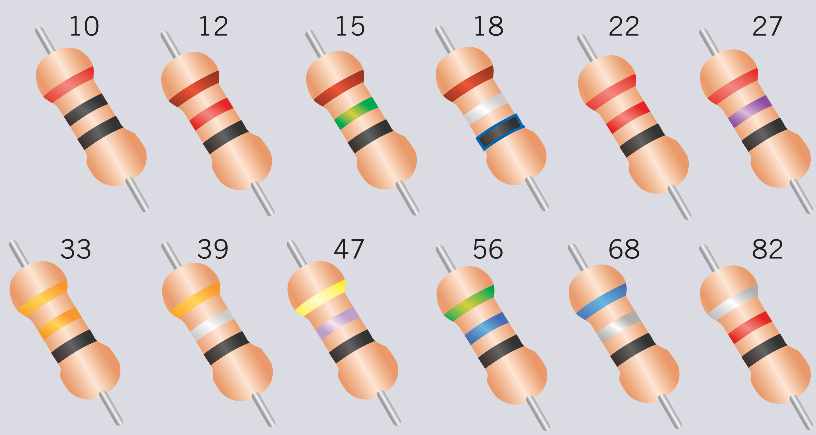
If a resistor has a value of, say, 18 Ω ±10%, its measured value could be anything from 16.2 to 19.8 Ω. Similarly, a resistor rated at 22 Ω ± 10% can have a range from 19.8 to 24.2 Ω. These two resistors together cover a range from 16.2 to 24.2 Ω.



Standard resistors are produced in values based on a series of non-overlapping tolerances. A section of this series for 20% tolerance is:



Note that the third band, shown as black here, can change to give any power of ten within the range produced.

Section 5C questions

Multiple-choice questions

1 What is the resistance of a light bulb in which the current is 0.5 A when it is connected to a potential difference of 240 V?

A 240 Ω
B 120 Ω
C 480 Ω
D 2 mΩ

2 What is the potential difference across a 50 Ω resistance when there is a 5 A current through it?

A 10 V
B 250 V
C 25 V
D 0.1 V

3 What is the current in an appliance of resistance 1000 Ω when it is connected to the 240 V mains supply?

A 0.24 A
B 2.4×10^5 A
C 4.2 A
D 24 A

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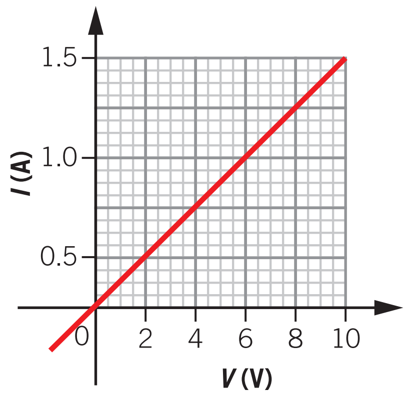
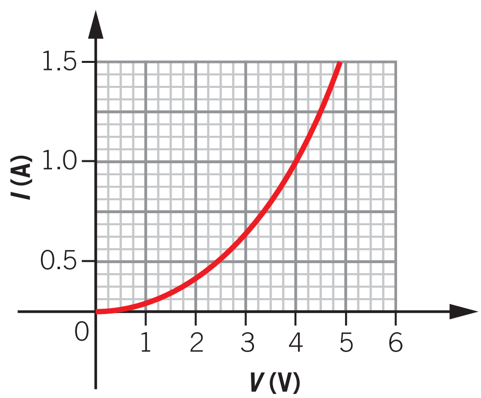
4 What is the resistance of the component that has an I–V characteristic (graph) as follows?



A 4.0 Ω
B 0.25 Ω
C 2.0 Ω
D 0.50 Ω

5 What is the resistance of the component that has an I–V characteristic (graph) as follows when the potential difference across the component measures 4 V?



A 4.0 Ω
B 0.25 Ω
C 2.0 Ω
D 0.50 Ω

Short-answer questions

6 Calculate the potential difference across a coil of wire with resistance 20 Ω if a total of 120 C of charge passes through it in 1 min.

7 Draw a diagram, then work out the equivalent resistance for each of the following.
a 25 Ω resistor in series with a 15 Ω resistor
b 10 Ω, 5 Ω and 3 Ω resistors in series

8 Resistors of 1 kΩ, 2 kΩ and 5 kΩ are joined in series and connected to the 24 V electricity supply of a caravan.
a Draw a circuit diagram of the arrangement. Include a switch.
b What is the total resistance in the circuit?
c What is the current in the circuit?

9 Draw a circuit diagram you could use to determine the I–V characteristic of an unknown component X. Hint: use a variable supply of potential difference like a power pack, and enough meters of the right types for your measurements. Be sure to arrange the meters correctly in the circuit.

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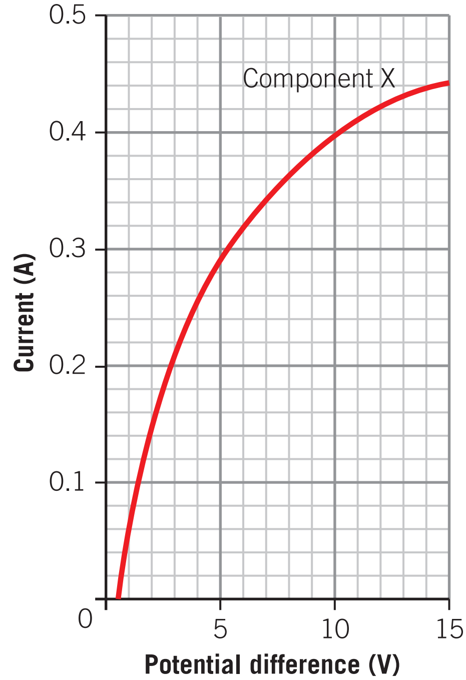
10 The I–V characteristic for component X is shown in the graph.

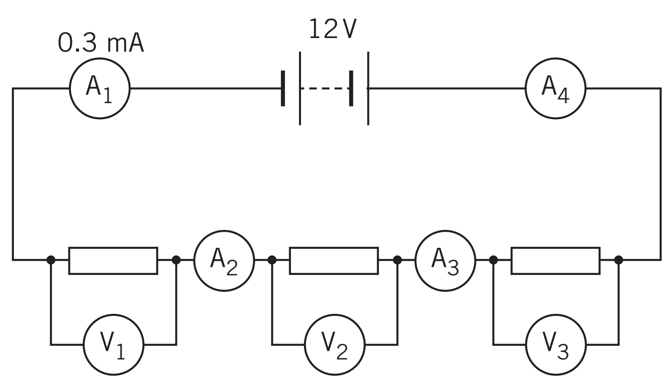


Find the resistance of X when the potential difference across it is:

a 5 V

b 10 V

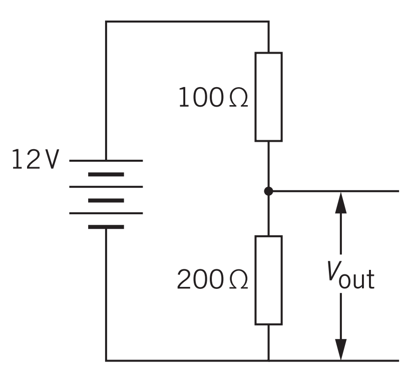
11 All the resistors in the following circuit are identical.



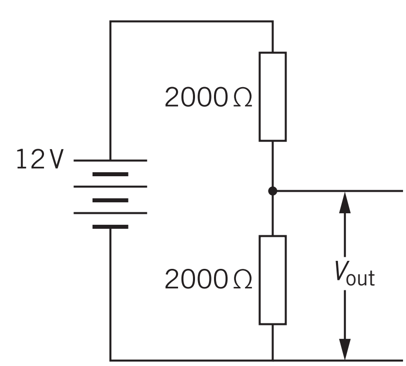
Calculate and state the readings on each of the meters, given the potential difference of the battery is 12 V, and the reading on A_1 is 3 mA.

12 What would the output potential difference, V_{out}, be in the following potential divider circuits?

a



b



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5D Modelling resistance in parallel circuits

Study Design:

- Model resistance in series and parallel circuits using:
  - current versus potential difference (I–V) graphs
  - resistance as the potential difference to current ratio, including R = constant for ohmic devices
  - equivalent resistance in arrangements in
    - series: $R_{equivalent} = R_1 + R_2 + \ldots + R_n$
    - parallel: $\frac{1}{R_{equivalent}} = \frac{1}{R_1} + \frac{1}{R_2} + \ldots + \frac{1}{R_n}$
- Calculate and analyse the equivalent resistance of circuits comprising parallel and series resistance

Glossary:

Parallel circuit

ENGAGE

When will air travel be electric?

In June 2022, an uncrewed aircraft with a 25 m wingspan and mass less than 75 kg was launched. Photovoltaic solar panels on top of its wings can power its electric motor and recharge onboard batteries, the Zephyr S can fly throughout the day and night. It smashed the previous flight duration record for an uncrewed flight, travelling at an average speed of 61.9 km h^{-1} at an average altitude of about 18 700 m. On 19 August 2022 the aircraft crashed after 64 days, 18 hours and 26 minutes of continuous flight. It had travelled around 80 000 km, beating the previous record duration for an uncrewed flight of 25 days, 23 hours and 57 minutes set by an earlier model Zephyr in 2018. Built by Airbus in the UK, both the record-breaking flights were operated by the US military in a flight zone above Arizona, United States. These aircraft are known in the military as high-altitude platform systems and are designed to carry out a similar function to geostationary satellites, staying above an area of interest and providing constant surveillance.

LINK UNIT 3

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While the Zephyr cannot carry passengers, or even a pilot, there are developments proposed for more ambitious electric flight. In Norway, where 65% of new car sales in 2021 were EVs, the ambition is to make all domestic flights electric by 2040. (By 2025, all new cars in Norway must be electric.) A demonstration in 2022 of a two-seater electric aircraft produced by Avinor attracted a lot of attention, although this is hardly a solution for mass-transit. Air travel, with its inherent weight limitations, is a difficult mode of transport to electrify. A solution may be electric motors with onboard generators and renewable biofuels, giving net zero rather than zero emissions.

Other modes of transport are way ahead: ships are being built with electric drives (albeit with diesel generation at the moment) and trains are routinely electrified. High-efficiency electric motors combined with advanced batteries will make both of these more feasible.

Slow progress in aviation is due to one problem: energy density. The advantage of most conventional propulsion is that liquid fuels can pack far more energy density than even the best batteries; that is, more energy per kilogram. In practice, an EV has a range defined by how much energy it can carry. For aircraft that's a much bigger issue because distances are so much greater. Until battery technology improves by at least an order of magnitude, hopes of large-scale commercial electric flight will be held back by limits on capacity and range.

However, if battery technology continues to improve at the current rate Norway may have a chance to achieve its 2040 goal. Electric aircraft will be incredibly quiet, powerful and fast. The planes would be emission free at the point of use, so airports and skies in the future could be considerably cleaner and quieter.

EXPLAIN

Parallel circuits: current, potential difference and resistance

5C MODELLING RESISTANCE IN SERIES CIRCUITS LINK

In a **parallel circuit** the path of the current branches so there is more than one way for current to go around the circuit. This is different from the series circuits you have looked at so far (in Section 5C). This means that in a parallel circuit, two or more components are connected across the same potential difference (A voltmeter is always connected in parallel, but it is built with a very high resistance so that negligible current travels through it.)

Parallel circuit a circuit that contains junctions; the current drawn from the battery, cell or electricity supply splits before it reaches components and rejoins afterwards

Parallel circuits can be drawn in several ways (Figure 5D–1).

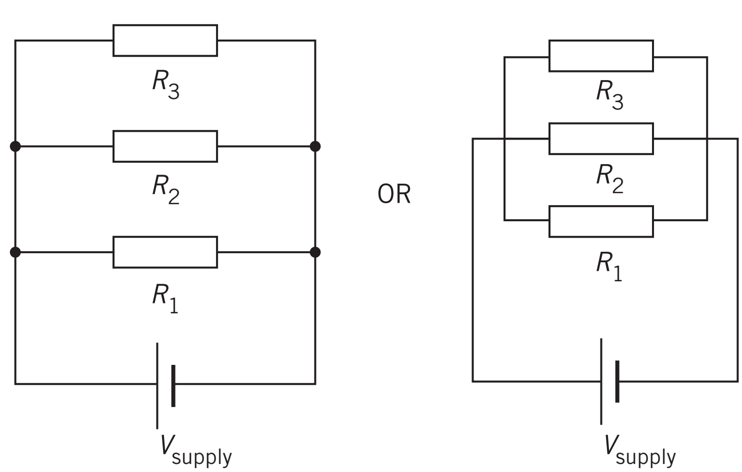

Figure 5D–1 Each of these diagrams show the same connections. The current leaving the supply splits into three, according to the size of the resistance in each branch, then rejoins the main circuit and returns through the battery. Each resistance has the same potential difference, the same as V_{supply}.

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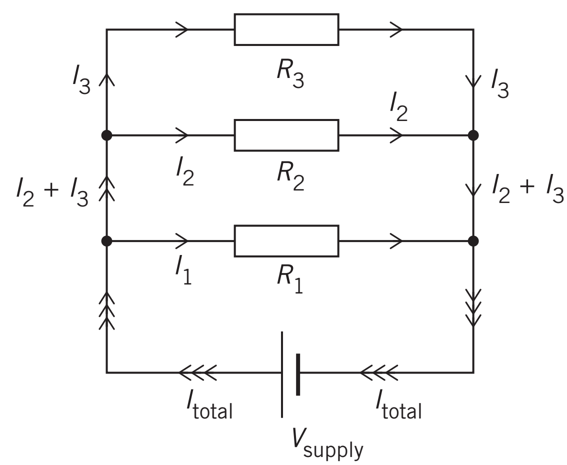
No matter which diagram is used, the effect is the same. Each of the resistors is connected directly to a battery terminal, so each resistor receives the full potential difference supplied, V_{supply}. This is one major advantage of a parallel circuit over a series circuit. Another is the ability to control each branch with a separate switch. In parallel, each component can be switched on and off without affecting the others.



Note that for parallel circuits, the:

- same potential difference, V, is across each component in the parallel section
- current, I_{total}, must divide into three component currents, I_1, I_2 and I_3. It must therefore be true that $I_{total} = I_1 + I_2 + I_3$.

Starting with $I_{equivalent} = I_1 + I_2 + I_3$ and substituting for I from Ohm's law, $I = \frac{V}{R}$, for each branch of the circuit gives:

$$\frac{V_{supply}}{R_{equivalent}} = \frac{V_{supply}}{R_1} + \frac{V_{supply}}{R_2} + \frac{V_{supply}}{R_3}$$

Taking V_{supply} as a common factor on the right-hand side and cancelling gives:

$$\frac{1}{R_{equivalent}} = \frac{1}{R_1} + \frac{1}{R_2} + \frac{1}{R_3}$$

The general form of this formula, for any number of resistors in parallel, is:

Formula 5D–1 Parallel resistance

$$\frac{1}{R_{equivalent}} = \frac{1}{R_1} + \frac{1}{R_2} + \ldots + \frac{1}{R_n}$$

Where $R_{equivalent}$ is the equivalent resistance (Ω) for resistors in parallel and R_1, R_2, … R_n is the resistance of each resistor (Ω).

If there are only two resistors, the parallel equivalent resistance formula reduces to:

Formula 5D–2 Two resistors in parallel

$$R_{equivalent} = \frac{R_1 R_2}{R_1 + R_2}$$

Where $R_{equivalent}$ is the equivalent resistance (Ω) for two resistors in parallel, and R_1 and R_2 are the resistances (Ω) of the two resistors.

Formula 5D–2 is generally easier to apply than Formula 5D–1. It also works for three or more resistors, by applying it first to two, then applying the formula again using that equivalent resistance with the next resistor, and so on.

In general, the equivalent resistance calculated in either parallel or series (or combined) gives the value of a single resistor that could replace a number of individual resistors, to give the same effect in the circuit.

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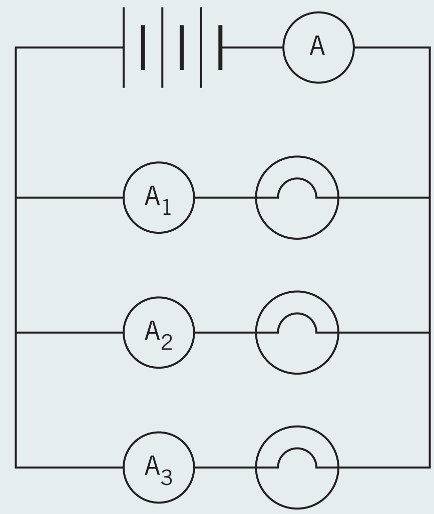
ACTIVITY 5D–1 PARALLEL CIRCUITS

1 Construct a parallel circuit and use an ammeter to measure the current through several points in each branch of the circuit.

2 Use a voltmeter to measure the potential difference across each resistance in the circuit and the power source, in the same circuit.

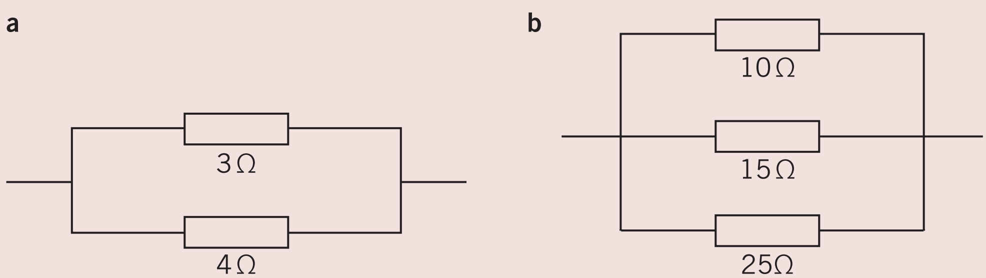
A possible circuit could be as shown, right.

3 What can you conclude about current and potential difference in a parallel circuit?



Worked example 5D–1 Resistance in parallel

Calculate the total resistance of each combination of resistors shown.



Solution

a For two resistors in parallel, the equivalent resistance is given by:

$$R_{\text{equivalent}} = \frac{R_1 R_2}{R_1 + R_2}$$

The individual resistances are $R_1 = 3\ \Omega$ and $R_2 = 4\ \Omega$. Therefore:

$$R_{\text{equivalent}} = \frac{(3)(4)}{(3)+(4)}$$

$$= \frac{12}{7}$$

$$= 1.71\ \Omega$$

The equivalent resistance is 1.71 Ω.

Alternatively, use:

$$\frac{1}{R_{\text{equivalent}}} = \frac{1}{R_1} + \frac{1}{R_2}$$

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Therefore:

$$\frac{1}{R_{\text{equivalent}}} = \frac{1}{3} + \frac{1}{4}$$
$$= \frac{4 + 3}{12}$$
$$= \frac{7}{12}$$
$$R_{\text{equivalent}} = \frac{12}{7}$$
$$= 1.71\ \Omega$$

b For three resistors in parallel, the equivalent resistance is given by:

$$\frac{1}{R_{\text{equivalent}}} = \frac{1}{R_1} + \frac{1}{R_2} + \frac{1}{R_3}$$

The individual resistances are $R_1 = 10\ \Omega$, $R_2 = 15\ \Omega$, and $R_3 = 25\ \Omega$. Therefore:

$$R_{\text{equivalent}} = \frac{1}{10} + \frac{1}{15} + \frac{1}{25}$$
$$= \frac{15 + 10 + 6}{150}$$
$$= \frac{31}{150}$$
$$R_{\text{equivalent}} = \frac{150}{31}$$
$$= 8.84\ \Omega$$

Alternatively, use the formula for two resistances in parallel twice:

$$R_{1,2} = \frac{R_1 R_2}{R_1 + R_2}$$
$$= \frac{(10)(15)}{(10 + 15)}$$
$$= \frac{150}{25}$$
$$= 6\ \Omega$$
$$R_{\text{equivalent}} = \frac{R_{1,2} R_3}{R_{1,2} + R_3}$$
$$= \frac{(6)(25)}{(6) + (25)}$$
$$= \frac{150}{31}$$
$$= 8.84\ \Omega$$

The equivalent resistance is 8.84 Ω, as expected.

NOTE

When resistors are connected in parallel an extra path for current is created. The equivalent resistance is *always less* than any of the individual resistors.

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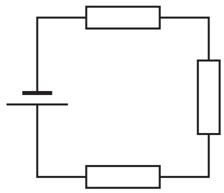
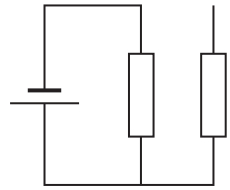
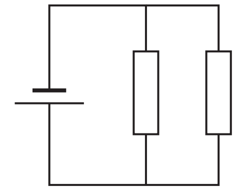
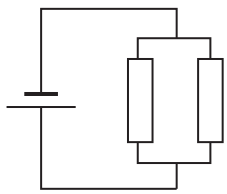
Check-in questions – Set 1

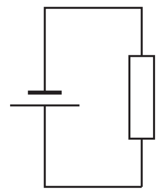
1 Which of the following diagrams represent parallel, series or simple circuits? The remaining circuit is incomplete or 'open'.

a


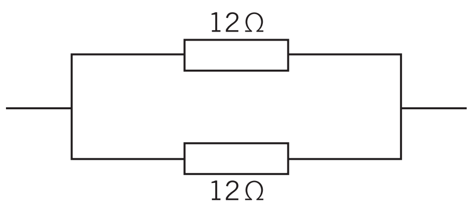
b


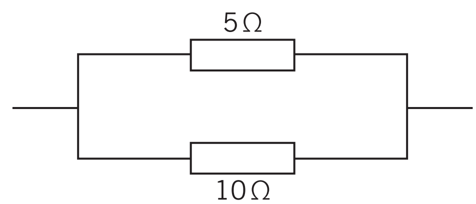
c


d


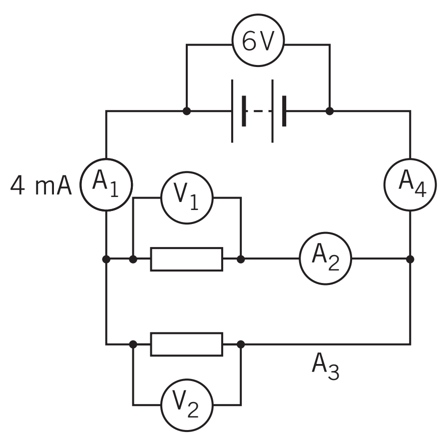
e


2 Calculate the equivalent resistance in the following parallel circuits.

a


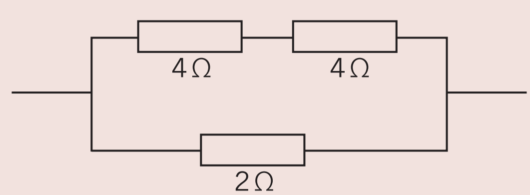
b


3 The two resistors shown are identical. State the values of current and potential difference readings for each of the meters shown.



Worked example 5D–2 Resistance in parallel and series

Calculate the total resistance of each combination of resistors shown.



Solution

First notice that the top branch of the circuit consists of two resistors in series.
Therefore, the equivalent resistance of the top branch is given by:

$$R_{top} = R_1 + R_2$$
$$= (4) + (4)$$
$$= 8\ \Omega$$

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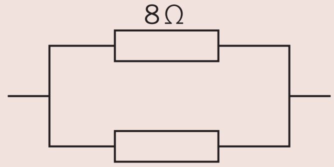
This means that the circuit can be redrawn as the equivalent one shown below.



Now you can apply the formula for two resistances in parallel:

$$\begin{aligned} R_{\text{equivalent}} &= \frac{R_1 R_2}{R_1 + R_2} \\ &= \frac{(8)(2)}{(8)+(2)} \\ &= \frac{16}{10} \\ &= 1.6\ \Omega \end{aligned}$$

Therefore, the equivalent resistance is 1.6 Ω.

Alternatively:

$$\frac{1}{R_{\text{equivalent}}} = \frac{1}{R_1} + \frac{1}{R_2}$$

Therefore:

$$\begin{aligned} \frac{1}{R_{\text{equivalent}}} &= \frac{1}{8} + \frac{1}{2} \\ &= \frac{1+4}{8} \\ &= \frac{5}{8} \\ R_{\text{equivalent}} &= \frac{8}{5} \\ &= 1.6\ \Omega \end{aligned}$$

The equivalent resistance is 1.6 Ω, as expected.

A graphical method for series and parallel circuits

So far two formulas have been used to calculate the equivalent resistance of simple circuits.

For series combinations:

$$R_{\text{equivalent}} = R_1 + R_2 + \ldots R_n$$

For parallel circuits:

$$\frac{1}{R_{\text{equivalent}}} = \frac{1}{R_1} + \frac{1}{R_2} + \frac{1}{R_3}$$

When designing circuits with several components, their total resistance must be found before the circuit can be fully analysed. Components may be connected in series, in parallel or in a combination of the two. A graphical method allows you to predict the way a circuit will behave from the characteristics of the individual components. First, methods of analysing combinations of simple resistors in series and parallel connections separately are needed. In Chapter 6 these techniques will be developed for non-ohmic components.

LINK CHAPTER 6

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Resistors in series: a graphical method

The components in the circuit shown in Figure 5D–2 have resistances of 2 Ω and 3 Ω respectively. A characteristic graph of *I* vs *V* can be created for each component separately, using the techniques learned in Section 5C. Then you can use the graph to analyse the circuit as follows.

5C MODELLING RESISTANCE IN SERIES CIRCUITS LINK

As it's a series circuit, the current is the same through each resistor. Choosing a current of 2 A, for example, the p.d. across each component is read from the graph (4 V and 6 V). The total p.d. is the sum of these two values, so a point can be plotted on the graph corresponding to the $\frac{V}{I}$ ratio for the total resistance (10 V, 2 A). An *I* vs *V* graph for the combination of resistors is plotted point by point for each current value (dotted line). The total resistance is the value of $\frac{V}{I}$ determined from this graph, 5 Ω in this case. This is the sum of 2 Ω and 3 Ω, as you would expect from $R_{equivalent} = R_1 + R_2 + \ldots R_n$. This constructed graph can be compared to the results measured from current through and potential difference across the whole combination.

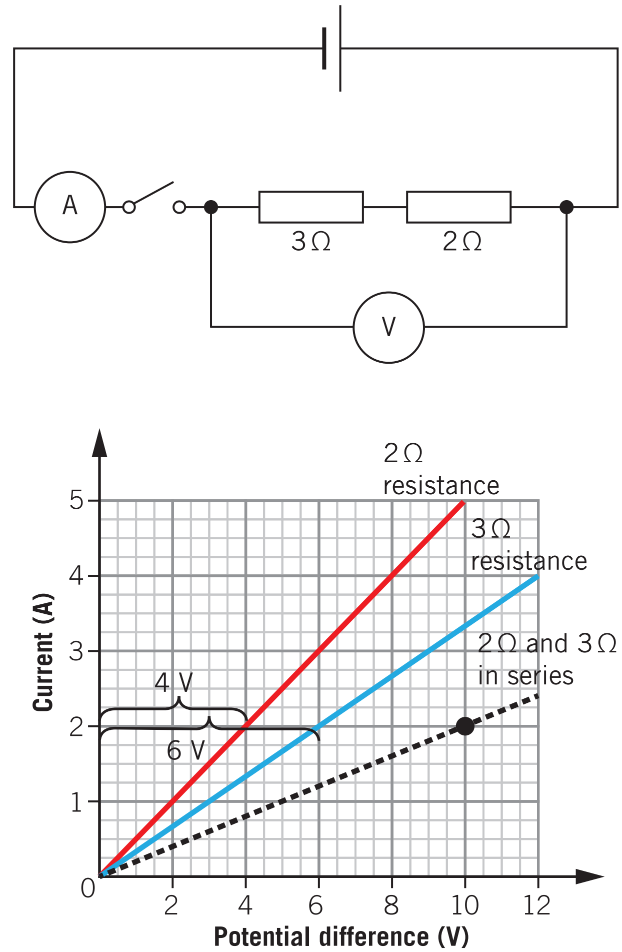

Figure 5D–2 A graphical method for calculating the total resistance in a series circuit (top). As the current flowing through each component must be the same, the individual potential drops across each component can easily read off the graph. A graph of *I*–*V* (bottom) can be constructed for the series combination (black dotted line).

Resistors in parallel: a graphical method

For a parallel combination, using the same *I*–*V* characteristic graph of the individual components, the analysis is as follows.

As it's a parallel circuit (Figure 5D–3), the potential difference across each resistor is the same. Choosing a potential difference (6 V for example), the current through each resistance is read from the graph (2 A and 3 A). The total current in the circuit is then the sum of the two separate currents (5 A). A point can be plotted corresponding to the values of *V* and *I* for the equivalent resistance of the circuit (6 V, 5 A). An *I* vs *V* graph can be plotted point by point for each value of p.d. (for the combination of resistors).

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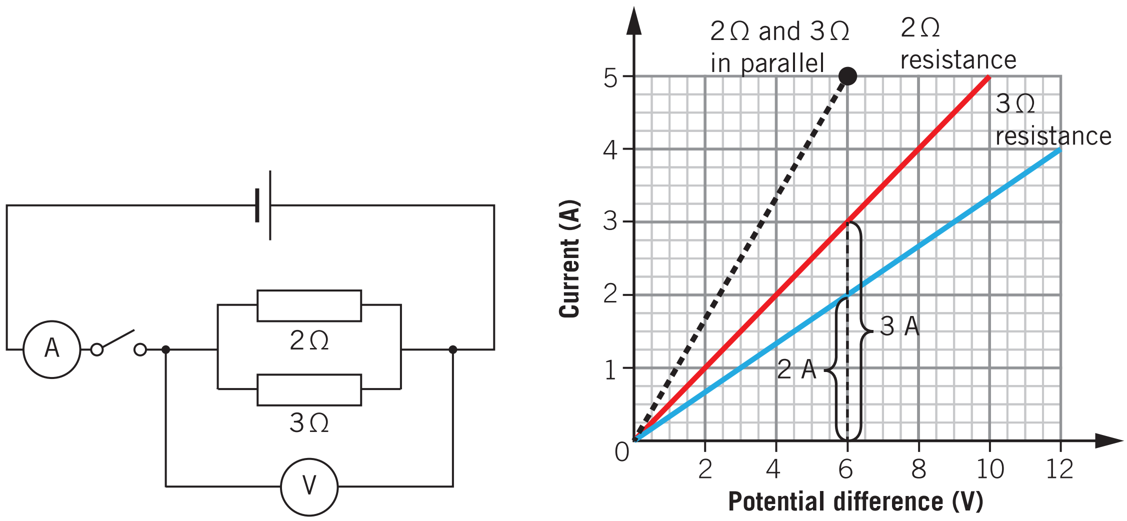


Figure 5D–3 A simple graphical method for calculating the total resistance in the parallel circuit on the left. As the voltage across each element must be the same, the individual current flowing through each component can be easily read off the graph on the right.

Again, the ratio $\frac{V}{I}$ from the inverse gradient of this graph is equal to the total resistance, $\frac{6}{5} = 1.25\ \Omega$ in this case, as you would expect from the formula $\frac{1}{R_{\text{equivalent}}} = \frac{1}{R_1} + \frac{1}{R_2} + \ldots \frac{1}{R_n}$.

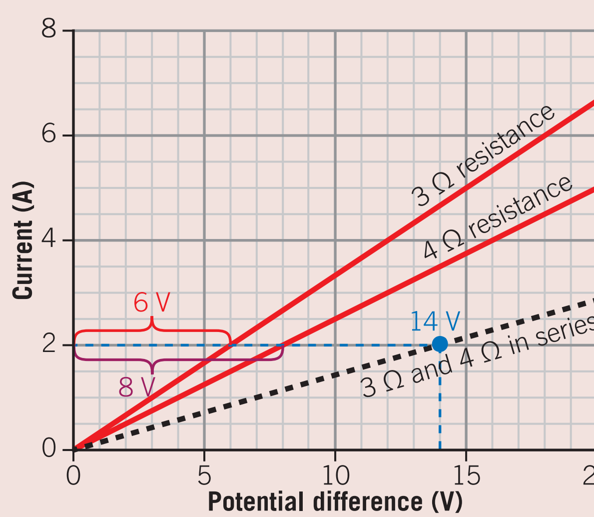
Notice that the I–V graph for series resistors has a smaller gradient, meaning $R_{\text{equivalent}}$ is larger than either component; the I–V graph for parallel resistors has a steeper gradient, meaning smaller resistance than either component.

Worked example 5D–3 Graphical approach to series resistance

A 3 Ω and 4 Ω resistor are wired in series. Use a graphical approach to determine the total potential difference across each resistor if the current is 2 A. Hence find the equivalent resistance of the series combination.

Solution

The I–V curve of a 3 Ω and a 4 Ω resistor are shown. Reading off the graph for a current of 2 A, the resistance of 3 Ω contributes 6 V of potential difference, and the resistance of 4 Ω contributes 8 V of potential difference. Therefore, the total potential difference across the resistances is 6 + 8 = 14 V.



$$R_{\text{equivalent}} = \frac{V_{\text{total}}}{I}$$

$$= \frac{14}{2}$$

$$= 7\ \Omega$$

This is what you would expect from the formula.

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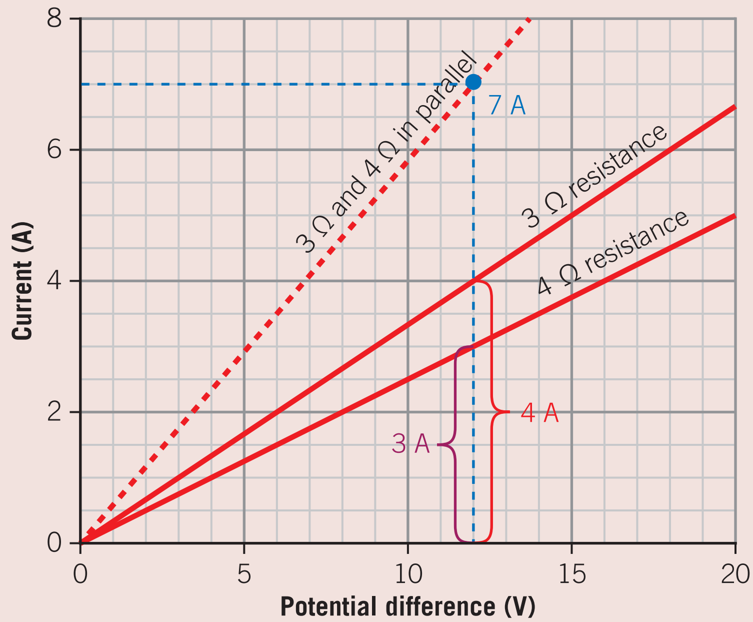
Worked example 5D–4 Graphical approach to parallel resistance

A 3 Ω and a 4 Ω resistor are wired in parallel. Use a graphical approach to determine the total current through the circuit if the potential difference is 12 V. Hence find the value of $R_{equivalent}$ for the parallel combination.

Solution



The I–V curve of a 3 Ω and 4 Ω resistor are shown above. Reading off the graph for a 12 V potential difference, the resistance of 3 Ω carries 4 A of current, and the resistance of 4 Ω carries 3 A of current. So, the total current through the battery is 4 + 3 = 7 A.

To find $R_{equivalent}$:

$$R_{equivalent} = \frac{V}{I_{equivalent}}$$
$$= \frac{12}{7}$$
$$= 1.7\ \Omega$$

You can check the answer for this simple case using the formula for parallel resistance (Formula 5D–1 or 5D–2).

WORKSHEET 5D–1 MODELLING RESISTANCE IN PARALLEL CIRCUITS

Check-in questions – Set 2

1 Explain why you read off potential differences at a fixed current in the graphical approach for resistances in series.

2 Explain why you read off currents at a fixed potential difference in the graphical approach for resistances in parallel.

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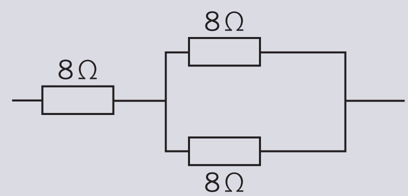
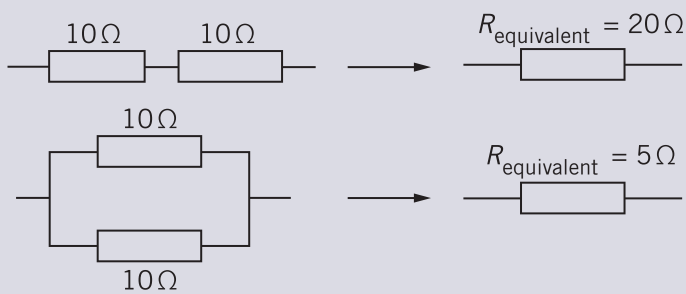
5D SKILLS

VIDEO 5D–1
SKILLS: COMPLEX CIRCUIT SKILLS

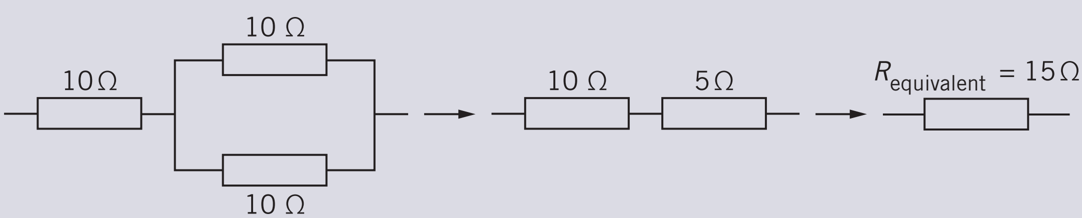
Complex circuit skills

When a circuit has both parallel and series sections, the skills you have learned for analysing each of these can be applied. The diagram (right) shows a compound circuit composed of three 8 Ω resistors. The two in parallel are equivalent to a single 4 Ω resistor. Try to calculate this using Formula 5D–1 or 5D–2; it always works that two identical resistors in parallel have an equivalent resistance of half of either one. It's a similar concept to opening doors in an auditorium of people trying to exit: the more doors that are opened, the less the resistance to leaving. Try different numbers:

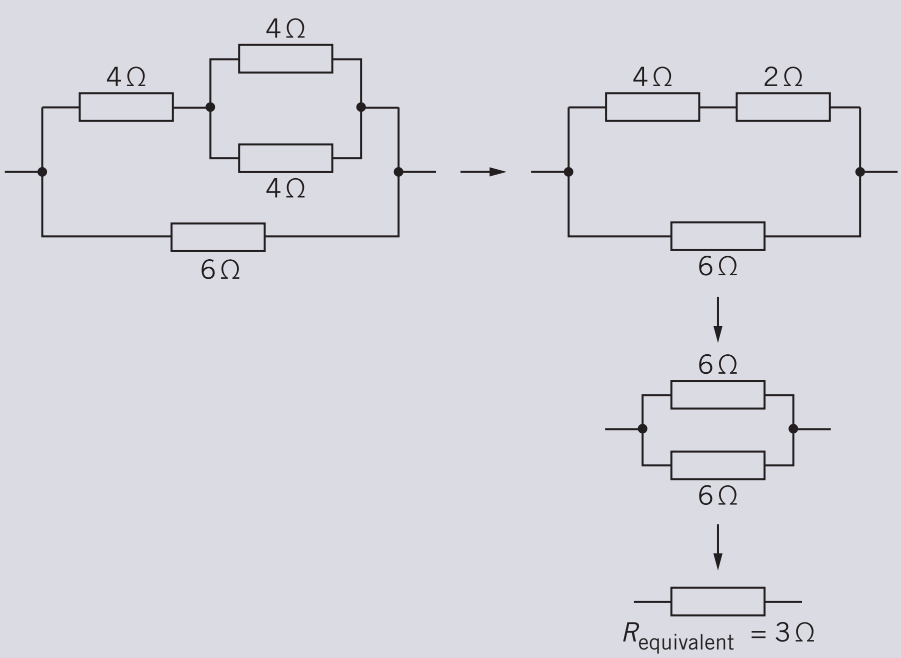




Once we have an equivalent resistance we can treat the parallel components as a single resistor in series with the other 10 Ω resistor. Applying Formula 5C–1 now gives:



More complex circuits can be broken down in the same way, beginning with the parallel combinations as shown:



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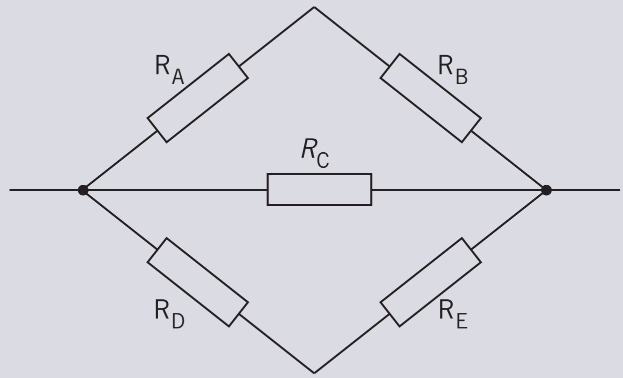
Note: simple values have been used for the resistances in these examples to make the calculations easier, but the techniques can be applied across the most complex resistive circuits. Also note that parallel resistors are sometimes shown on different angles, so it might not be as obvious that they are in parallel. For example:



In this case:

- R_A and R_B are in series with each other, so their total resistance is $(R_A + R_B)$.
- Likewise R_D is in series with R_E, total $(R_D + R_E)$.
- Each of these series combinations is in parallel with R_C.
- The $R_{equivalent}$ would then be calculated from Formula 5D–1, applied to three resistors.

5E ELECTRIC POWER LINK

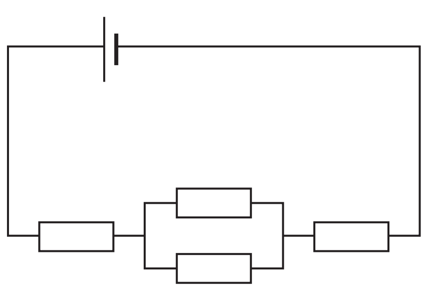
You can see more combinations like this in Section 5E Skills.

Section 5D questions

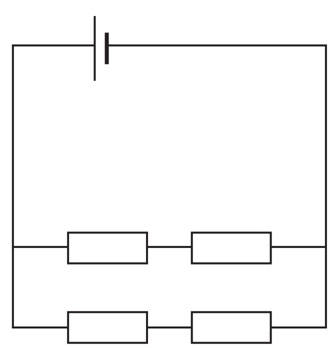
Multiple-choice questions

1 Which of the following diagrams does **not** show a circuit that is equivalent to the others? Assume all resistors are identical.

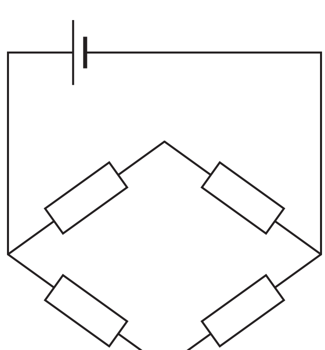
A



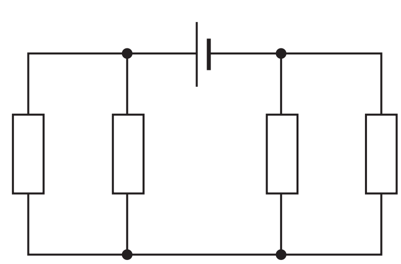
B



C



D



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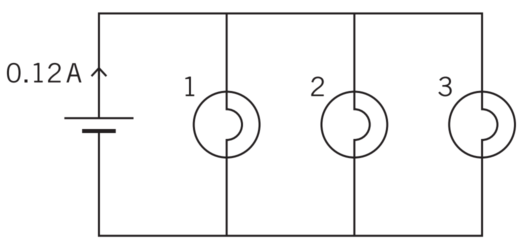
2 Which meter is always connected in parallel?
A ammeter
B voltmeter
C multimeter
D galvanometer

3 Which type of circuit is most useful for supplying the same potential difference to several components at once?
A series
B parallel with an extra series component
C series with a parallel component
D parallel

4 How much charge leaves a car battery, if it supplies current to four headlights connected in parallel, each of which has a current of 4 A in it?
A 4 coulombs per second
B 8 coulombs per second
C 12 coulombs per second
D 16 coulombs per second

5 In the following circuit, each lamp is identical.



If the current through the battery is 0.12 A, what is the current in lamp 3?
A 0.04 A
B 0.12 A
C 0.40 A
D 4.0 A

Short-answer questions

6 Refer to the diagram in Question 5. What is the potential difference across each of the lamps if the battery supplies 6 V?

7 Lamps of resistance 300 Ω, 400 Ω and 600 Ω are connected in parallel and connected to a 12 V battery.
a Draw a circuit diagram of the arrangement.
b What is the total resistance in the circuit?
c What is the current in each resistance?
d What is the total current leaving the battery?

8 How much charge leaves a car battery each second if it supplies current to four headlights in parallel, each of which draws a current of 5 A?

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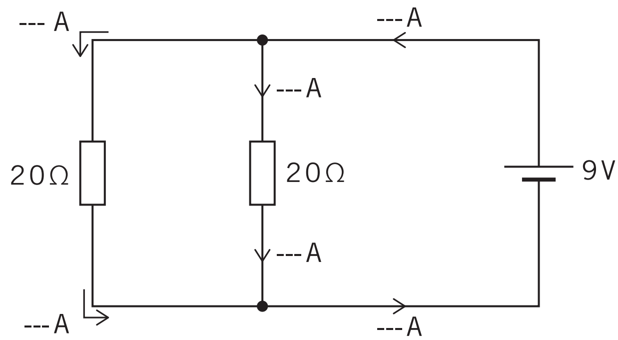
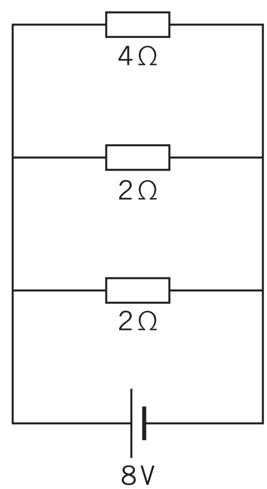
9 In the circuit shown below there is a potential drop of 9 V across each 20 Ω resistor.



a Use Ohm's law to determine the current through each resistor.
b What is the current through the battery?
c Copy the diagram and fill in the spaces to show the correct current measurements.

10 Consider the diagram below of a parallel circuit.

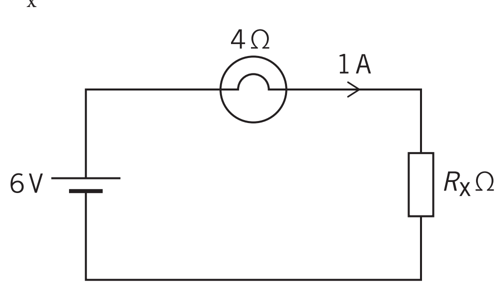


Find the:

a potential difference across each branch
b current through each branch
c current through the battery
d equivalent resistance of the circuit. (You should be able to do this in at least two ways!)

11 The light bulb in each the following circuits is identical, with a resistance of 4 Ω. Calculate the unknown resistance(s) in each circuit so that the current through the bulb is always 1 A. Assume resistors with the same label are identical.

a R_x =?



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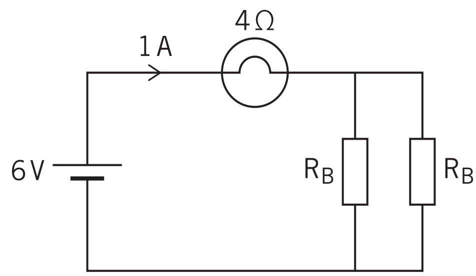
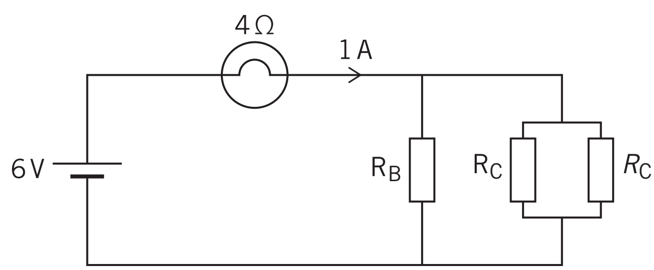
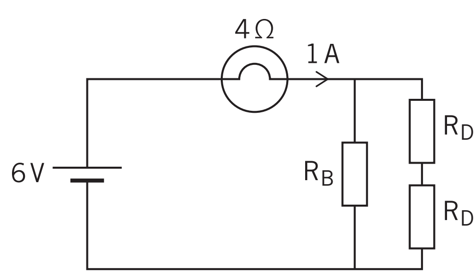
b Two identical resistors, R_B, replace R_x. What value is R_B?



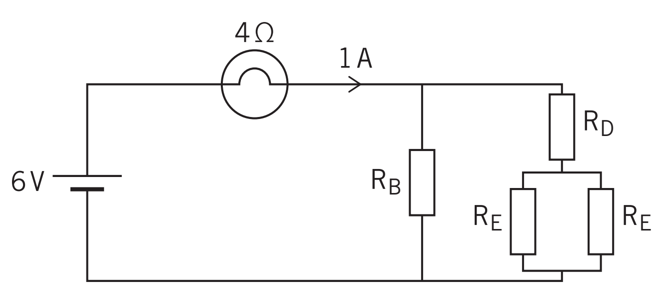
c Two identical resistors, R_C, replace one R_B. What value is R_C?



d Two identical resistors, R_D, replace R_B in the circuit diagram from part **b**. What value is R_D?



e Two identical resistors, R_E, replace one of the R_D in the circuit diagram from part **d**. What value is R_E?



f In the circuit diagram of part **e**, how much current flows through the battery?

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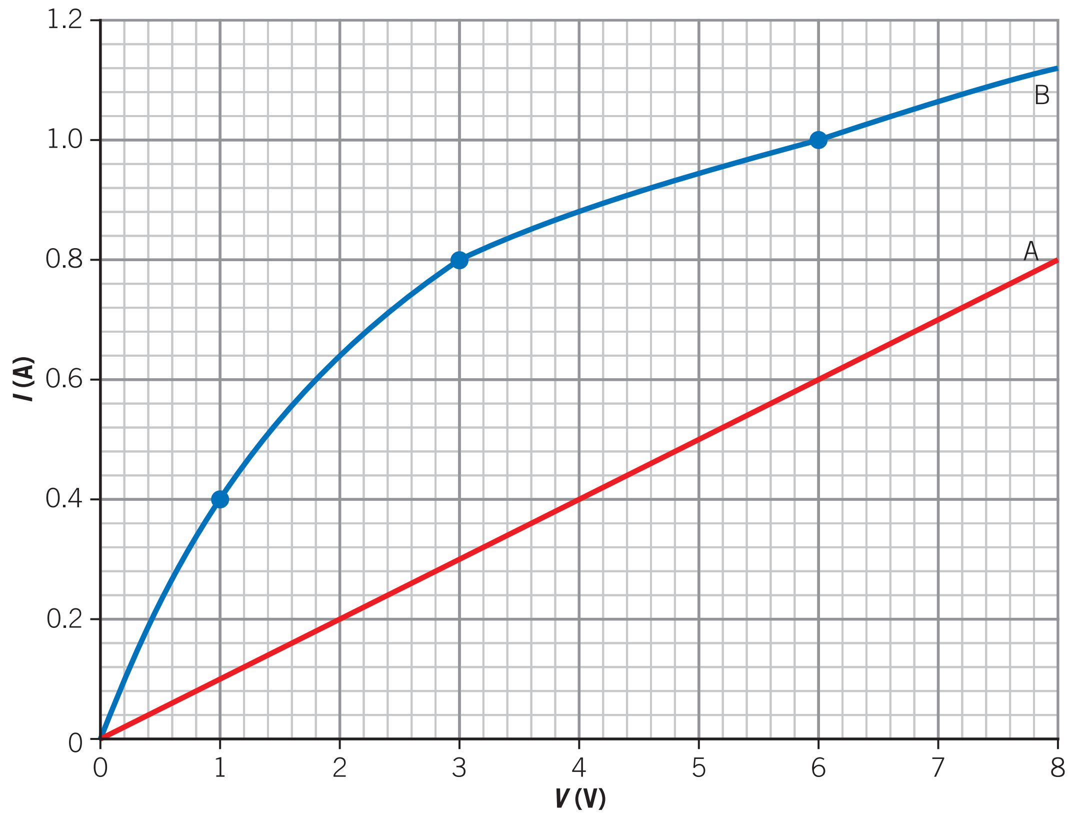
12 The following graph shows the *I*–*V* characteristics of two components, A and B.



- **a** What is the resistance of component A? What is special about it?
- **b** What is the current through a 6 V battery when the component A and component B are connected to it *in parallel*?
- **c** What is the equivalent resistance of components A and B connected *in parallel* to a 6 V battery?
- **d** A different battery is now connected. What is the equivalent resistance of components A and B connected *in series* when the current in the circuit is 0.6A?

13 Series and parallel circuits have different advantages (and disadvantages). Which type of circuit would be better for each of the following uses. Sketch a circuit diagram for each.

- **a** A circuit with a heating coil and a warning light, for an electric kettle. The light must show when the coil is heating.
- **b** A circuit with two lights and one switch, where each light needs to be as bright as the other and receive the full potential difference.
- **c** A battery backup safety circuit with two switches and one light, for the top and bottom of a stairwell. See if you can design this one!

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5E Electric power

Study Design:
- Apply concepts of charge (Q), electric current (I), potential difference (V), energy (E) and power (P), in electric circuits
- Investigate and analyse theoretically and practically electric circuits using the relationships:

$$I = \frac{Q}{t}, \quad V = \frac{E}{Q}, \quad P = \frac{E}{t} = VI$$

- Compare power transfers in series and parallel circuits
- Explain why the circuits in homes are mostly parallel circuits

Glossary:
Power
Watt (W)

ENGAGE

Electricity: the energy supply for technology

The key technology for the future is electricity. Our ability to design systems of production and control has expanded since the invention of the solid-state transistor in 1948 and its commercialisation throughout the 1950s. Your smartphone has more computing power than all the computers used to put the first astronauts, Neil Armstrong and Buzz Aldrin, on the Moon in 1969. All of these devices rely on varying amounts of electrical energy, delivered at various rates.

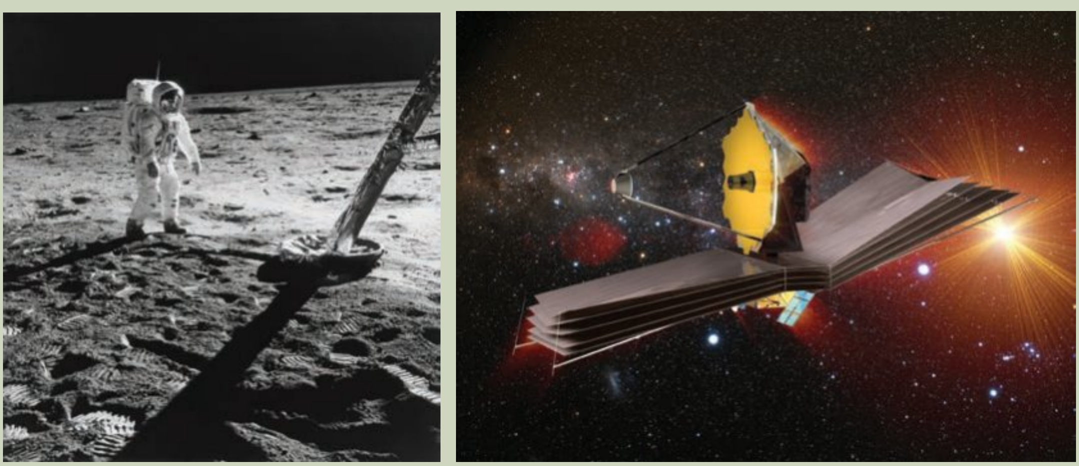

Figure 5E–1 Developments in space exploration have been made possible by developments in electronics and robotics. Left: Lunar module pilot Edwin 'Buzz' Aldrin Jr near the leg of the lunar module, the Eagle during his extravehicular activity on NASA's *Apollo 11* lunar landing mission, 20 July 1969. The photograph was taken by Commander Neil Armstrong with a 70 mm lunar surface camera. Right: Artist's impression of the James Webb Space Telescope unfolded in its new orbit.

Why can some things, like your calculator or an emergency phone on the side of a road, run on a small battery with electricity generated from solar energy while others, like a kettle, need to be plugged into the mains supply? Sometimes this is because of the total amount of energy required to run the appliance, but often it is that the kettle needs lots of energy *quickly*, more quickly than can be easily supplied by a small solar panel. The rate of energy supply, the electric power, is at times more important than the value of current, potential difference or total energy required.

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Figure 5E–2 Devices that use small amounts of energy per second ('power'), such as a calculator with a built-in solar panel (left) and an emergency roadside phone (centre), can often be supplied from solar panels. Appliances that use greater power, such as an electric kettle (right), need a connection to the mains electricity.

You might have noticed that using a different USB plug pack can recharge your phone faster or slower, even though the battery started at the same level. Some plugs are rated 5 V 12 W others 5 V 1 A, or even 5 V 18 W, as you can see on their labels. They could all charge your phone to 100%, but the time it takes to deliver the energy will be different.

Electric vehicles (EVs), like phones, recharge at different rates. This ranges from a 'trickle-charge' of around 2 kW from a normal power point overnight to a massive 250 kW from a DC supercharger, which can recharge an EV from 20 to 80% in under 30 minutes. Limiting factors are not only the electricity supply but also the capacity of the car's battery and the charging cable, and whether rapid charging will damage the battery and reduce its life. Fast charging and battery health is a balancing act, controlled by each EV's computer-controlled charging protocol. One analogy compares charging a battery to people squeezing through a door. If 100 people all rush into a room at once, some are going to get stuck in the doorway, so not as many will manage to enter the room within a short time. Similarly, fast charging a battery can lead to a lower capacity. Also, when so many people rush in, the door might get broken. Likewise, the battery materials can potentially be damaged. Research teams are continually testing better charging protocols, using computer models to predict battery ageing and then testing with real batteries. Ramping current or potential difference to improve charging capacity and reduce battery aging can also reduce charge time.

For engineers designing large-scale electricity supply grids, the rate that energy must be delivered is also important. In the future, it could cause problems if everyone drove home in their EV and plugged it in overnight to recharge, as this would create a large demand for electrical energy at a time when no solar electricity is directly available. In California, one study predicted that a 25% surge in demand overnight could be created when EV ownership reaches 50%, possibly in 2035. The need to build expensive big batteries for storage can be reduced by providing recharging infrastructure in car parks and workplaces, so vehicles can be recharged cheaply during the day. This would level out the power demand on the grid, which would save money on infrastructure as well as efficiently use daytime solar power.

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EXPLAIN

What is power?

In its everyday usage, **power** is intertwined with 'energy' and the two are often used as synonyms. For example, both are used conversationally to mean the ability to do work. We talk loosely about our domestic 'power supply' that provides the 'energy' required to run appliances. In physics though they have specific, separate but closely related meanings and must be used carefully. Energy, measured in joules, is the capacity to do work. Power, P, is the rate at which energy is transformed or work is done.

Power could be measured as joules of energy per second, but instead is given the name **watt**, defined as 1 watt (W) = 1 joule per second J s^{-1}. Note that whether a device with a power rating of 100 W is turned on for a millisecond, or for 10 hours, its power is still 100 W. Power does not depend on duration of time.

Power
the rate at which work is done; the rate at which energy is transformed; a scalar quantity measured in watts (W)

Watt (W)
a unit of power defined as 1 watt = 1 joule per second

Calculating power as rate of energy transfer

When designing a circuit, it's important to know not only how much energy will be used, but also how rapidly it needs to be supplied. This leads to:

VIDEO 5E–1 ELECTRIC POWER

Formula 5E–1 Power as a rate of energy transfer or transformation

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

Where:

P = Power (W)

E = Energy transferred (J)

t = Time that the energy is transferred over (s)

In words: power (W) = energy (J) transferred per second (s). This definition of power applies any time energy is transferred, not just in electric circuits.

LINK CHAPTER 9

LINK CHAPTER 6

Figure 5E–3 A wireless energy monitor linked to the electricity meter can display a home's present electric power use, 0.71 kW in this case, equivalent to 710 joules per second.

NOTE

An example of a common error when stating power in watts is to say 'the power of this device is 100 watts per hour'. But because power is already a rate (energy per second), it does not need 'per hour' added after 'watts' or 'kilowatts'. In most contexts, adding 'per hour' makes no more sense that saying, 'I can run at 4 metres per second per hour'. In the next chapter you will learn a unit called the kilowatt-hour, but this is a unit of energy not power, and needs careful understanding and use to avoid confusion.

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Worked example 5E–1 Power in a kettle

An electric kettle is rated at 2 kW. It is filled with water, then turned on.

a Calculate the thermal energy delivered to the water in 1 minute.

b How long would the kettle need to run to supply 4 kJ of energy to the water?

c A different kettle supplies 3 kJ of energy per 30 seconds. Calculate the power of this kettle.

Solution

a Use the relationship $P = \frac{E}{t}$, where:

$$P = 2\text{ kW} = 2 \times 10^3\text{ W}$$

$$t = 1\text{ min} = 60\text{ s}$$

gives:

$$E = P \times t$$

$$= 2 \times 10^3 \times 60$$

$$= 1.2 \times 10^5\text{ J} = 120\text{ kJ}$$

b For the same kettle:

$$P = 2 \times 10^3\text{ W}$$

$$E = 4\text{ kJ} = 4 \times 10^3\text{ J}$$

Use the same formula to find time:

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

$$= \frac{4 \times 10^3}{2 \times 10^3}$$

$$= 2\text{ s}$$

Time is 2 seconds.

c Use the relationship $P = \frac{E}{t}$, where:

$$E = 3\text{ kJ}$$

$$t = 30\text{ s}$$

gives:

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

$$= \frac{3 \times 10^3}{30}$$

$$= 100\text{ W}$$

Power is 100 W. This would be much slower to boil than the kettle from parts a and b.

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Worked example 5E–2 Power in a stove

An electric stove that is turned on uses 1.8 MJ of energy to heat up the hotplate every 10 minutes. Calculate the:

a power of the electric stove in watts
b time it takes for the stove to use 1.7 kJ of energy
c energy used by the stove in 40 seconds, if the power of the stove is increased by 500 W.

Solution

a The power of the stove can be found using the formula for power with $E = 1.8\text{ MJ} = 1.8 \times 10^6$ and $t = 10\text{ min} = 10 \times 60\text{ s} = 600\text{ s}$.
This gives:

$$\begin{aligned} P &= \frac{E}{t} \\ &= \frac{1.8 \times 10^6}{600} \\ &= 3000\text{ W} \end{aligned}$$

Therefore, the power of the stove is 3000 W.

b Rearrange the power formula to make t the subject.
As $P = 3000$ W and $E = 1.7\text{ kJ} = 1700\text{ J}$, this gives:

$$\begin{aligned} t &= \frac{E}{P} \\ &= \frac{1700}{3000} \\ &= 0.57\text{ s} \end{aligned}$$

Therefore, the time it takes for the stove to use 1.7 kJ of energy is 0.57 s.

c The power of the stove is increased by 500 W so that $P = 3500$ W. To find the energy used by the stove in 40 seconds, rearrange the power formula to make E the subject.
This gives:

$$\begin{aligned} E &= Pt \\ &= 3500 \times 40 \\ &= 0.14 \times 10^6\text{ J} \\ &= 0.14\text{ MJ} \end{aligned}$$

Check-in questions – Set 1

1 Rearrange the power formula (Formula 5E–1) to give an expression for energy in terms of power and time.
2 Calculate the power supplied when 3000 J of electrical energy is supplied to an electric drill in 10 seconds.

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Calculating power in electric circuits

The formula defining power, as energy produced or used per second is:

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

5B ELECTRICAL ENERGY AND POTENTIAL DIFFERENCE LINK

This applies to all types of energy and can become more relevant to electric circuits by substituting for electrical energy, E, using $E = VIt$ (from Section 5B):

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

The t cancels out, leaving a formula for electric power.

Formula 5E–2 Electrical power

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

Where:

P = Power in an electric circuit (W)

V = Potential difference (V)

I = Current (A)

The power supplied or consumed in a circuit, which is the rate that energy is converted, depends on how many coulombs of charge go past per second (the current), as well as how much energy each coulomb carries (the potential difference).

Worked example 5E–3 Power in a light bulb

a Calculate the power drawn by a light bulb that, when connected to a 12 V battery, carries a current of 0.5 A.

b If the light bulb described in part **a** is switched on for 2 minutes, how much energy does it transform?

Solution

a Use the power formula in the form $P = VI$ and substitute $V = 12$ V and $I = 0.5$ A:

$$P = VI$$
$$= 12 \times 0.5$$
$$= 6 \text{ W}$$

The power drawn by the light bulb is 6 W.

b Rearrange $P = \frac{E}{t}$ and substitute $t = 2$ min = 120 s and $P = 6$ W:

$$E = Pt$$
$$= 6 \times 120$$
$$= 720 \text{ J}$$

The electrical energy transformed in the bulb is 720 J.

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Worked example 5E–4 Comparing power consumption

A kettle and an induction cooktop are both connected to 230 V mains power. If 10 A flows through the kettle and 32 A through the cooktop, calculate the power used by each appliance.

Solution

To calculate the power used by the electrical appliances, the best formula is $P = VI$. For both appliances, as they are connected to mains power, $V = 230$ V.

For the kettle $I = 10$ A, which gives:

$$\begin{aligned} P &= VI \\ &= 230 \times 10 \\ &= 2300 \text{ W} \end{aligned}$$

For the cooktop $I = 32$ A, which gives:

$$\begin{aligned} P &= VI \\ &= 230 \times 32 \\ &= 7360 \text{ W} \end{aligned}$$

The power used by the kettle is 2.3 kW and the power used by the cooktop is 7.36 kW. If they were used to heat the same mass of water from 20°C, you would expect the induction cooktop to boil the water sooner.

LINK CHAPTER 2

Check-in questions – Set 2

1 Calculate the power drawn by a refrigerator connected to mains power supply (230 V) if the current is 1.5 A.

2 Calculate the energy used by a light bulb in 10 minutes when connected to a 12 V power supply that carries 0.6 A of current.

Alternative forms of $P = IV$

Recall that power is the rate at which energy is transformed or transferred from one form to another.

Usually, power is calculated from the formula $P = IV$. In some cases, the current or potential difference may not be known, but must be calculated using $V = IR$. As a short cut, $P = IV$ may be written in alternative ways, as shown below. These are not new equations, they are just different forms of the same equation.

$$P = V \times I$$

Substituting from $V = IR$:

$$P = IR \times I$$

Therefore:

$$P = I^2R$$

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This is the first useful variation, for when I and R are known but V is not. All appliances, and even electric connecting wires, transform some electrical energy every second they are switched on. If an appliance transforms too much electrical energy into heat, it may melt or burn out. This happens when either the current or the resistance is very large, or both.

The next variation comes from substituting for I $(= \frac{V}{R})$:

$$P = V \times I$$

$$P = V \times \frac{V}{R}$$

Therefore:

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

This variation is useful when V and R are known but I is not.

To summarise:

Formula 5E–3 Three expressions for electrical power

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

For a circuit with ohmic resistors, where:

P = Power (W)

I = Current (A)

R = Resistance (Ω)

V = Potential difference (V)

When to use each power formula

First

$P = VI$ is often useful in general calculations, as in Worked examples 5E–3 and 5E–4.

Second

$P = I^2R$ is best used when considering power 'lost' as thermal energy in wires, as the larger the current, the greater the energy 'loss'.

Third

$P = \frac{V^2}{R}$ is best used for finding the power used by circuits of differing resistance; for example, series versus parallel. As parallel combinations have lower resistance than the same resistors in series, you expect from the inverse relationship between power and resistance in this formula, that the power used will be greater in parallel.

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Worked example 5E–5 Power loss due to resistance

A caravan is to be connected to a 240 V AC power supply by a 10 m extension cable. Two cables are available with resistances of 1 Ω and 5 Ω respectively. If the appliances in the caravan use a current of 10 A, find the power loss that would occur in each cable.

Solution

To find the power loss in each cable due to heating in the wires, use the power formula in the form $P = I^2R$.

For cable 1: $R = 1\ \Omega$, $I = 10$ A, so:

$$P = 10^2 \times 1$$
$$= 100 \text{ W loss in cable 1}$$

For cable 2: $R = 5\ \Omega$, $I = 10$ A, so:

$$P = 10^2 \times 5$$
$$= 500 \text{ W loss in cable 2}$$

Hence, the 5 Ω cable transforms 400 W more power than the 1 Ω cable, due to heating in the larger resistance. You would choose the cable with lower resistance to obtain the greatest possible power for the appliances in the caravan.

LINK UNIT 3

Check-in questions – Set 3

1 A long extension lead carrying a current of 2 A has a potential difference of 0.5 V across it, from one end to the other. Calculate the power loss in the cable.

2 A 1 kΩ resistor in a circuit has a current of 0.05A flowing through it. Calculate the power loss in the resistor.

Comparing power delivered in series and parallel circuits

Worked example 5E–6 Resistance from power consumption

Calculate and compare the resistance of a 5 W LED bulb and a 9 W LED bulb when each is plugged in to the 230 V mains supply.

Solution

To calculate the resistance of the bulbs, use the power formula in the form $P = \frac{V^2}{R}$.

Rearrange to make R the subject, $R = \frac{V^2}{P}$, and substitute into the formula.

$V = 240$ V and $P = 5$ W:

$$R = \frac{V^2}{P}$$
$$= \frac{230^2}{5} = 10\,580\ \Omega$$
$$= 10.6\text{ k}\Omega$$

For the 9 W LED bulb: $V = 230$ V and $P = 9$ W, which gives:

$$R = \frac{230^2}{9} = 5878\ \Omega$$
$$= 5.9\text{ k}\Omega$$

Comparing the two, you see that the 5 W LED bulb has almost twice the resistance of the 9 W LED bulb.

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Worked example 5E–7 Power loss in series and parallel

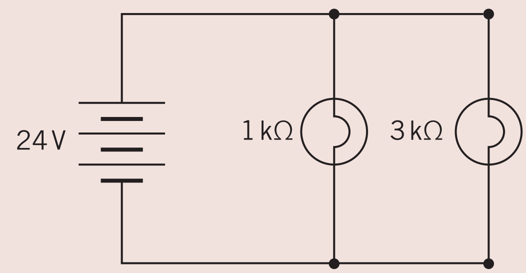
Consider two light globes, 1000 Ω and 3000 Ω, connected in parallel to a 24 V battery.

a Calculate the power used by the parallel combination.

b Calculate the power used if the same two globes are now wired in series to the same battery.

Solution:

a First, sketch a circuit diagram.



As the globes are in parallel, first calculate the equivalent resistance of the globes:

$$\frac{1}{R_{\text{equivalent}}} = \frac{1}{R_1} + \frac{1}{R_2}$$

$$= \frac{1}{1000} + \frac{1}{3000} = \frac{1}{750}$$

$$= 750\ \Omega$$

The potential difference across each globe will be 24 V since they are parallel. Use the formula for power:

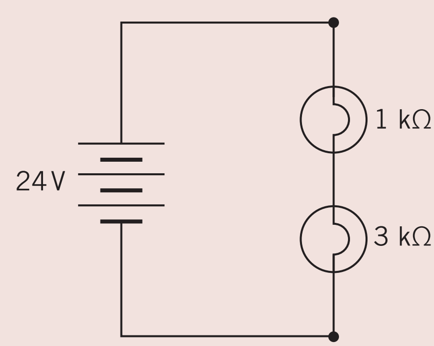
$$P = \frac{V^2}{R}$$

$$= \frac{24^2}{750}$$

$$= 0.0768 = 0.77\ \text{W}$$

This is the power used by the two globes in parallel.

b First, sketch a circuit diagram.



As the globes are in series, add their resistances together to get $R_{\text{equivalent}}$. This gives 4000 Ω. The potential difference across the equivalent system will be 24 V and so the power used, using the same formula as above, will be:

$$P = \frac{24^2}{4000}$$

$$= 0.144\ \text{W}$$

This is the power used by the two globes in series. Clearly the globes use more power in parallel than in series as they draw more current due to the lower $R_{\text{equivalent}}$. The parallel globes will be brighter (more energy transformed) but the battery will run flat sooner!

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Advantages of parallel and series circuits

There are other advantages of parallel circuits. Individual components can each receive the same potential difference and can be switched on and off independently of other components in the circuit.

LINK CHAPTER 6

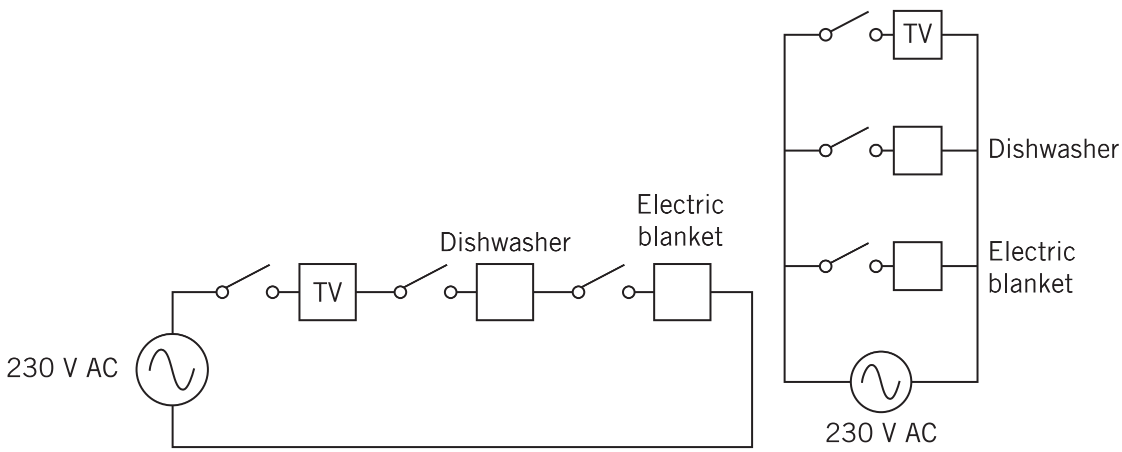

Figure 5E–4 The two circuits have the same three appliances, each with a switch nearby, connected to a 230 V AC household power supply. Left: the appliances in series. Right: the appliances in parallel

As an example, consider the two circuits in Figure 5E–4. In Figure 5E–4 (left), the series circuit requires all three switches to be closed before any of the appliances will work – and then they will all be on at the same time. There is no way to operate them independently. Also, each appliance will only get a proportion of the 230 V potential difference, so none of them will work correctly as designed. In Figure 5E–4 (right), the parallel circuit allows each component to be operated by its own switch without affecting the others and each is connected to the full 230 V potential difference.

Of course, the parallel circuit will draw more current (and hence power) than the series circuit because each branch will draw the same current as if it were the only branch. Therefore, care must be taken not to overload the power supply.

Another disadvantage of the series circuit is that if one appliance is broken, neither of the others will work. In parallel circuits this is not an issue because each appliance is supplied with its own current, regardless of the others.

For these reasons, household electrical circuits are wired in parallel, not series. Chapter 6 deals with household uses of electricity in more detail.

LINK CHAPTER 6

As noted in Section 5D, an advantage of series connections is that one switch can control all appliances. For example, to turn on a TV, DVD player and soundbar at the same time, a single power switch is more convenient. Usually this would be placed in series with the power supply, with the circuit branching into parallel paths.

LINK UNIT 3

LINK 5D MODELLING RESISTANCE IN PARALLEL CIRCUITS

WORKSHEET 5E–1 ELECTRIC POWER

Check-in questions – Set 4

1 Explain why the power used in a parallel circuit is more than the power used in a series circuit of the same components, supplied by the same potential difference.

2 Explain the advantages of parallel circuits over series circuits, especially for household use of electricity.

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ACTIVITY 5E–1 POWER USED IN PARALLEL CIRCUITS

1 Construct a parallel circuit and use an ammeter to measure the current through the main branch of the circuit and a voltmeter to measure V_{supply}. Record the results in a suitable table. In a new column, calculate the power drawn.
2 Construct a series circuit from the same equipment. Use an ammeter to measure the current through the circuit and a voltmeter to measure V_{supply}. Record the results and calculate the power used.
3 Compare the power used in the parallel circuit with that of the series circuit.

5E SKILLS

VIDEO 5E–2 SKILLS: MORE COMPLEX CIRCUIT SKILLS

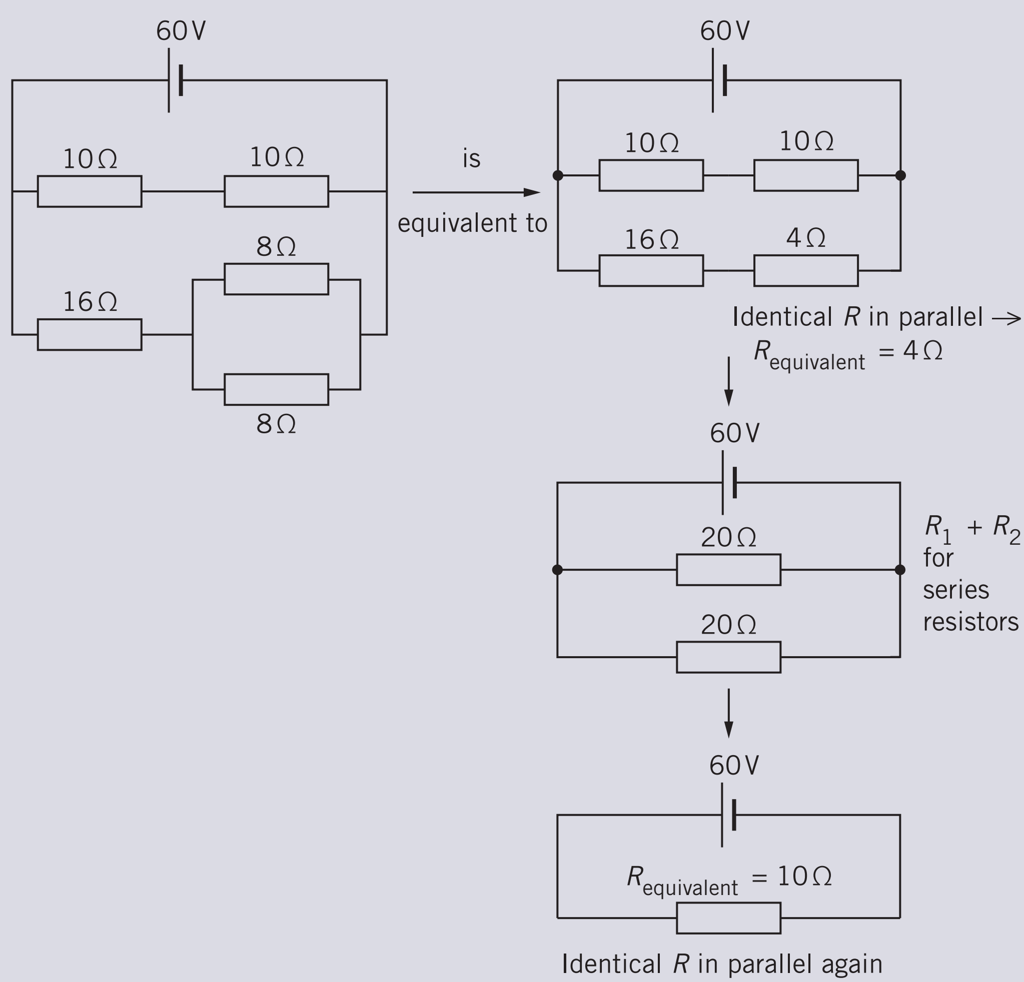
5D MODELLING RESISTANCE IN PARALLEL CIRCUITS LINK

More complex circuit skills

To calculate the power transformed in a complex circuit, first apply the analysis described in Section 5D Skills to find the equivalent resistance and total current, then use $P = VI$ to calculate the power.

For example:

1 The following circuit can be simplified to an equivalent 10 Ω by resistor using your knowledge of series and parallel resistance, in the steps shown.



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2 The current through the battery can now be calculated:

$$V_{battery} = IR_{equivalent}$$

$$I = \frac{V_{battery}}{R_{equivalent}}$$

$$= \frac{60}{10}$$

$= 6$ A through the battery

3 Power supplied by the battery is then calculated:

$$P_{battery} = V_{battery} I_{battery}$$

$$= 60 \times 6$$

$$= 360 \text{ W}$$

This power will be dissipated among all the resistors in the circuit.

Section 5E questions

Multiple-choice questions

Note that in these calculations, a mains supply at 240 V is used for ease of calculation, even though in Australia the supply is now 230 V (+10%, −6%)

1 What is the power of a lamp that is designed to operate at 240 V, 0.5 A?

- **A** 0.5 W
- **B** 120 W
- **C** 240 W
- **D** 480 W

2 What is the power of a lamp that is designed to operate 240 V, 0.25 A?

- **A** 0.25 W
- **B** 60 W
- **C** 120 W
- **D** 960 W

3 What current will there be in a 100 W motor connected to a 240 V power supply?

- **A** 0.42 A
- **B** 100 A
- **C** 240 A
- **D** 24 000 A

4 How much energy is produced per second by a bulb labelled '12 V, 0.25 A' when it is operating correctly?

- **A** 0.25 W
- **B** 3.0 W
- **C** 12 W
- **D** 48 W

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5 A set of AA cells for a doorbell has a potential difference of 3.0 V. What is the power rating of the doorbell if the current is 4.8 mA?

A 1.4 mW

B 14 mW

C 144 W

D 144 mW

Short-answer questions

6 Calculate the current in a 20 W motor connected to a 12 V power supply.

7 Calculate the power drawn by a lamp that is designed to operate at 12 V, 1.5 A.

8 A microwave oven operates at 1200 W.

a How much current does it draw from the 240 V mains supply?

b How much energy would it consume if it was used at full power for 2 min?

9 Which carries the greater current, an 11 W mains LED or a 9 W mains LED?

10 An automatic washing machine is labelled '240 V, 960 W'.

a Find the current when the machine is operating normally.

b What is the equivalent resistance in the circuit when the machine is in use?

11 Find the resistance of the following mains appliances.

a a 100 W garden spotlight

b the element in a 1000 W convection heater

c the element in a 2 kW kettle

12 A set of decorative lights consists of 20 bulbs wired in series. Each bulb is labelled '12 V, 1 W'. The set is designed to operate from the 240 V mains supply.

a What is the total power consumed by the set of lights?

b What is the potential difference across each bulb?

c What is the current in each bulb?

d What is the resistance in each bulb?

e What is the equivalent resistance of the set of lights?

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Chapter 5 review

Summary

Create your own set of summary notes for this chapter on paper or in a digital document. A model summary is provided in the Teacher Resources, which can be used to compare with yours.

Checklist

In the Interactive Textbook, the success criteria are linked from the review questions and will be automatically ticked when answers are correct. Alternatively, print or photocopy this page and tick the boxes when you have answered the corresponding questions correctly.

Success criteria – I am now able to:		Linked questions
5A.1	Model a metal as having a sea of electrons free to move	4☐, 5☐
5A.2	Describe current in a metal in terms of drift velocity of negatively charged electrons	6☐
5A.3	Use analogies to model charge and current in a circuit	18☐
5A.4	Use circuit symbols to draw a circuit diagram from a given picture, practical simple circuit or description in words	13☐, 22☐, 23☐, 17☐, 19☐, 24☐, 25☐, 26☐, 28☐, 30☐
5A.5	Use an ammeter to measure current in a simple circuit; construct a circuit and a suitable circuit diagram to show the use of an ammeter	3☐, 17☐, 22☐
5A.6	Apply the formula $I = \frac{Q}{t}$ for calculations involving current, charge and time	1☐, 11☐, 12☐
5B.1	Recall that separating positive and negative charges creates a potential difference, *V*, and requires an input of energy, *E*	6☐
5B.2	Apply the formulas $V = \frac{E}{Q}$ and $E = VIt$ to calculate the energy supplied to a charge flowing in a circuit	2☐, 14☐, 18☐
5B.3	Use analogies to model potential difference and current in a circuit	18☐
5B.4	Use a voltmeter to measure potential difference in a simple circuit; construct a circuit and draw a suitable circuit diagram to show the role of an ammeter	3☐, 17☐, 22☐
5B.5	Distinguish between the positioning of an ammeter (in series) and a voltmeter (in parallel) in a simple circuit	3☐, 17☐, 22☐
5C.1	Construct a simple circuit to measure current and potential difference across an ohmic resistance; change potential difference and record data in a table of *I* vs *V*; plot or create *I* vs *V* graph	9☐, 20☐, 26☐, 27☐
5C.2	Recall that resistance is the ratio of potential difference to current, including *R* = constant for ohmic devices	9☐, 20☐, 21☐, 24☐, 30☐

Success criteria – I am now able to:		Linked questions
5C.3	Recognise that: the current flows continuously through resistors in a series circuit, without reducing; current is constant at all points in a series circuit	3☐, 13☐, 22☐, 24☐, 30☐
5C.4	Recall that the potential difference drops across each resistance in a series circuit, as energy is converted to other forms: $V_{supply} = V_1 + V_2 + \ldots + V_n$	22☐, 24☐, 30☐
5C.5	Recognise and calculate that equivalent resistance in a series circuit is the sum of each resistance: $R_{equivalent} = R_1 + R_2 + \ldots + R_n$	19☐, 24☐, 30☐
5C.6	Calculate the potential difference output of a potential divider, V_{out}, given the ratio of resistances and the supply voltage	23☐, 30☐
5D.1	Recognise a parallel circuit as one with junctions, where the current takes more than one path around the circuit	25☐, 26☐, 27☐, 28☐, 29☐, 30☐
5D.2	Recall that the current flows continuously through resistors without reducing, but splits at the junctions in a parallel circuit and reunites to return to the main branch through the battery: total current supplied by the battery is $I_{supply} = I_1 + I_2 + \ldots + I_n$	26☐, 25☐, 30☐
5D.3	Recognise that the potential difference across each branch of a parallel circuit is the same, as energy is converted to other forms	25☐, 30☐
5D.4	Recognise and calculate that equivalent resistance in a parallel circuit is $\frac{1}{R_{equivalent}} = \frac{1}{R_1} + \frac{1}{R_2} + \ldots + \frac{1}{R_n}$	25☐, 28☐, 30☐
5D.5	Use I–V graphs of individual components to predict the equivalent resistance of those components in series and in parallel	21☐, 26☐
5E.1	Calculate power as the rate of energy transfer $P = \frac{E}{t}$ in a simple circuit	15☐, 16☐
5E.2	Calculate power from $P = VI$ supplied and consumed in a simple circuit; use alternative formulas $P = \frac{V^2}{R} = I^2R$	7☐, 8☐, 10☐, 16☐, 30☐
5E.3	Calculate the power supplied to loads in series and in parallel	24☐, 29☐, 30☐
5E.4	Explain the advantages and disadvantages of series and parallel circuits, in particular relating to household circuits	27☐, 30☐

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Multiple-choice questions

1 How many coulombs of charge pass through a motor in which a current of 0.25A is maintained for 1 h?

A 25 C
B 60 C
C 900 C
D 9000 C

2 What energy is gained by a charge of 15 C when it passes through a generator producing a potential difference of 110 V?

A 7.3 J
B 110 J
C 110 V
D 1650 J

3 The current flowing through a circuit can be measured using an ammeter. The potential difference between two points in a circuit can be measured using a voltmeter. When they are placed in their correct positions, the

A ammeter is in parallel and the voltmeter in series.
B voltmeter is in parallel and the ammeter in series.
C voltmeter and the ammeter are both in parallel.
D voltmeter and the ammeter are both in series.

4 Which of the descriptions below best matches an electrical conductor?

A tightly bound molecules with + and – polarity
B lattice of negative ions in a sea of positive charges
C lattice of positive ions in a sea of electrons
D tightly bound atoms or molecules, no free charges

5 Which of the descriptions below best represents an electrical insulator?

A tightly bound molecules with + and – polarity
B lattice of negative ions in a sea of positive charges
C lattice of positive ions in a sea of electrons
D tightly bound atoms or molecules, no free charges

6 Which of the following descriptions does *not* describe the flow of current in a metal wire?

A Positive current drifts around the circuit from negative terminal to positive terminal of a battery.
B Negative electrons drift around the circuit from negative terminal to positive terminal of a battery.
C Chemical energy separates positive and negative charges in the battery, which allows negative electrons to drift around the circuit from negative terminal to positive terminal of a battery.
D The potential difference created by separating charges causes electrons to drift towards the positive terminal of a battery.

7 How much current is drawn by a USB fan rated 5 V, 4 W?

A 20 A
B 5.0 A
C 4.0 A
D 0.80 A

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8 How much power is dissipated in a 10 Ω speaker with potential difference of 9 V?

A 0.9 W
B 8.1 W
C 81 W
D 90 W

9 An ohmic conductor is one in which, as the potential difference across it is increased, the current through it would

A increase proportionally.
B decrease proportionally.
C be inversely proportional.
D remain constant.

10 A student looked at an electric light globe but noticed that the power rating had worn off. The student found that the globe carried a current of 250 mA when used on a 24 V battery. What was the power rating of the globe?

A 6 W
B 60 W
C 96 W
D 600 W

Short-answer questions

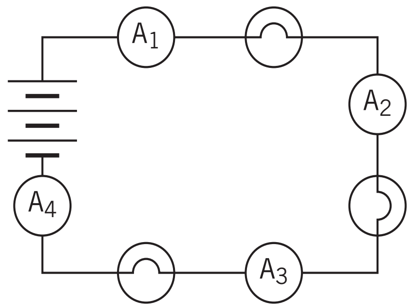
11 How many electrons are there in the following charges?

a 2 C (1 mark)
b 15 C (1 mark)
c 1000 C (1 mark)

12 What is the current in a circuit in the following circumstances?

a 20 C of charge passes a point in 5 s. (1 mark)
b 10 C of charge passes a point in 20 s. (1 mark)
c 180 C of charge passes a point in 3 min. (1 mark)

13 What would each ammeter (A_1, A_2 etc.) read in the following circuit? The reading on A_4 is 0.2 A. (2 marks)



14 The potential difference across a lamp is 12 V. How many joules of thermal and light energy are produced when

a 6 C passes through it? (1 mark)
b 30 C passes through it? (1 mark)
c it carries a current of 1 A for 2 min? (1 mark)

15 **a** How many joules of energy are generated each second by a 12 V battery supplying a current of 0.5 A? (1 mark)

b How many joules of thermal and light energy are produced if a 12 V car battery supplies a current of 15 A for 15 min? (1 mark)

c How many joules of thermal energy are generated by a coil of wire connected to a 12 V battery if there is a current of 0.5 A in it for 2 min? (1 mark)

16 A passenger reading light operates from a 12 V car battery.

a How much energy is converted to thermal and light by the bulb if it draws a current of 1.5 A for a time of 15 min? (1 mark)

b What power does the light draw during this time? (1 mark)

17 Draw a circuit diagram including a power supply, resistor and both an ammeter and a voltmeter correctly positioned. (3 marks)

18 Answer the following questions using the kayaking analogy for electric circuits in Section 5B.

a What part of the analogy represents electric current? (2 marks)

b What part of the analogy represents potential difference? (2 marks)

c How could this analogy represent power dissipated in a circuit? (2 marks)

19 Draw a circuit diagram, then work out the equivalent resistance for each of the following.

a a 20 Ω resistance in series with a 10 Ω resistance (2 marks)

b 20 Ω, 8 Ω and 2 Ω resistances in series. (2 marks)

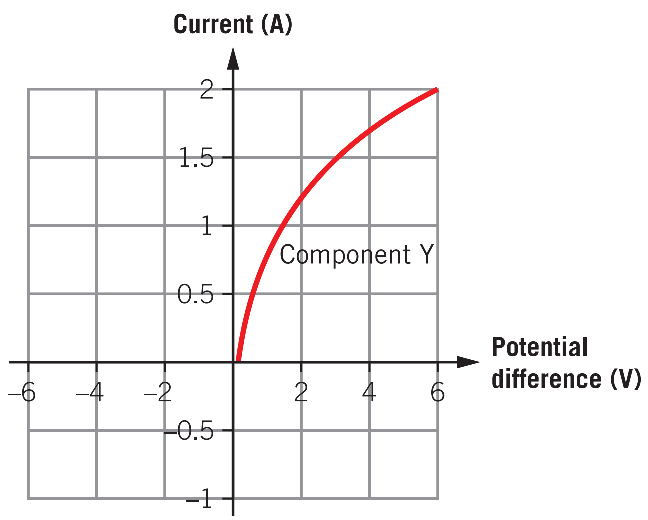
20 Use Ohm's law to calculate the

a resistance of a light bulb in which the current is 0.6 A when it is connected to a potential difference of 12 V (1 mark)

b potential difference across a 25 Ω resistance when there is a 5 A current in it (1 mark)

c current in a resistance of 500 Ω when it is connected to a 12 V battery. (1 mark)

21 Refer to the *I*–*V* characteristic graph below.



a Find the resistance of component Y when the potential difference across it is 3 V. (1 mark)

b Find the resistance of component Y when the potential difference across it is 6 V. (1 mark)

c What would the resistance be when the potential difference is 6 V and the battery is reversed? (2 marks)

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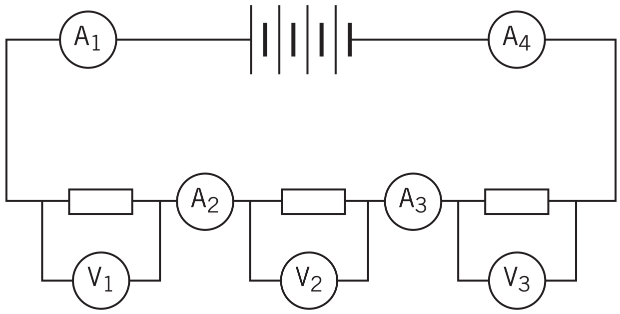
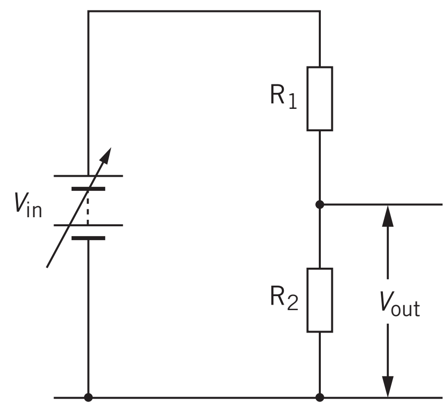
22 All the resistors in the following circuit are identical. What would the readings on the meters be, given the potential difference of the battery is 9 V, and that the reading on A_1 is 0.4 A. (3 marks)



23 What would the output potential difference, V_{out}, be in the following potential divider circuit, where the two resistors R_1 and R_2 are varied? V_{in} is steady at 16 V.



a $R_1 = 20\ \Omega$, $R_2 = 20\ \Omega$ (2 marks)
b $R_1 = 50\ \Omega$, $R_2 = 1000\ \Omega$ (2 marks)
c $R_1 = 100\ \Omega$, $R_2 = 50\ \Omega$ (2 marks)
d $R_1 = 200\ \Omega$, $R_2 = 800\ \Omega$ (2 marks)
e $R_1 = 800\ \Omega$, $R_2 = 200\ \Omega$ (2 marks)

24 Resistances of 12 Ω, 20 Ω and 40 Ω are joined in series and connected to a 12 V battery.
a Draw a circuit diagram of the arrangement. (2 marks)
b What is the equivalent resistance in the circuit? (1 mark)
c What is the current in the circuit? (1 mark)
d Find the potential difference across each of the three resistors. (2 marks)

25 Lamps of resistance 300 Ω, 400 Ω and 600 Ω are joined in parallel and connected to the 240 V mains supply.
a Draw a circuit diagram of the arrangement. (2 marks)
b What is the equivalent resistance in the circuit? (1 mark)
c What is the current in each resistance? (1 mark)
d What is the total current in the circuit? (1 mark)

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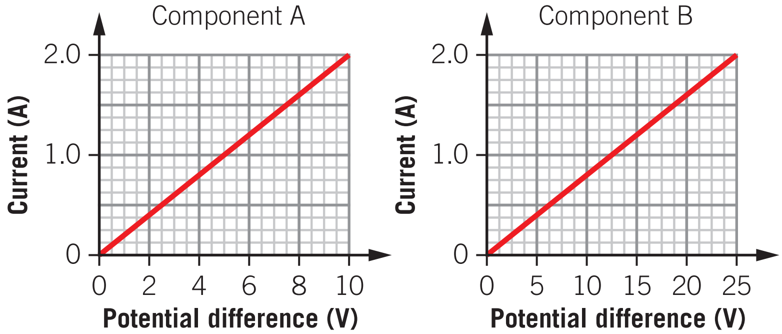
26 The I–V characteristics of two components (A and B) are shown below.



a Draw a circuit diagram that could be used to obtain the measurements required to plot one of these I–V graphs. (2 marks)

b What would the total current be if components A and B were placed in series and connected to a 10 V battery? (2 marks)

c What would the total current be if components A and B were placed in parallel and connected to a 10 V battery? (2 marks)

d What would be an alternative way to calculate the total current through components A and B in series or parallel? (3 marks)

27 **a** Give an example where a parallel circuit is more useful than a series circuit and explain why. (3 marks)

b Give an example where a series circuit is more useful than a parallel circuit and explain why. (3 marks)

28 Draw a circuit diagram and then work out the equivalent resistance for

a a 1000 Ω resistance in parallel with a 500 Ω resistance (2 marks)

b 5 Ω, 6 Ω and 7 Ω resistances in parallel. (2 marks)

29 **a** Find the power used by three 11 W LED light globes connected in series to a 240 V supply. (2 marks)

b Find the power used by three 11 W LED light globes connected in parallel to a 240 V supply (2 marks)

c Compare the power used in series and in parallel and suggest reasons for this. Which would be the best arrangement for lighting a benchtop in the kitchen? (3 marks)

30 Design and build a circuit that would turn on and off the turning indicators in a car. Include both the front and back turning lights and the dash lights that tell the driver his indicator is on. (3 marks)

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UNIT 1 HOW IS ENERGY USEFUL TO SOCIETY?

CHAPTER 6 USING ELECTRICITY

Introduction

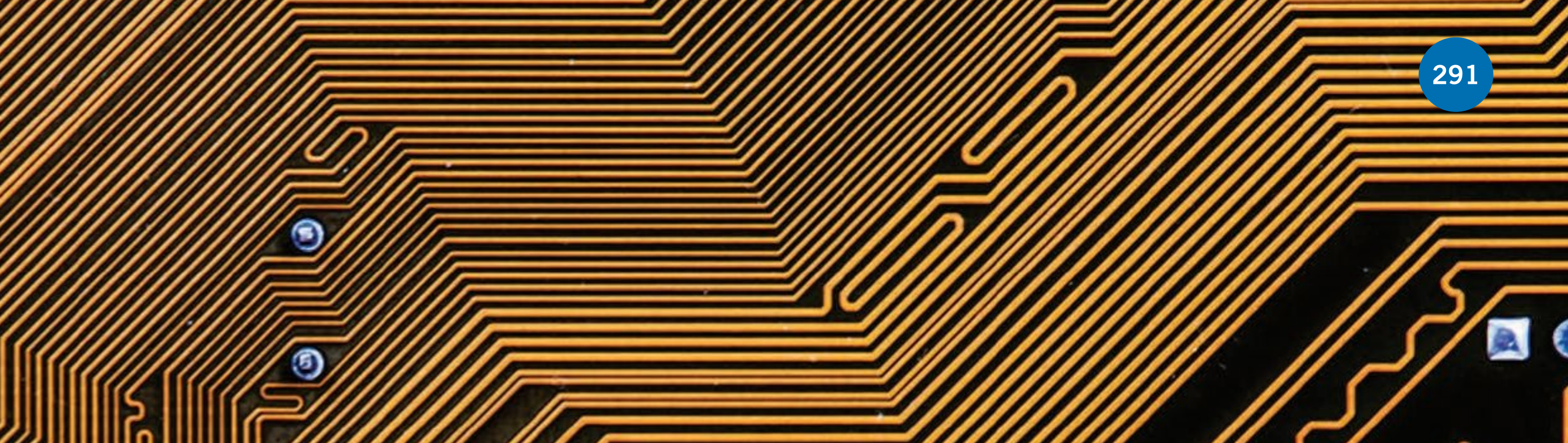
Building on concepts used to model electricity and electric circuits in Chapter 5, this chapter focuses on useful transducers for controlling electronic circuits, domestic use of electricity and electrical safety. Household (AC) electrical systems are modelled as equivalent DC circuits. The chapter explores why circuits in homes are mostly parallel circuits, by comparing power use and effective operation of appliances. The kilowatt-hour is introduced as a household unit of electrical energy. Electrical safety devices found in the home are studied, along with the causes and effects of electric shock on the human body and the latest first aid treatment.

Curriculum

Area of Study 3 Outcome 3

How can electricity be used to transfer energy?

Study Design	Learning objectives – at the end of this chapter I will be able to:
Using electricity • Investigate and apply theoretically and practically concepts of current, resistance, potential difference (voltage drop) and power to the operation of electronic circuits comprising resistors, light bulbs, diodes, thermistors, light dependent resistors (LDRs), light-emitting diodes (LEDs) and potentiometers (quantitative analysis restricted to use of $I = \frac{V}{R}$ and $P = VI$)	**6A Useful electronic components** **6A.1** Recognise the way a diode behaves in a circuit and relate this to its I–V characteristic (I–V graph) **6A.2** Recognise the way an LED behaves in a circuit and relate this to its I–V characteristic; compare this to the characteristic for a diode, and relate it to the uses for each **6A.3** Recognise a variable resistor (or potentiometer) as a long, high-resistance wire of which a selected section is used; apply this to use in a volume control or dimmer, or in a circuit where current is to be varied



Study Design	Learning objectives – at the end of this chapter I will be able to:
• Investigate practically the operation of simple circuits containing resistors, variable resistors, diodes and other non-ohmic devices • Describe energy transfers and transformations with reference to resistors, light bulbs, diodes, thermistors, light dependent resistors (LDRs), light-emitting diodes (LEDs) and potentiometers in common devices	**6A.4** Recognise the way an LDR behaves in a circuit and relate this to its resistance vs light level graph **6A.5** Recognise the way a thermistor behaves in a circuit and relate this to its resistance vs temperature graph **6A.6** Calculate the potential difference output of a potential divider given the ratio of resistances used and the supply potential difference **6A.7** Predict and analyse the behaviour of potential divider circuits using resistors, LDRs, thermistors and LEDs; understand some of the uses for these non-ohmic components **6A.8** Predict and analyse the behaviour of other components in a circuit where variation is created using potentiometers, diodes, LEDs and switches
Circuit electricity • Model household (AC) electrical systems as simple direct current (DC) circuits **Electrical safety in the home** • Model household electricity connections as a simple DC circuit comprising fuses, switches, circuit breakers, loads and earth **Concepts used to model electricity** • Apply concepts of charge (Q), electric current (I), potential difference (V), energy (E) and power (P), in electric circuits • Apply the kilowatt-hour (kW h) as a unit of energy **Circuit electricity** • Compare power transfers in series and parallel circuits • Explain why the circuits in homes are mostly parallel circuits	**6B Electricity at home** **6B.1** Re-draw a picture of a circuit as the equivalent circuit diagram for series, parallel and complex **6B.2** Identify household electrical systems as mostly parallel circuits, with AC supplied in Australia at 230 V 50 Hz **6B.3** Justify the use of series or parallel circuits for household circuits using the characteristics of each type of circuit **6B.4** Calculate the power and energy supplied to household appliances in a parallel circuit and compare this to power use in a series circuit **6B.5** Consider the energy used in a household (and other applications) and apply the kilowatt-hour (kW h) as a unit of energy; for example, as it relates to cost and to battery storage

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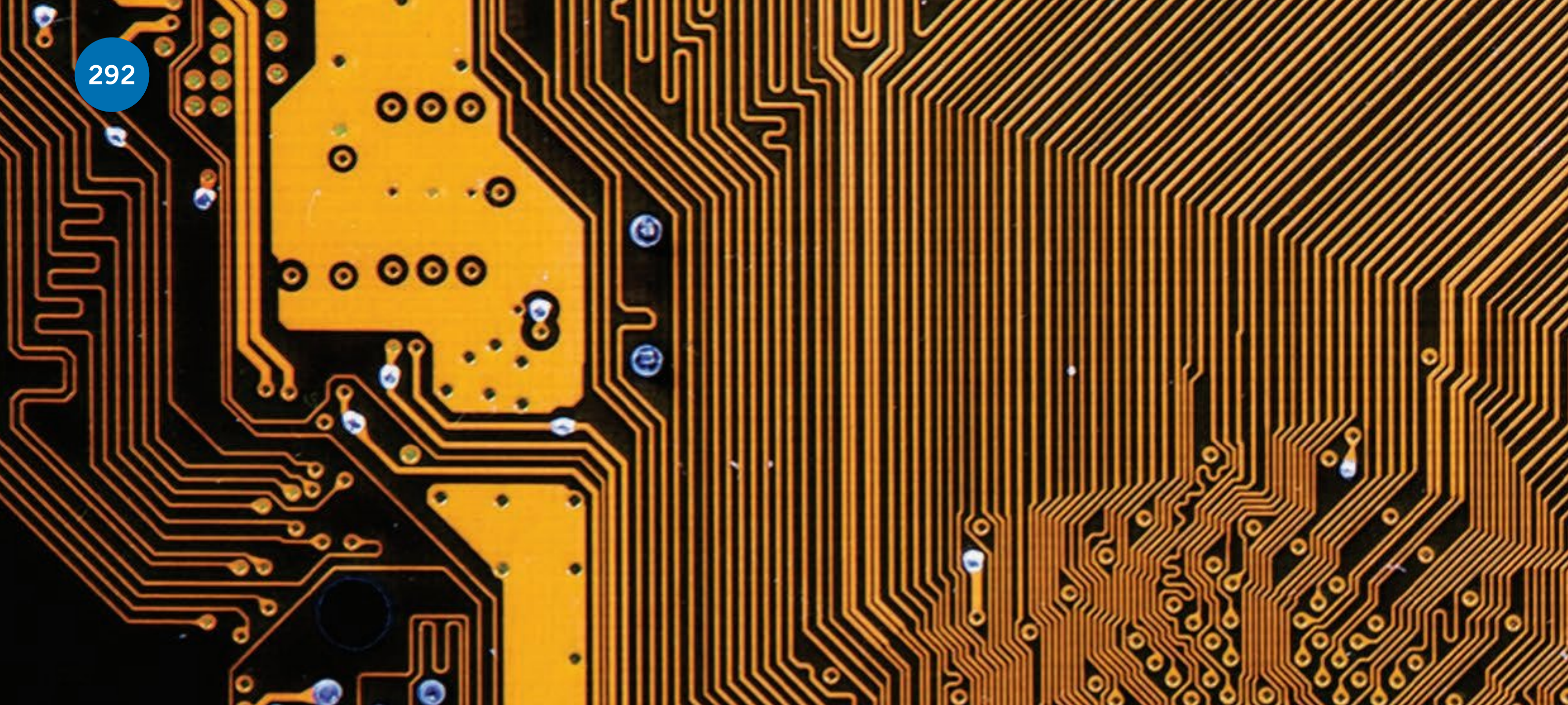

Study Design	Learning objectives – at the end of this chapter I will be able to:
Electrical safety in the home • Model household electricity connections as a simple DC circuit comprising fuses, switches, circuit breakers, loads and earth • Compare the operation of safety devices including fuses, circuit breakers and residual current devices (RCDs) • Describe the causes, effects and first aid treatment of electric shock and identify the approximate danger thresholds for current and duration	**6C Electrical safety** **6C.1** Describe the causes, effects and first aid treatment of electric shock **6C.2** Identify and recall the approximate danger thresholds for current and duration passing through a human body **6C.3** Recall that the mains supply in Australia is 230 V 50 Hz; recognise the need for safety devices such as fuses, switches and circuit breakers to make a circuit safe **6C.4** Recognise the Australian standard three-pin plug with active, neutral and earth connections; relate this to a model of an AC circuit compared with DC **6C.5** Understand the earth connection as a low resistance path to 0 V, hence as a safety connection; also as a zero of potential; recall the conditions under which double-insulated devices do not require an earth connection **6C.6** Describe the operation of these safety devices in Australia: switch, fuse, circuit breaker, residual current device (RCD)

Glossary

Active
Circuit breaker
Diode
Double insulated
Earth
Electromagnetic switch
Fibrillation
Fuse
Kilowatt-hour (kW h)
Light dependent resistor (LDR)
Light-emitting diode (LED)
Neutral
Potentiometer
Residual current device (RCD)
Short-circuit
Thermistor
Transducer
Transformer

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Concept map

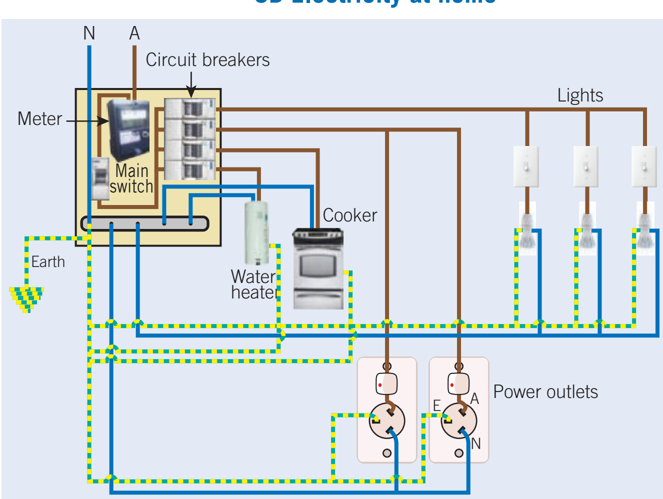
The operation of simple circuits containing transducers to control their energy transfers and transformations

6A Useful electronic components

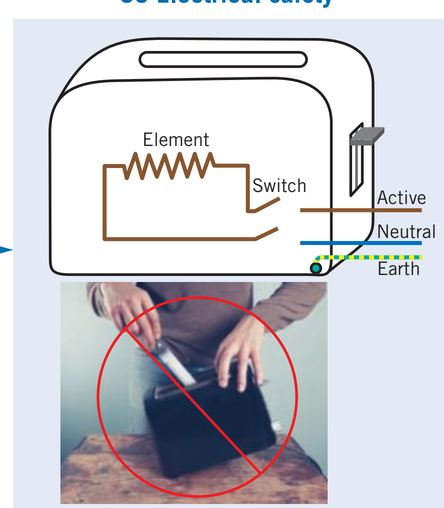
Compare energy transfers in series and parallel circuits, explain why the circuits in homes are mostly parallel circuits, and apply the kilowatt-hour (kW h) as a unit of energy

Discuss the operation of safety devices for electricity, causes, effects and first aid for electric shocks

6B Electricity at home



6C Electrical safety



See the Interactive Textbook for an interactive version of this concept map interlinked with all concept maps for the course.

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6A Useful electronic components

Study Design:

- Investigate and apply theoretically and practically concepts of current, resistance, potential difference (voltage drop) and power to the operation of electronic circuits comprising resistors, light bulbs, diodes, thermistors, light dependent resistors (LDRs), light-emitting diodes (LEDs) and potentiometers (quantitative analysis restricted to use of $I = \frac{V}{R}$ and $P = VI$)
- Investigate practically the operation of simple circuits containing resistors, variable resistors, diodes and other non-ohmic devices
- Describe energy transfers and transformations with reference to resistors, light bulbs, diodes, thermistors, light dependent resistors (LDRs), light-emitting diodes (LEDs) and potentiometers in common devices

Glossary:
Diode
Light dependent resistor (LDR)
Light-emitting diode (LED)
Potentiometer
Thermistor
Transducer

ENGAGE

Controlling electric circuits

Have you ever wondered how your fridge ‘knows’ to switch on the motor to maintain the cool temperature after the door has been open, or how streetlights ‘know’ to come on as it gets dark? There is a control circuit for each of these, which is a straightforward application of what we have studied in series circuits and potential dividers in Chapter 5, and a couple of useful inventions we will explore in this chapter.

CHAPTER 5 LINK

As part of the electrical revolution in the twentieth century, valves (devices made of evacuated glass bulbs with various metal plates and terminals within them) were replaced from the 1960s onwards with semiconductor devices able to perform the same functions. Where valves were large, expensive to produce and run, and extremely fragile, semiconductor devices are small, much cheaper to produce and more robust. Among the first of these to be mass-produced was the transistor, so well known that the portable battery-powered radios in use from 1954 onwards were commonly called ‘transistors’, short for ‘transistor radios’. Before this, the radio, often combined with a record turntable (‘radiogram’), was a large item of furniture in only one room of the house, or a heavy box sitting on a bench, plugged into a wall outlet.

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Semiconductor devices using materials such as silicon and germanium can be manufactured into sensors to detect changes in light levels, temperature, pressure, forces (stresses and strains) and many other environmental factors. They draw very little current and operate at small potential differences, so are generally used to operate electronic switches. These in turn control external circuits involving higher current and potential difference.

Figure 6A–1 'Small' valve radio

Other semiconductor devices, like diodes and transistors of various types, are used to control the size and direction of electrical signals. Integrated circuits (ICs), or chips, are the basis of most twenty-first century technology, from mobile phones to satellites to nanobots capable of performing microsurgery inside a living body. Next time you notice the streetlights turning on at dusk, often one by one, think about the technology that allows light levels to control an electric circuit, and as you open the fridge to get your afternoon snack, remember to marvel at the electrical inventions that keep it cool all day.

EXPLAIN

Diodes and LEDs

A **diode** is a semiconductor made mainly of silicon, germanium or selenium and doped with impurities such as phosphorus and aluminium. The reasons for a semiconductor's function are beyond the scope of this course, but it is enough to say that a semiconductor conducts less well than a metal, and its resistance depends on the distribution of impurities and the temperature.

VIDEO 6A–1 USING ELECTRICITY

Diode
a semiconductor with very large resistance to current flow in one direction but very small in the other; a semiconductor device that will only allow electrical current to flow through it in one direction

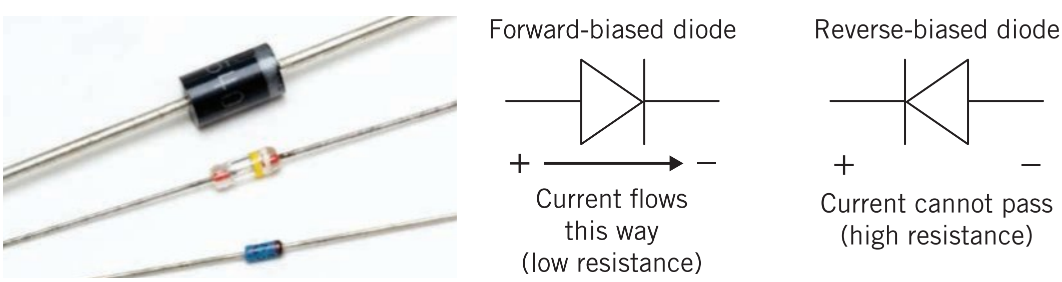

Figure 6A–2 Diodes and their symbols. Left: the banded end of a diode shows the side that should be connected facing the negative terminal of the supply potential difference, if current is to flow. Right: The circuit symbol for a diode reflects its function: the triangle is like an arrow showing the direction current can flow, and the line across the 'nose' of the triangle is like a wall that current cannot pass through when it approaches from that direction. This end of the diode has the band shown on left.

A diode is a non-ohmic resistance, and in fact its I–V characteristic is not even symmetrical: the size of the current depends on which way the potential difference is connected to the diode, or, to think of it another way, the direction of the potential difference, or polarity, affects the size of the current. The resistance of a diode is very large in one direction, but very small in the other.

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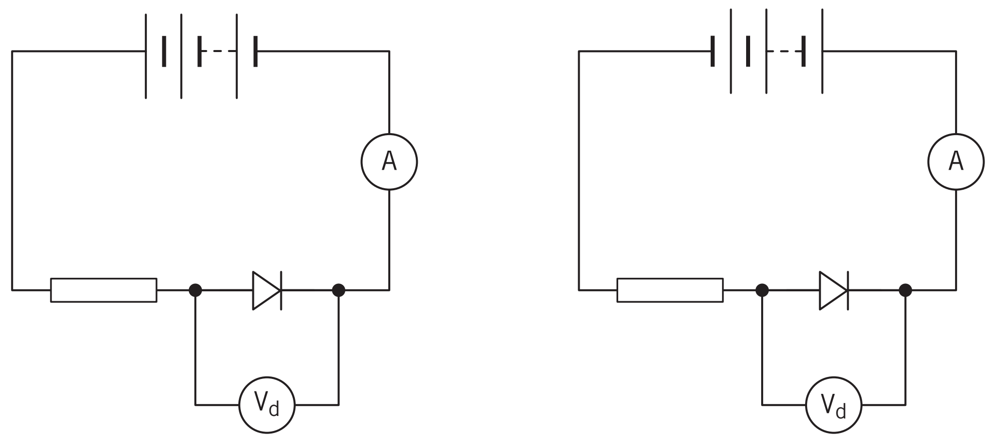

Figure 6A–3 Left: The diode in this circuit is 'forward-biased' so current will flow. Right: Swapping either the poles of the battery, as shown here, or of the diode gives a reverse-biased diode. A very tiny current will flow (until a very large potential difference is applied). Remember to reverse the connections on the ammeter and voltmeter if necessary.

5C MODELLING RESISTANCE IN SERIES CIRCUITS LINK

The *I*–*V* characteristic for a diode is obtained in the same way as the circuit used in Section 5C to record the characteristic of a resistor, but after the initial set of readings the potential difference must also be reversed (you may need to reverse the ammeter and voltmeter leads if using analogue meters) to measure the current in the opposite direction.

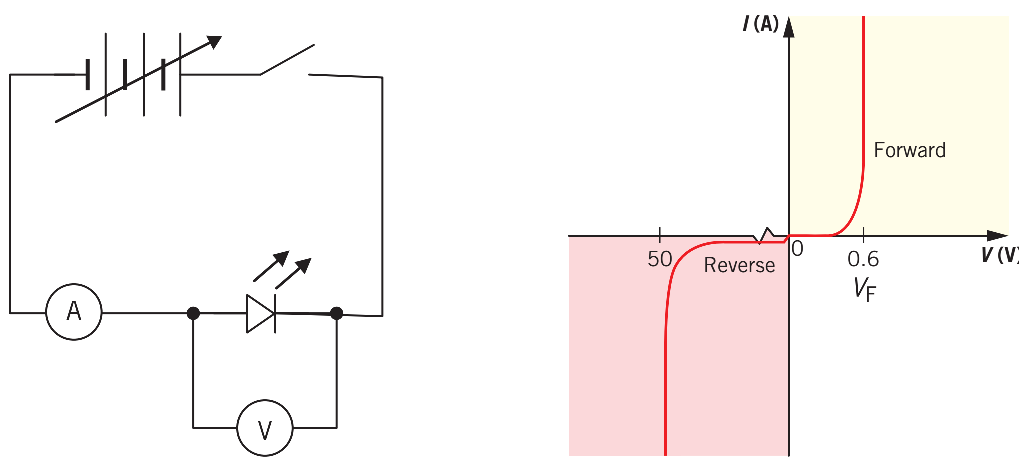

Figure 6A–4 Left: This circuit should look familiar from Section 5D. Right: *I*–*V* characteristic for a diode. Note that the scales in the positive and negative potential difference are not equal. The forward bias potential, V_F, varies depending on the semiconductor composition but is 0.6–1.0 V for silicon. When reverse biased, 50 V or more, V_{BR}, can be applied before the semiconductor breaks down and becomes a conductor.

Instead of a straight-line ohmic graph, the diode shows almost zero resistance in one direction, and a very large resistance in the other (note that the horizontal axis is not to scale). Under normal conditions, current can only flow through a diode in one direction. This can be useful to protect components that would be damaged by reverse current, and to change AC (alternating current) into DC (direct current); for example, in the charger for a laptop. Use of a diode alone in a rectifier circuit (changing AC to DC) results in the conversion of only 50% of the electrical energy, as the electrical energy carried by all the 'backwards' current that is blocked does not transfer to the DC current.

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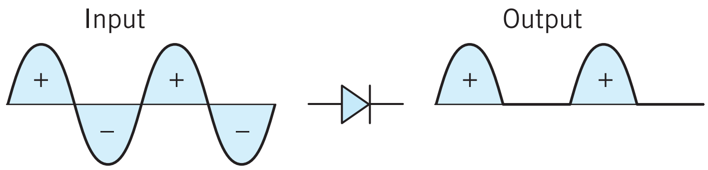

Figure 6A–5 When an alternating potential difference is supplied to a diode, only the forward-biased section appears at the output.

Safety note: like any component, diodes can only dissipate a certain amount of energy before they break down (or 'blow'). Always check the details before you connect one. If a diode is subject to more current or potential difference than it can handle, it will heat up, melt or smoke. Often a small value resistor is put in series with the diode for protection. Some of the potential difference will be across the resistor, not all across the diode, and the current will be lower.

Light-emitting diode (LED)

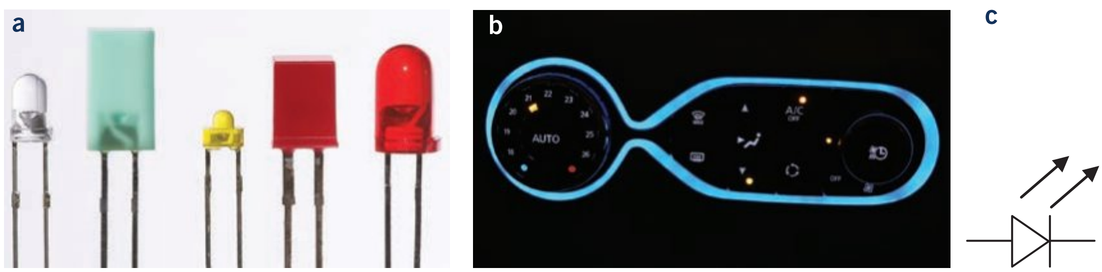

Figure 6A–6 a LEDs come in a range of colours. **b** Example of single LEDs and LED lamps used in a vehicle control panel. **c** Circuit symbol for an LED.

A more easily noticed component is a **light-emitting diode (LED)**, often seen as the 'power on' or 'standby' light on electrical appliances, and combined in lamps as an efficient replacement for filament and fluorescent household lighting. As the name suggests and the symbol shows, the LED lights up when current flows through it (it is said to be 'forward biased') but not when the potential difference is reversed because, being a diode, no current will flow 'backwards' through it. In the same way as the diode, the resistance of an LED is very small in one direction, but very large in the other.

Light-emitting diode (LED) a diode that lights up when current flows through it but since it is a diode current will not flow in the reverse direction

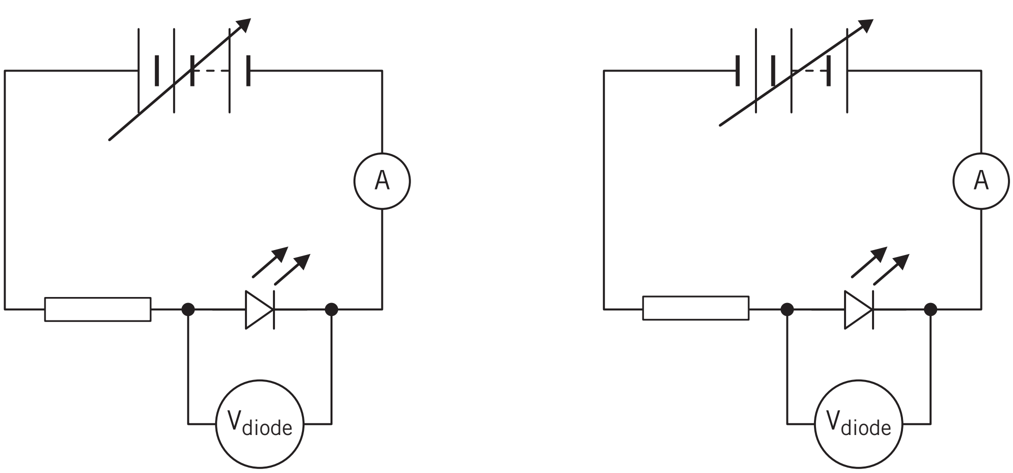

Figure 6A–7 A forward-biased LED (left) conducts electricity but a reverse-biased LED (right) has a very high resistance that blocks all current. It is reverse-biased because the battery polarity has been swapped – be sure to look carefully at the battery polarity in circuit diagrams with diodes. Notice that the symbol stays the same, regardless of whether the LED is actually glowing or not.

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The I–V characteristic of an LED can be obtained in the same way as usual, by varying the potential difference across it and recording the current through it, then reversing the polarity of the power supply and repeating the process. A typical I–V graph for an LED is shown in Figure 6A–8.

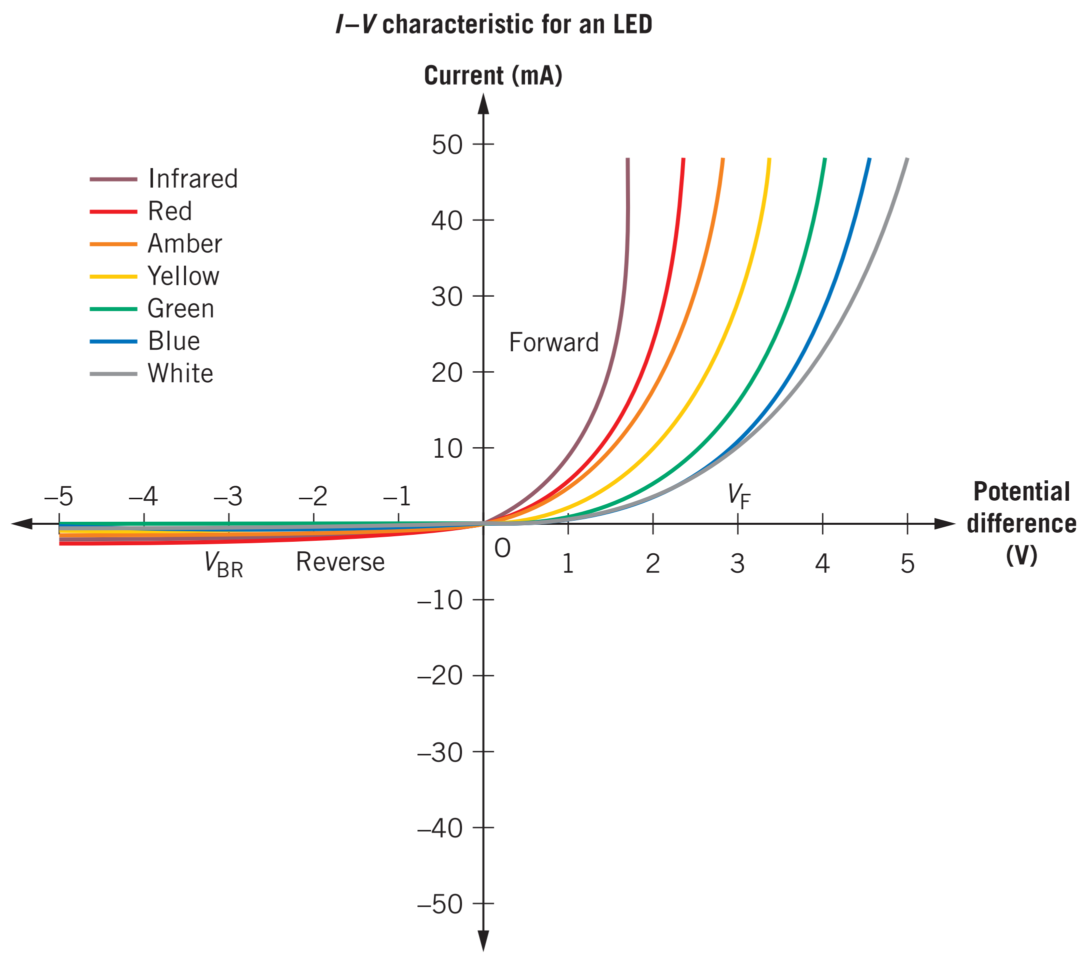

Figure 6A–8 An LED has similar characteristics to a diode, although the different doping and structure for different colours mean that values of resistance also vary.

For the same amount of light, arrays of LEDs in a mains-connected LED lamp use significantly less energy than filament bulbs or fluorescents. They are more efficient and are becoming cheaper to produce than older technology. LEDs and lighting are now part of the twenty-first century electrical revolution.

ACTIVITY 6A–1 OTHER TYPES OF DIODE

Research two other types of diode (besides basic or 'rectifier' diodes and LEDs) and write a two-line summary of the function of each. Is there such a thing as a diode with zero forward resistance, i.e. a superconducting diode?

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Check-in questions – Set 1

1 A diode can be used in a circuit to control the direction of applied voltage. What property of diodes is used in this application?
2 Explain why diodes and LEDs are often connected in a circuit in series with a small resistor.
3 If the protective resistor is always in the circuit, why is the voltmeter in Figure 6A–7 across only the LED and not the resistor?

Potentiometer (or variable resistor)

Figure 6A–9 shows different versions of a useful piece of equipment, a **potentiometer** ('pot'), that can be used in a couple of different ways, and, perhaps confusingly, often gets a different name according to how it is set up in a circuit. You might hear it called a potential divider, rheostat, variable resistor or dimmer switch. It is basically a long wire of high resistance, often insulated and coiled for convenience, with electrical contacts or terminals at each end (terminal A and C in Figure 6A–9) and a sliding contact which can be moved to different positions along the wire. Current flows between terminals A and B. See Figures 6A–12 and 6A–13 for circuit diagrams for the potentiometer in use.

Potentiometer a circuit device consisting of a three-terminal sliding or rotating contact (called the 'wiper'). Connections at one end and the wiper can be used to create a variable resistor. Often used as a volume control or light dimmer.

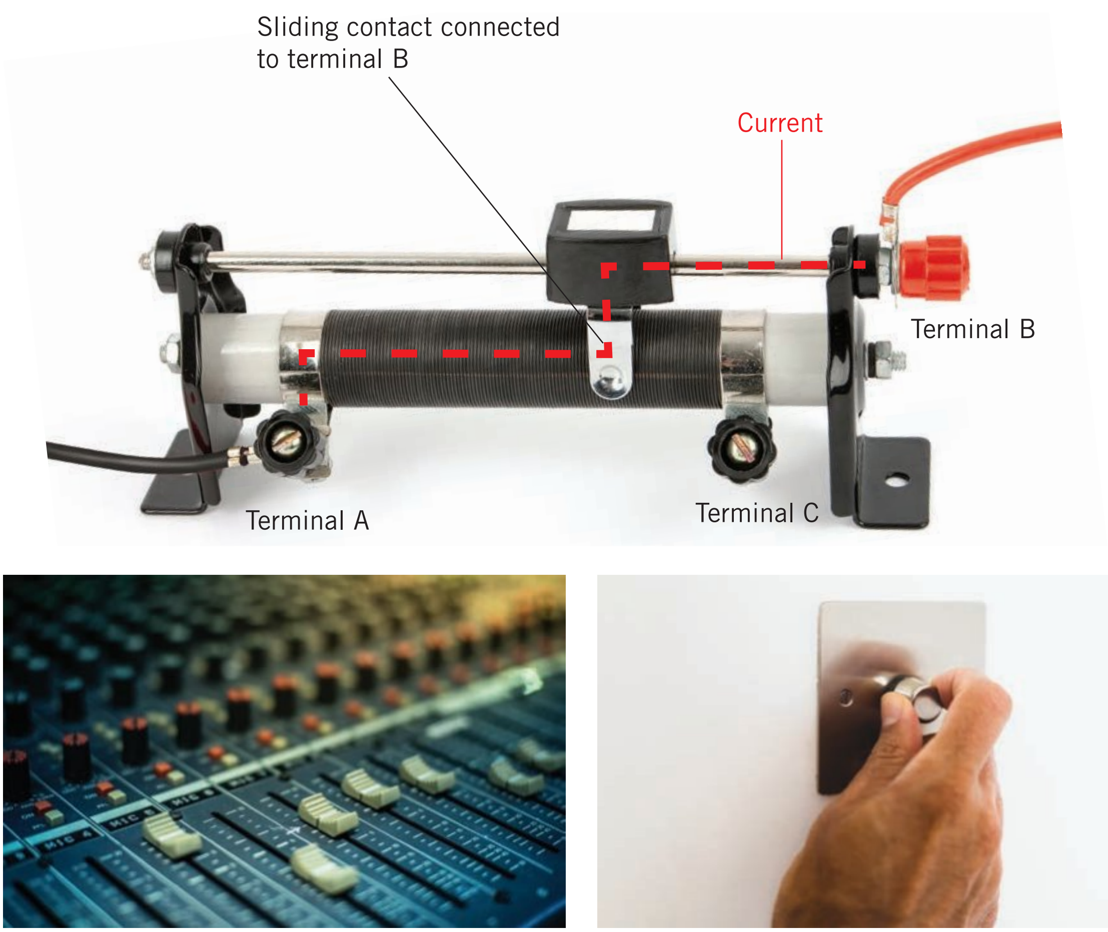

Figure 6A–9 Top: A physics laboratory potentiometer with terminal A connected to a power source and current flowing from there through the coils to the sliding contact and out though terminal B. This is the same connection as in Figure 6A–13 when it is used as a rheostat. Sliders controlling sound levels (bottom left), and a rotating knob dimmer switch (bottom right) use potentiometers to control the current of the circuit. The high-resistance wire may be straight, as in the slider type, or curved into an almost complete circle, like the rotating-knob type.

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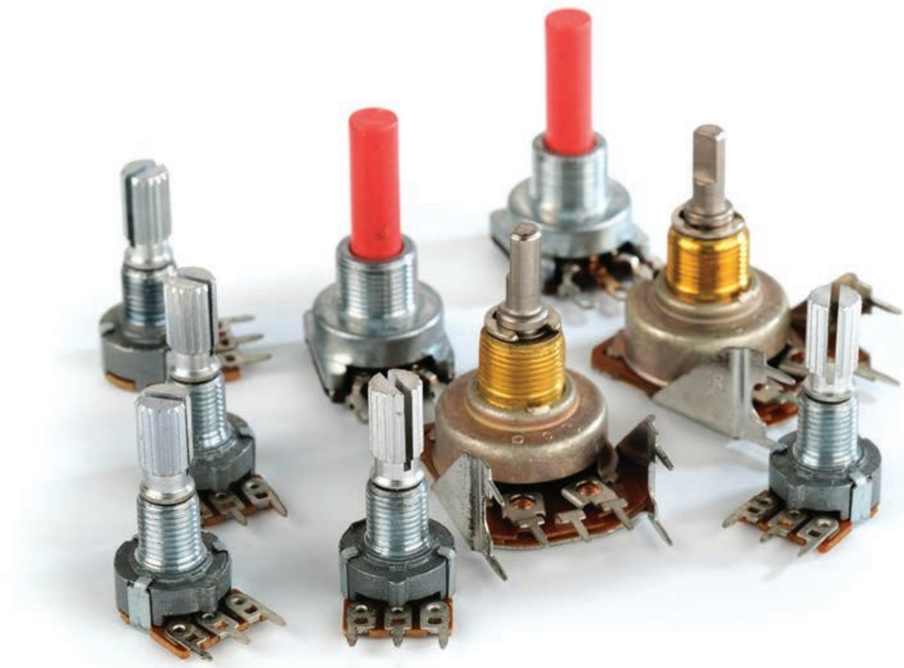

Figure 6A–10 Rotating-knob potentiometers or variable resistors are the most common type and come in a range of shapes and sizes to suit the current and potential difference requirements of different circuits.

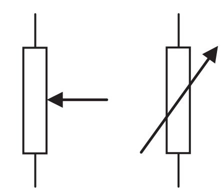

Figure 6A–11 Circuit symbol for a potentiometer or variable resistor

The circuit symbol for a potentiometer is shown in Figure 6A–11. You choose which two or three of the terminals to connect depending on the job you want the pot to do in the circuit.

5C MODELLING RESISTANCE IN SERIES CIRCUITS LINK

Recall that in Section 5C you learned how two resistors in series can be used to divide up the potential difference according to the ratio of their resistances, creating a potential divider. The same idea is used in a potentiometer. The two resistors are replaced by a long piece of ohmic resistance wire with a sliding contact that can be moved to any position, from one end of the wire to the other.

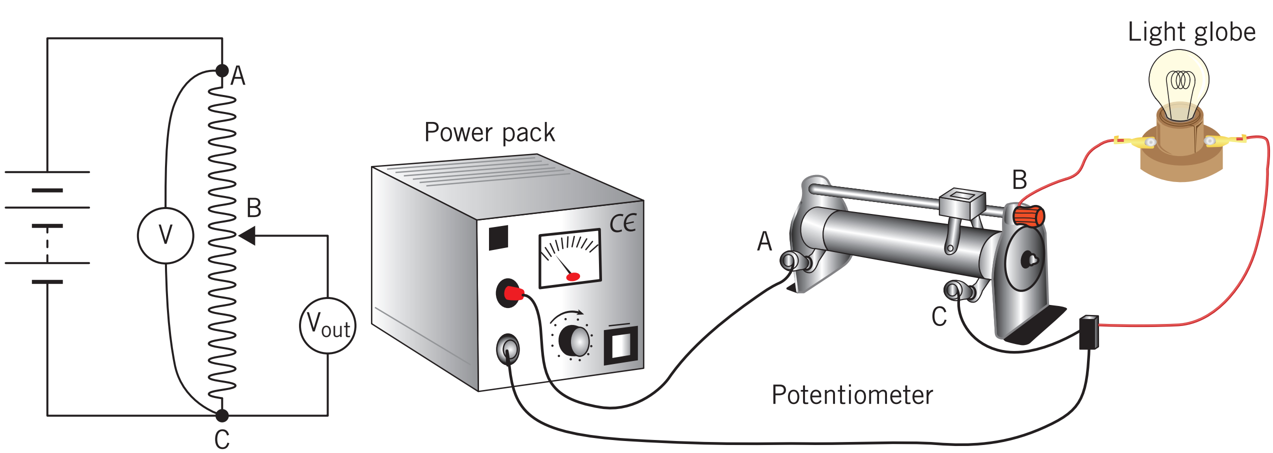

Figure 6A–12 Left: A circuit diagram of a potentiometer connected to a battery, with a voltmeter connected to measure the potential difference. This type of connection to a potentiometer can be used as a dimmer for lights or as a volume control. Right: Drawing of a globe connected in place of the voltmeter, V_{out}.

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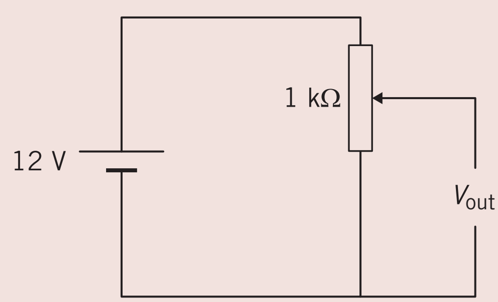
Because they are made from resistance wire that obeys Ohm's law, the proportion of the lengths of wire on each side of the sliding contact is the same as the proportion of potential difference across each end of the wire. As seen in Figure 6A–12, the sliding contact for V_{out} moves along the wire. If it's half-way along, then $V_{out} = \frac{1}{2}V$. If the slider is three-quarters of the way up, then $V_{out} = \frac{3}{4}V$; if it's a quarter of the way up, then $V_{out} = \frac{1}{4}V$. Mathematically, we would say that the resistance is directly proportional to the length. If you know the total resistance of the whole wire, the resistance can be obtained with simple ratios from an accurate length measurement.

For circuits with this arrangement, there is always current in the whole length of the potentiometer, and the slider can be positioned to provide varying potential difference to the output side of the circuit when a connection is made between points C and B. Note that all three terminals are in use. The rest of the circuit will effectively be in parallel with the section B to C of the potentiometer, so extra current flows from the power supply when a load is connected to V_{out}. The potential difference across the pot doesn't change, nor does the current through the lower part of the potential divider (below the slider). Any value of potential difference, V_{out}, can be chosen for the load, simply by moving the slider.

Worked example 6A–1 Potentiometer

When the slider of the potentiometer shown is set at the middle of the potentiometer, calculate the potential difference at V_{out}.



Solution

With the slider halfway down the potentiometer, the potential difference V_{out} is half that across the pot, i.e.:

$$V_{2k\Omega} = \frac{1}{2} \times 12$$
$$= 6\text{ V}$$

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A second method of setting up the circuit involves deliberately controlling the current, rather than the potential difference, by using the same piece of equipment as a variable resistor (sometimes called a rheostat). Figure 6A–13 shows that only two terminals are connected, one end (A) and the slider (B).

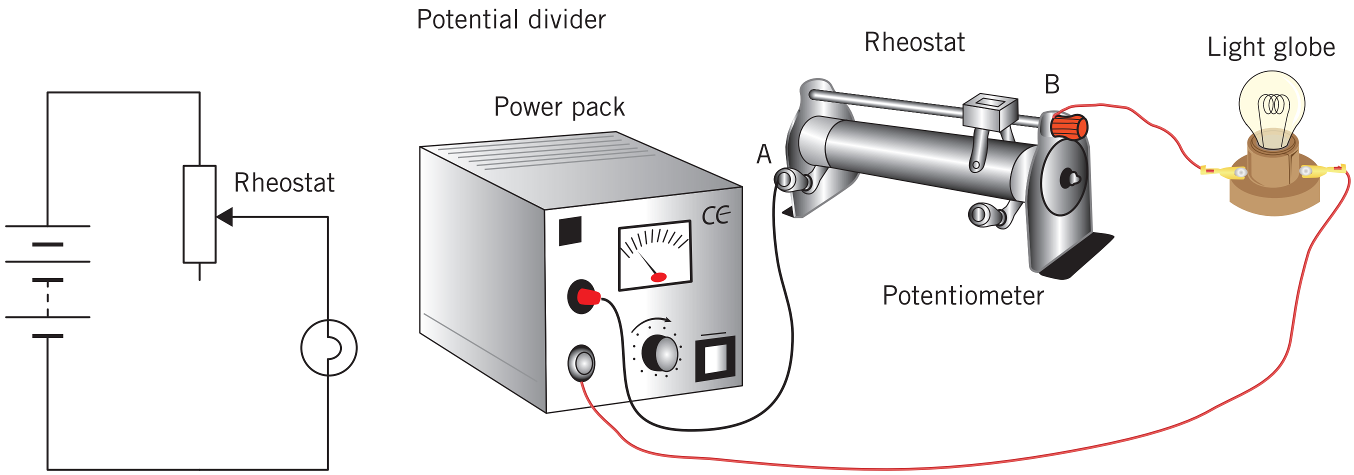
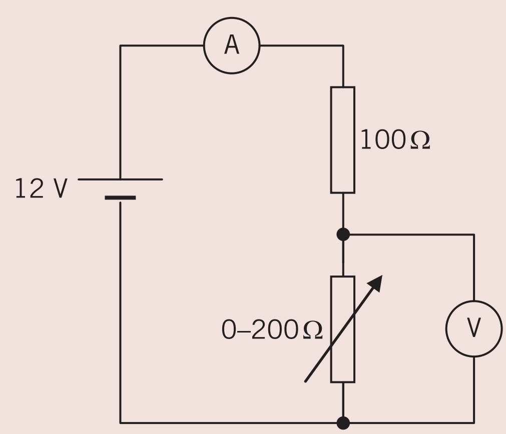


Figure 6A–13 A circuit diagram (left) and a drawing of the set-up for using a potentiometer (rheostat) with only two terminals connected –- one end (A) and the slider (B) – to vary the current (right)

The longer the wire included in the circuit, the greater the resistance and the lower the current in the circuit, so moving the sliding contact directly controls the current. The variable resistor is effectively in series with the rest of the circuit. Current only flows through the part of it that is selected (A to B in this case), and both the current and the potential difference are affected when the slider is moved.

Worked example 6A–2 Rheostat or variable resistor



In the circuit shown, the fixed resistor has a value of 100 Ω, and the variable resistor can be adjusted between 0 and 200 Ω.

Calculate the maximum and minimum values of the current possible through the ammeter and the potential difference, V, measured by the voltmeter in each case.

Solution

Current will be maximum when variable is minimum, i.e. zero.

So using Ohm's law:

$$I_{max} = \frac{V}{R_{min}}$$

$$= \frac{12}{100}$$

$$= 0.12 \text{ A or } 120 \text{ mA}$$

In this case, V_{pot} = zero as $R_{pot} = 0$ (Ohm's law)

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Current is minimum when variable is maximum, so total resistance in the circuit:

$$R_{max} = 100 + 200$$
$$= 300\ \Omega$$

Again, using Ohm's law:

$$I_{min} = \frac{V}{R_{max}}$$
$$= \frac{12}{3000}$$
$$= 0.004\ \text{A or } 4\ \text{mA}$$

In this case, $V_{pot} = IR_{pot}$, so:

$$V_{pot} = 0.004 \times 2000$$
$$= 8\ \text{V}$$

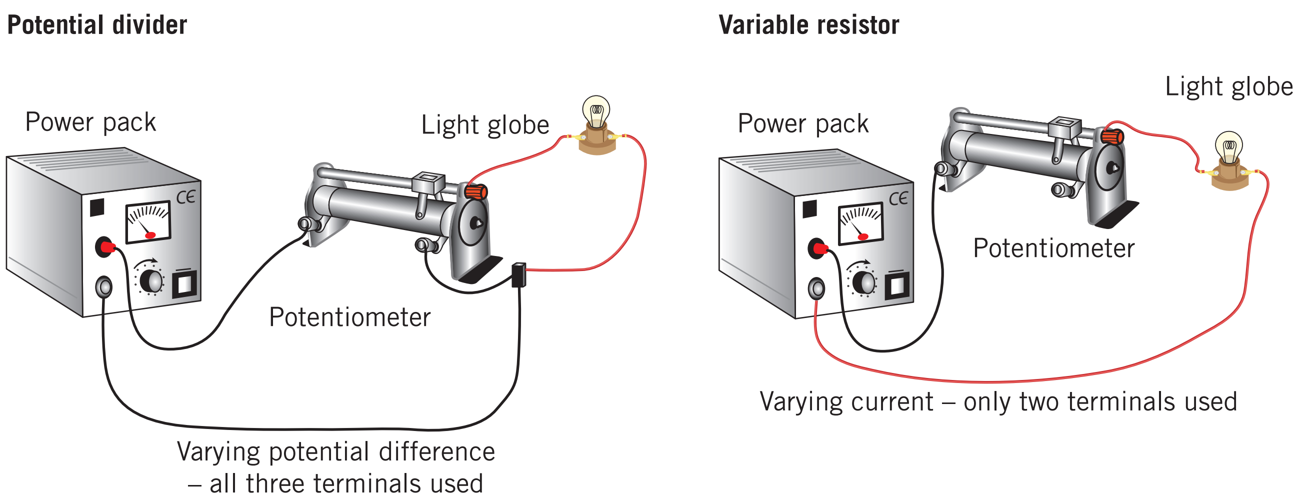
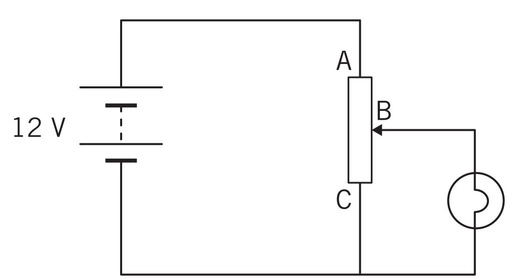


Figure 6A–14 Compare the circuits shown here of a potential divider (left) and variable resistor (right) each set up to power a globe. Notice the different number of connections to the rheostat in each case, and the different way the potential difference across the rheostat would change if the slider is moved.

Check-in questions – Set 2



1 How would the brightness of the globe vary as the slider is moved up towards A?
2 How would the brightness of the globe vary as the slider is moved down towards C?

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Light dependent resistor (LDR)

Light dependent resistor (LDR) a semiconductor device whose resistance depends on the intensity of light shining on it

The **light dependent resistor (LDR)** is a semiconductor device whose resistance depends on the intensity of light of suitable wavelength shining on it. The incident light might vary with the distance from a light source, or due to night falling, or because the door of a cupboard is opened.

For a particular light intensity, the LDR behaves as a resistor of constant resistance, obeying Ohm's law over a small range of potential difference. To obtain the *I–V* characteristic, it is necessary to measure and state the light level at which the potential difference and current measurements were taken. A more useful graph is resistance versus light level. It is measured in units of lux (lx). As the brightness of light increases, the resistance decreases in an exponential way. These relationships are shown in the graphs in Figure 6A–16.

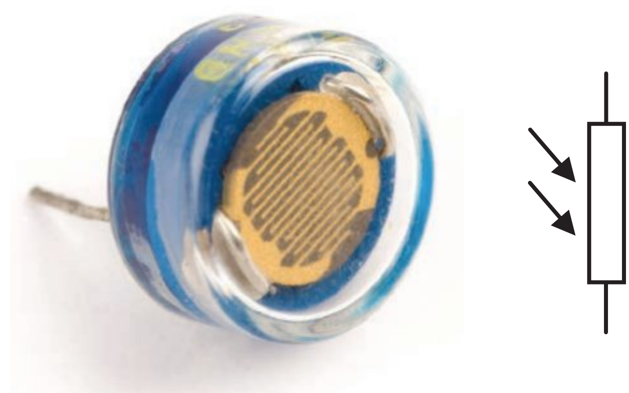

Figure 6A–15 An LDR (left) and its circuit symbol (right)

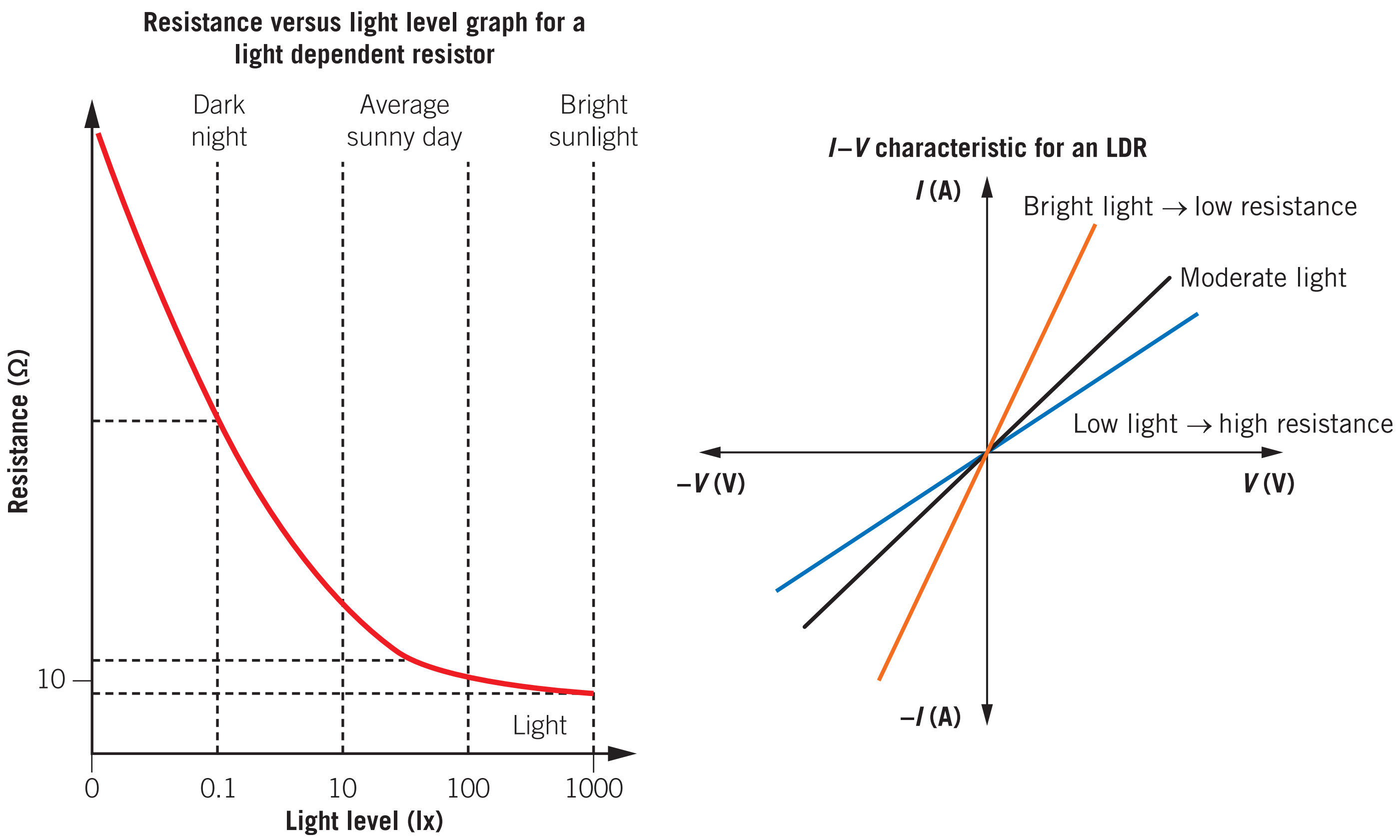

Figure 6A–16 Left: Graph of resistance versus light intensity level (in lux, lx) for a light dependent resistor. Note the logarithmic scales on both axes. With light of low intensity of about 10 lx, $R = 10^6\ \Omega$ or 10 MΩ. With 1000 lx, the resistance is as low as 10 Ω. Right: *I–V* characteristic of an LDR. For a given light level, the LDR is ohmic within a given range of potential difference.

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LDRs can be used in a range of applications; for example, in light meters or to control an automatic flash. Streetlights or night lights that turn on as it gets dark can use an LDR in a potential divider circuit. If a variable resistor is used, the level of light that turns on the streetlights can be altered. A very common use of an LDR is to trigger a buzzer or an alarm when a person entering a doorway breaks a beam of light.

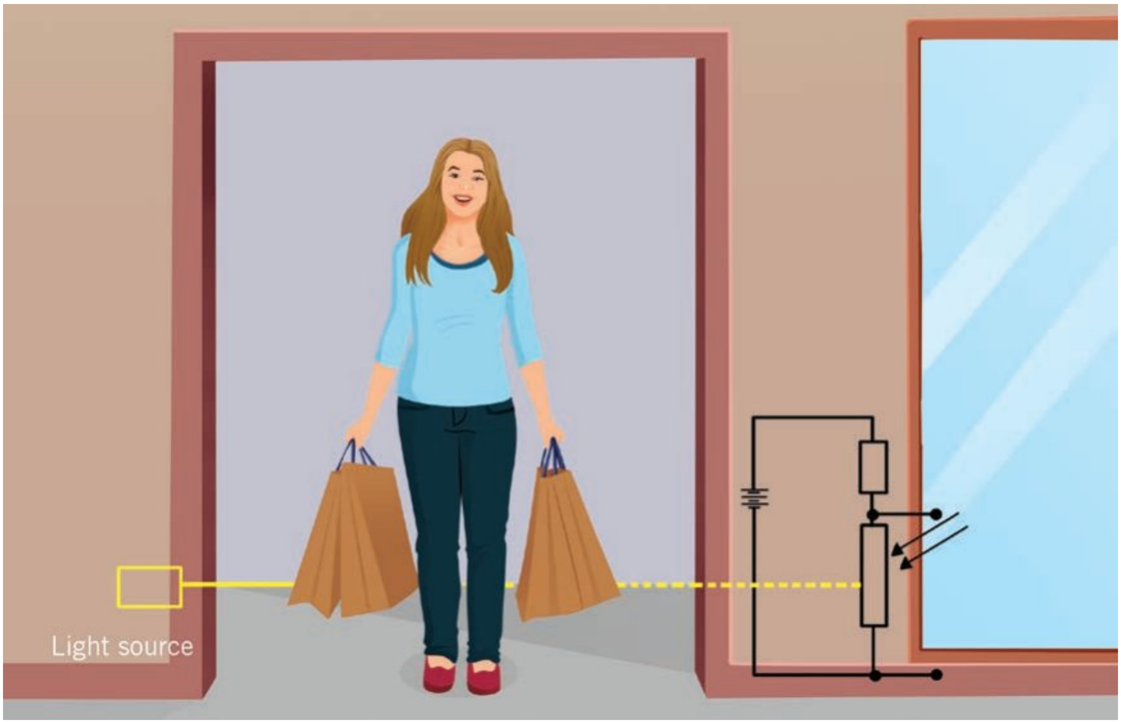
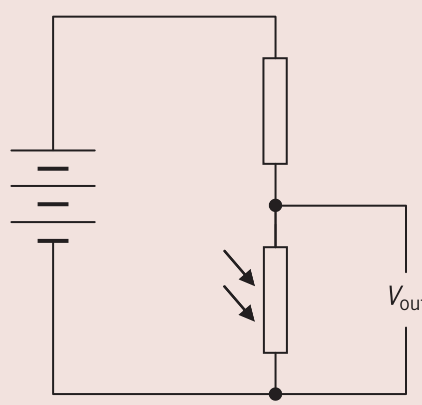


Figure 6A–17 A very common LDR use is to trigger a buzzer or alarm when a person entering a doorway breaks a beam of light. When the LDR is in shadow, its resistance increases, so the potential difference across it increases, which can trigger a switch which turns on a buzzer.

Worked example 6A–3 LDR circuit



a Describe the way the output potential difference, V_{out}, changes in the circuit shown operates as it gets dark.

b Describe an application for such a circuit.

Solution

a The LDR is acting as part of a voltage divider in this circuit (since it is wired in series with a resistor). The output voltage, V_{out}, in this case is then related to the ratio of resistances of the LDR and variable resistor. As it gets darker, the resistance of the LDR increases, so V_{out} would increase, activating the switch that then turns on the spotlight.

b This kind of circuit has a number of applications. One use could be in a nightlight. If the output voltage is connected to an electronic switch that can turn on a globe, then as night falls the resistance of the LDR increases, so a greater share of the battery potential difference will appear across the LDR, which will trigger the electronic switch. The nightlight globe is powered from an external circuit, controlled by this switch.

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Check-in questions – Set 3

1 What property of LDRs make them useful in circuits?
2 List some possible real-world applications of LDRs.

Thermistor

Thermistor a thermal resistor, a non-ohmic semiconductor device whose resistance changes with temperature; two main types: NTC (negative thermal coefficient) increases *R* with decreasing temperature, is the most common type. PTC (positive thermal coefficient) increases *R* with increasing temperature, is made for special jobs.

The **thermistor** (short for 'thermal resistor') is another semiconductor device.

Figure 6A–18 Left: A bead-type thermistor; its resistance changes with temperature. Right: Thermistor symbol

The resistance of a thermistor changes with temperature, so an *I*–*V* graph needs to specify what the temperature was when the current and potential difference were measured. It can also show different lines on the graph for different temperatures. For a particular temperature, most thermistors obey Ohm's law over a small range of potential differences. The more useful graph in Figure 6A–19 shows two types of thermistors:

- negative thermal coefficient thermistor (NTC): as the temperature rises, resistance falls in an exponential-like manner. Most thermistors are this type, so you may assume a thermistor is NTC type unless stated otherwise
- positive temperature coefficient thermistor (PTC): as the temperature rises, resistance suddenly rises steeply in an exponential-like manner. These are mostly custom-designed for specific applications.

Thermistors can be used for temperature control in heaters and air conditioners, refrigerators and ovens, and in digital thermometers, among other applications.

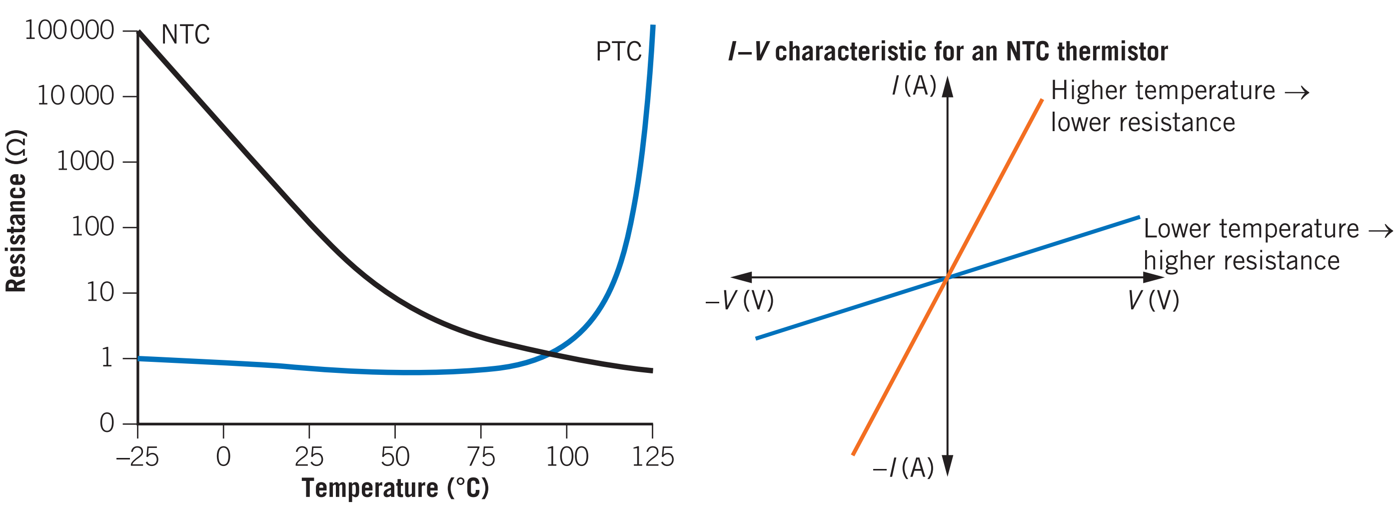

Figure 6A–19 Left: A typical relationship between temperature and resistance for two types of thermistor, NTC and PTC. Note the logarithmic scale for resistance. Right: An *I*–*V* graph for a given thermistor needs to state the temperature at which the current was measured for each potential difference.

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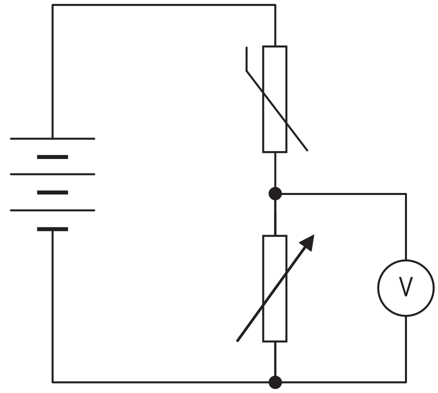


Figure 6A–20 A digital thermometer (left) can be made using a thermistor. What would be the limitation to this thermometer if it worked according to the circuit shown (right)?

Check-in questions – Set 4

1 What property of thermistors make them useful in circuits, specifically those used to control temperature?
2 List some possible real-world applications of thermistors.

WORKSHEET 6A–1 USEFUL ELECTRONIC COMPONENTS

Transducers

Devices that change one form of energy into another are called **transducers**. They can be used as input to a circuit; for example, an LDR that detects the level of light (light → electrical energy) or a microphone that detects a sound and then triggers a change in the circuit (sound → electrical energy). There are also output transducers, like the buzzer that sounds (energy given out) when a current flows in the circuit (electrical → sound energy).

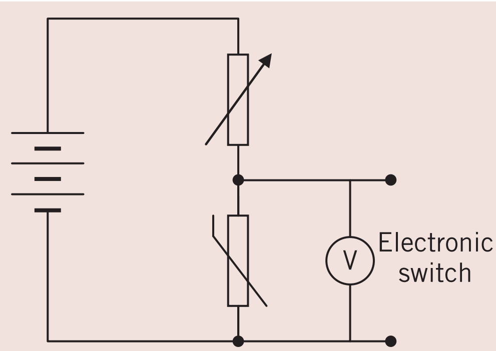
Transducer a device that receives input signal as one form of energy and converts it to a different form of energy output

Varying the switching level in a potential divider circuit with a transducer

You have learned how a potential divider can be used with a transducer to perform a set task, but often you need to vary the level of light or temperature at which a circuit will switch on or off. To do this, a variable resistor in one half of the potential divider is used. This can be set by trial and error (wait until the temperature is right and adjust the rheostat until the circuit switches on or off) or using a pre-set scale (1–10 on an amplifier or 150–300°C on an oven).

Worked example 6A–4 Thermistor circuit

a Describe the way this NTC thermistor circuit operates as temperature increases.
b Find an application for the circuit.



Solution

a In this circuit the thermistor is installed as part of a potential divider. This means as temperature increases, the thermistor resistance will decrease, which in turn will increase (or decrease) the output voltage at *V*. The required temperature can be achieved by changing the value of the variable resistor in the top part of the potential divider. Larger resistance in the top section means a lower temperature turns off the switch and vice versa.

b This circuit could control the settings for an oven. As the required high temperature is reached, the low output voltage triggers a switch to turn off the heating circuit.

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VIDEO 6A–2
SKILLS: TECHNIQUE FOR ANALYSING POTENTIAL DIVIDER CIRCUITS

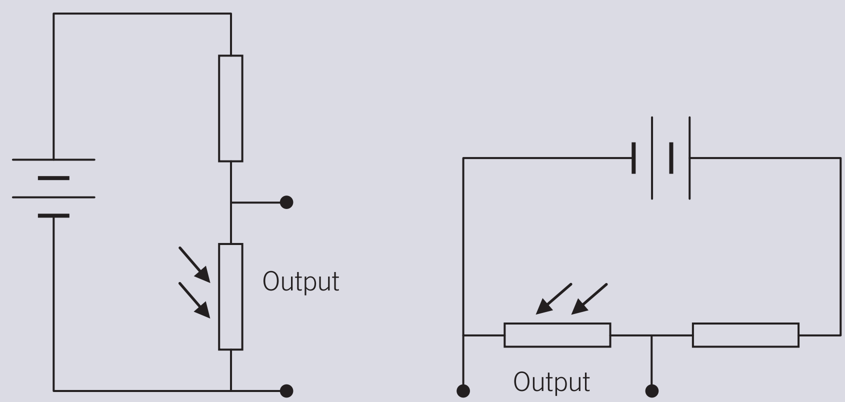
6A SKILLS

Technique for analysing potential divider circuits containing input transducers

The best way to approach any potential divider circuit containing transducers is to recognise that these circuits are designed to change their output (usually potential difference) when the input conditions change. The input conditions are related to the transducer: temperature for thermistors, light intensity for LDRs.

The following steps are useful.

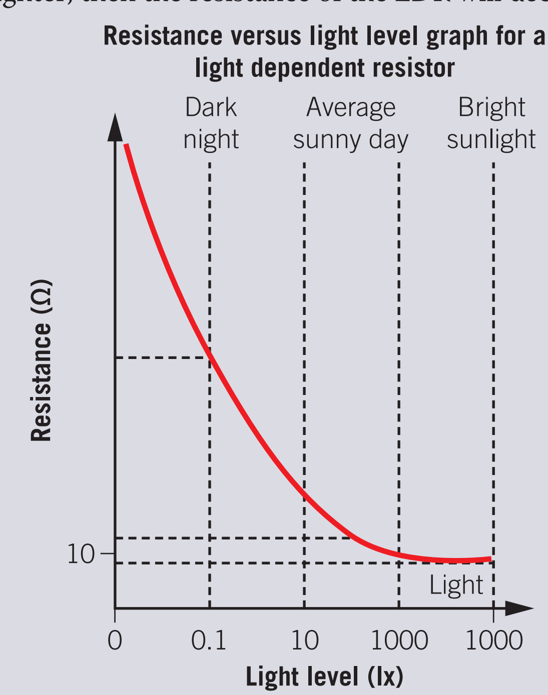
1 Recognise a potential divider circuit. This will have a transducer in series with a resistor (or possibly a variable resistor) across a source of potential difference. Usually the diagrams are vertical, but they could be drawn in any direction. For example:



Don't be misled by the shape – look for the circuit connections to determine what will happen.

2 Which component varies with the environment? Is it sensitive to temperature? Light intensity? Something else? Other transducers can detect things such as strain, stress, force, torque and sound intensity. In the circuit above, it is the LDR.

3 What change is taking place? Will this change increase or decrease the resistance of the transducer? Hint: recall the shape of the graphs for thermistors and LDRs. If the light is getting brighter, then the resistance of the LDR will decrease.



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4 If the resistance of the transducer changes, what effect does this have on the output, V_{out}? It will be a different effect if the transducer is in the 'top' of the potential divider or the 'bottom' position. In the case above, when R_{LDR} decreases, less of the supply potential difference will be across the LDR (and $V_{resistor}$ increases in the other section of the potential divider). A *decreased* V_{out} would be likely to turn *off* an electronic switch – but read each question carefully to understand the set-up before you write your answer.

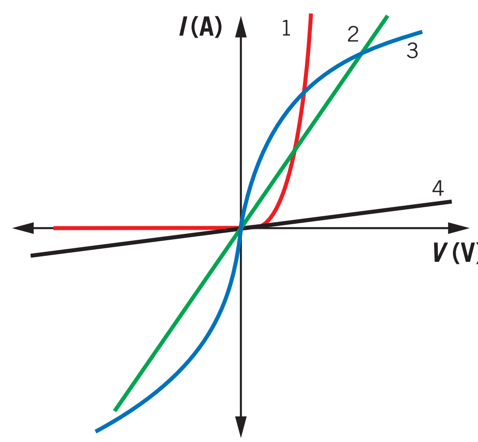
If you keep these steps in mind when analysing a problem, you will be able to write a clearer, more logical answer.

Section 6A questions

Multiple-choice questions

1 Consider the *I*–*V* characteristics of the graphs, labelled 1–4, below.

Which statement is correct?



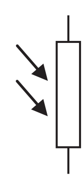
A 1 is a diode, 2 is an ohmic resistor with a larger resistance, 3 is a light globe, 4 is an ohmic resistor with smaller resistance.

B 1 is a diode, 2 is an ohmic resistor with a smaller resistance, 3 is a light globe, 4 is an ohmic resistor with a larger resistance.

C 1 is a light globe, 2 is an ohmic resistor with a smaller resistance, 3 is a diode, 4 is an ohmic resistor with large resistance.

D 1 is a diode, 2 is a light globe, 3 is an ohmic resistor with a smaller resistance, 4 is an ohmic resistor with large resistance.

2 Which of these components is represented by this symbol?



A LED
B resistor
C thermistor
D LDR

3 Which of these components is most likely to be used in a potential divider control circuit that turns on a security light at dusk?

A LED
B battery
C thermistor
D LDR

4 Which of these components is most likely to be used in a potential divider control circuit that turns on an air conditioner when the temperature reaches 27°C?

A LED
B battery
C thermistor
D LDR

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5 Which of these components is most likely to be used in a potential divider circuit that counts tins of tomatoes passing on a conveyor belt?

A LED
B resistor
C thermistor
D LDR

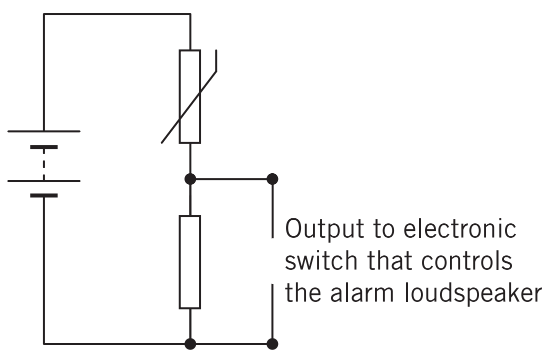
Short-answer questions

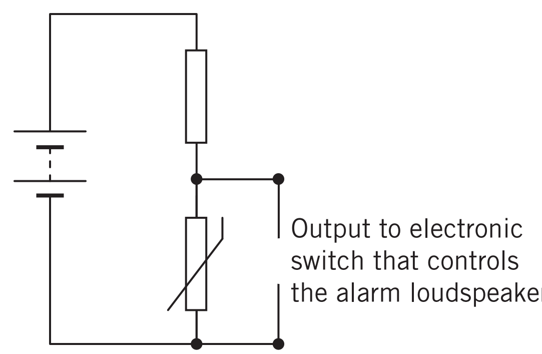
6 Give two similarities and one difference between a diode and an LED.

7 Complete the following scenario by filling in the gaps to indicate changes (increase or decrease).

A thermistor is used in a building to assist in detecting fires and triggering the alarm. As the fire starts, the temperature ____a____, so the resistance of the thermistor ____b____ This allows a ____c____ in potential difference to control a loudspeaker (fire alarm circuit).

8 Which of the following circuits will turn on the alarm when the temperature increases, and which will turn on the alarm when temperature decreases? Explain your reasoning for how each circuit behaves when the temperature changes. (Hint: the alarm will sound when there's sufficient change in potential difference across it to change a switch.)





How could you adjust the circuits above to enable variation in the temperature at which the alarm sounds?

9 When the sun sets, a light comes on outside the front door of a house.

a Design a circuit to make this occur, using an LDR, a potential divider and an electronic switch for a spotlight across V_{out}.

b Why is this more useful than a security light on a timer?

10 Design a circuit to turn on the switch for a pool pump when the sun shines. Hint: connect the switch for the pump across V_{out}.

11 Design a circuit to turn on the 'ready' LED light on a coffee machine when the correct temperature is reached in the ceramic heater block.

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6B Electricity at home

Study Design:
- Model household (AC) electrical systems as simple direct current (DC) circuits
- Model household electricity connections as a simple DC circuit comprising fuses, switches, circuit breakers, loads and earth
- Apply concepts of charge (Q), electric current (I), potential difference (V), energy (E) and power (P), in electric circuits
- Apply the kilowatt-hour (kW h) as a unit of energy
- Compare power transfers in series and parallel circuits
- Explain why the circuits in homes are mostly parallel circuits

Glossary:
Kilowatt-hour (kW h)

ENGAGE

Electric vehicles

Until recently, the biggest consumer of electricity in the home, as well as the most expensive electrical equipment in most homes, was heating and air conditioning systems. That is changing rapidly as more and more families now have an electric vehicle (EV) as their most expensive (if not most power-hungry) electrical device, requiring a charging station hooked up to the main electricity supply to be installed in the garage.

EVs store energy in batteries that power electric motors to drive the wheels rather than burning liquid fuels in internal combustion engines. For about 130 years, the internal combustion engine has been the unrivalled source of power for road vehicles. It is only since about 2015 that EVs have started to challenge that domination. In Norway, for example, EVs made up 65% of new car sales in 2021 (85% in January 2022 due to changed tax rates), and in the UK new petrol and diesel passenger vehicles will not be sold after 2030.

It may surprise you to know therefore that the concept of vehicles using electricity to power their movement is actually a slightly older technology than fossil fuels. The first electric motors and internal combustion engines appeared in the early 1800s but were not applied to road vehicles until later. Then, the first battery-powered electric cars appeared in the early 1880s, while the first internal combustion engine-powered car only appeared in the late 1880s.

Subsequently, the low cost of liquid fuel, the ease of distributing it and the greater distance travelled on a tank of fuel for combustion-powered cars led to their complete dominance on the roads during the twentieth century. Batteries were too heavy and expensive, and their lower energy capacity (therefore short range) and the lack of battery recharging points confined EVs to a footnote in history for more than a century.

What changed in the last decade to make EVs so popular that sales of new EVs around the world are predicted to overtake the sale of combustion engine vehicles by 2030? First battery technology has improved and become cheaper, while the cost of oil-based fuel has steadily risen. Lithium-ion batteries store more energy, have faster battery charging speeds and are much lighter than the previous alternative – lead–acid batteries.

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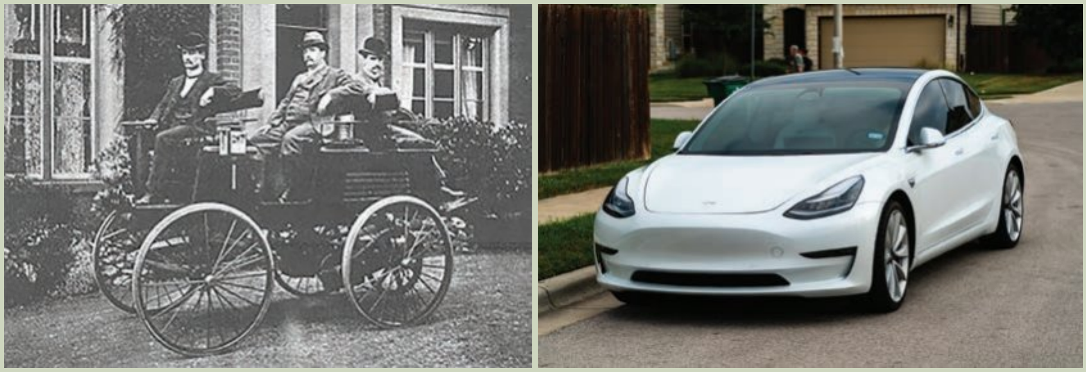

Figure 6B–1 A passenger-carrying electric car developed by Thomas Parker, photographed in 1895 (left) and a 2020 Tesla Model 3 electric car (right)

Second, public opinion has increasingly favoured the reduction of greenhouse gases and other pollutants produced by combustion engine vehicles so, even though EVs cost more, consumers are willing to pay the extra. Third, governments and local authorities have encouraged the provision of more recharging points as part of a policy to reduce greenhouse gas emissions.

An example of an EV that has achieved mass production and increasing consumer demand is the Tesla Model 3. Launched in the middle of 2017, the Model 3 became the first EV to surpass one million sales globally in June 2021. Other major car makers have all commited to produce more EV models by 2025 and to gradually phase out internal combustion vehicles by 2035.

Our use of electricity has developed in the last 40 years, and more changes are planned for the next 10 years. Household electrical systems will need to be adapted to suit the new energy environment. In Victoria we already have smart meters, which can account for production from solar panels and can be read remotely. Infrastructure for EV charging and/or batteries that can run a house and store solar output will be key to the electrical revolution taking place. The basics of how homes are wired and made safe, however, are unlikely to change in the near future.

EXPLAIN

Circuits at home (or series versus parallel)

The focus of this section is the analysis of electrical circuits commonly found in the home. Typical appliances are included, to demonstrate how to investigate the way they work. Some features of house wiring are included too, since an understanding of how mains electricity is distributed around a house contributes to its safe use.

NOTE

Safety note: any investigation of mains-operated appliances or domestic installations should be carried out only under strict supervision. An appliance should never be opened up for study until its mains plug and cord have been permanently removed. Mains fittings should never, under any circumstances, be tampered with. An electrician's licence is required to work on mains circuits and appliances connected to the mains. Work carried out by unlicensed people could cause fires, malfunctioning of appliances or personal injury.

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Features of mains electrical circuits

All mains electrical circuits have the following in common:

- a source of EMF (potential difference) such as the mains supply (230 V AC)
- a form of protection against excessive currents (e.g. a fuse or circuit breaker)
- a form of control (e.g. a switch)
- the load, which converts electrical energy to some other form of energy (e.g. a bulb or motor)
- low-resistance cables to join the parts together (Figure 6B–2).

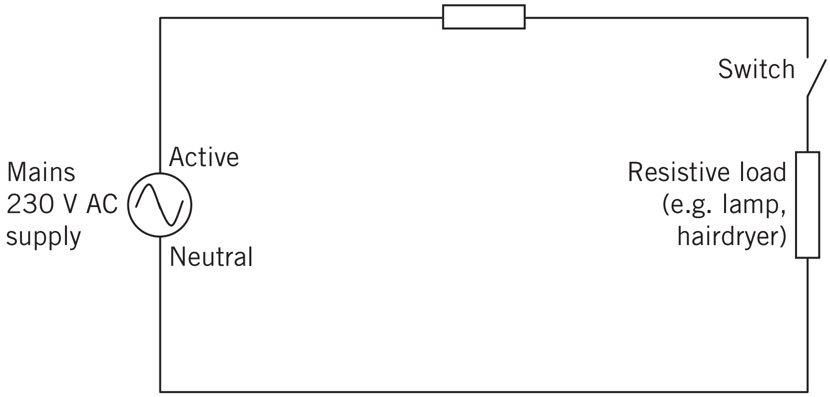


Figure 6B–2 Simplified circuit diagram for household appliances that do not require an earth connection

Most of the mains voltage appears across the load. Because the connecting wires and fuses are of low resistance, the potential dropped across them may only amount to about 1 V.

Circuits are made up of combinations of series and parallel connections, so it is important to be able to identify each in a circuit diagram.

Mains supply is AC (alternating current) in which the current and potential difference oscillate backwards and forwards 50 times per second (Figure 6B–3 top). This can be modelled as a DC circuit of the type considered in Chapter 5. Instead of a power supply with + and – terminals, there is an active and a neutral wire, the significance of which will be covered in Section 6C, along with other safety devices, including the earth wire.

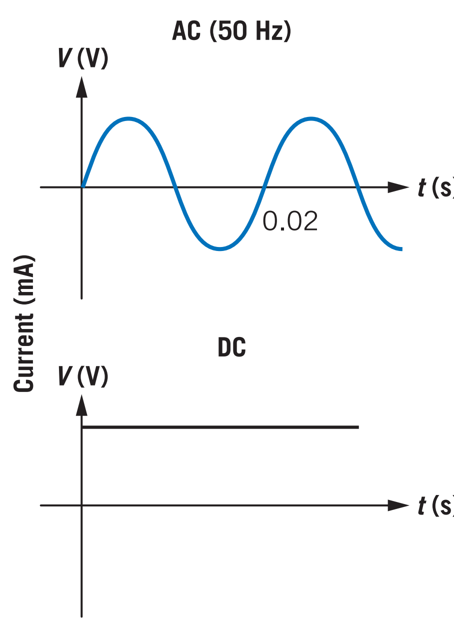
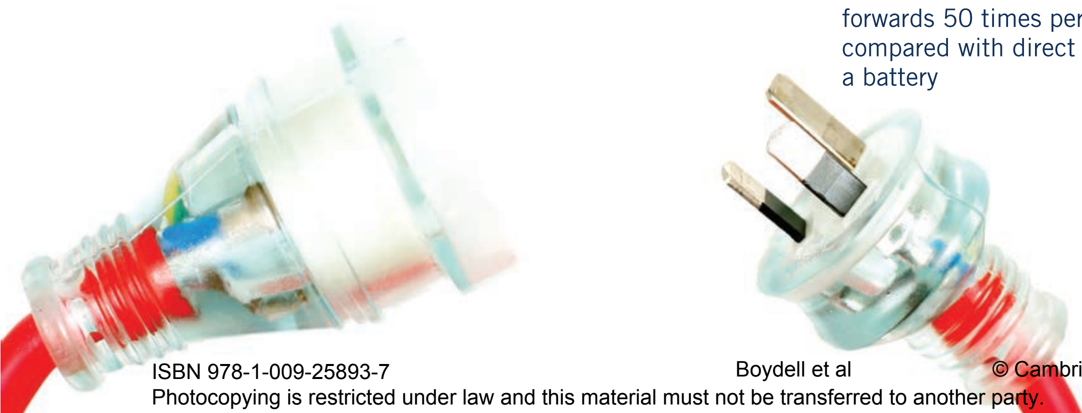


Figure 6B–3 Alternating current (AC) in which the current and potential difference oscillate backwards and forwards 50 times per second, compared with direct current (DC) from a battery

LINK CHAPTER 5

LINK 6C ELECTRICAL SAFETY



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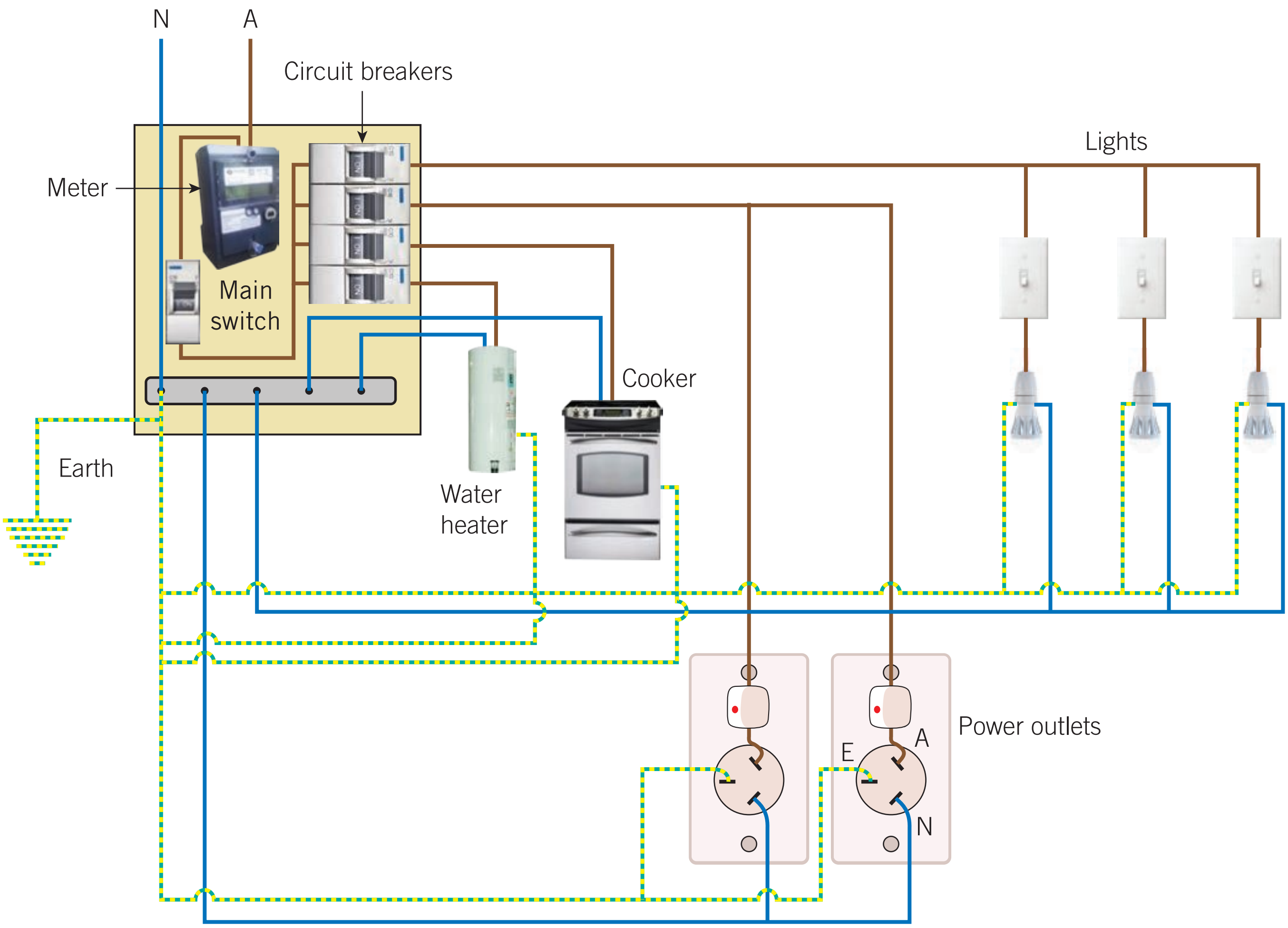

Figure 6B–4 A simple schematic house wiring diagram, with the mains supply connecting at the top. It is usual to have lights, power outlets, cooker and water heater on separate circuits. (There may also be separate circuits not shown here for heavy consumers of power such as heating systems, air conditioning units, heat pumps or pool pumps.) Trace the circuit for each appliance, starting at the brown active wire (A). Neutral (N) wires are blue, and earth (E) wires are green with a yellow stripe. Each appliance is in parallel with all the others, meaning they each have a potential difference of close to 230 V across them, and receive the correct current to run at their given power rating.

More series and parallel circuits

When the electricity supply enters a house, it first passes through the meter. Since the meter must measure the total energy consumption, all the current flowing into the house must pass through it. The meter is, therefore, connected in series with the active (live) wire of the supply. A mains switch, also in series in the active wire, is added here so that the electrical supply to the whole house may be cut off for repairs and maintenance or in an emergency.

The supply divides into separate circuits, corresponding to discrete areas of the house, and is further divided into power and lighting circuits. Every power point and light fitting must deliver the full mains potential difference, so the separate circuits are in parallel with one another.

6C ELECTRICL SAFETY LINK

To protect the circuits from excessive current loading, each has its own circuit breaker (or fuse in older houses). These safety devices are covered in Section 6C. They automatically cut the circuit when excessive current flows, isolating each circuit from the others. The circuit breakers and switch are wired in series in the active wire for each circuit.

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In each room, power points are wired in parallel with one another, so that each can deliver the full mains voltage. A parallel connection is also used for lights within a room (Figure 6B–5).

Light fittings are connected with a switch in series with the active wire. Note that the neutral and earth wires loop into the switch on their way to the light fitting. While most light fixtures do not require an earth, because they have no exposed metal parts (they are 'double insulated'), an earth wire must be included in the wiring so that a light fixture needing an earth may be installed at a later date.

Several lights in a room may be controlled from one switch. In such a situation, the lights are wired in parallel with one another, with the switch in series with the group of lights (Figure 6B–5). However, in some cases low-voltage bulbs are preferred because of their small size and for safety. Transformers are required to provide this low voltage (see Unit 3).

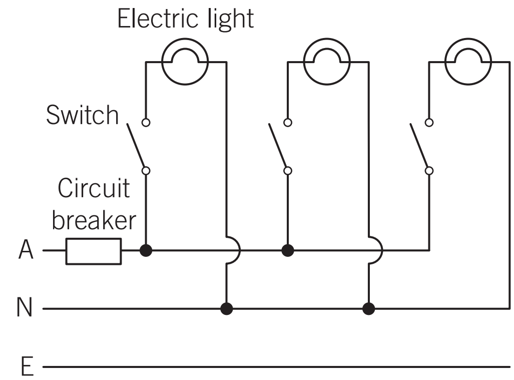

Figure 6B–5 In a normal household circuit, the lights in a room are wired in parallel so they can be switched on and off independently. Each has full mains voltage (230 V).

LINK UNIT 3

Check-in questions – Set 1

1 Recall two advantages of parallel circuits over series circuits and explain how these make it more convenient to wire household lights and power points in parallel.
2 Why are switches and circuit breakers wired in series with their appliances, not parallel?

Measuring the amount of electrical energy used: the kilowatt-hour

Electricity supplied to a house passes through a meter before it can be used. The meter records the amount of electrical energy used. It is read regularly (advanced or 'smart' meters installed in Victoria since 2011 can be read remotely as well as onsite). This provides the electricity supply company with a record of energy consumption from which the cost can be calculated and a bill produced. Smart meters are also able to record a second number, for the usage by storage appliances that use off-peak electricity (since energy used between about 11 p.m. and 5 a.m. is sometimes priced at a lower rate) and other time-of-use tariffs can be easily calculated. Input to the grid from solar panels and home battery storage is also recorded on the smart meter. In most installations of solar panels, the energy produced locally is used in the house if possible, rather than being immediately exported.

Figure 6B–6 Meter box (left) and a 'smart' meter (right) can be read remotely as well as on-site. This meter has a PowerPal attached, which measures the power consumed in real time and relays it via Bluetooth to a phone app, which allows a view of total energy consumption through the day and also an estimate of the cost.

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Kilowatt-hour (kW h)
a unit of electrical energy based on a power of 1 kW running for 1 h, equivalent to 3.6 MJ; used on electricity supply meters and bills

When the consumer buys energy from the supplier, it would be possible to measure consumption in joules, the SI unit of energy, if the power is measured in watts and the time in seconds. However, it is more convenient to measure the consumption of domestic electricity in a unit called the **kilowatt-hour (kW h)** because it is easy to calculate consumption directly from the power rating of each appliance. (All devices for use with the mains supply carry a nameplate which shows the rating of the appliance; how much power it consumes under normal conditions.) The rating of an electric kettle, for example, may be up to 3 kW (3000 W).

The kW h is a unit of energy and it is possible to compare it directly to the SI unit of energy, the joule, as follows:

$$1\text{ kW} = 1000\text{ W} = 1000\text{ J s}^{-1}$$
$$1\text{ h} = 3600\text{ s}$$

Therefore:

$$\begin{aligned}1\text{ kW h} &= 1000\text{ J s}^{-1} \times 3600\text{ s}\\ &= 3\,600\,000\text{ J}\\ &= 3.6\text{ MJ}\end{aligned}$$

Worked example 6B–1 Using kilowatt-hours

a How much energy would an electric kettle with a power rating of 2500 W use in 1 hour? Answer in kW h and in J.

b How much energy (in kW h and J) will the same electric kettle use in 5 minutes?

Solution

a The kettle has a power rating: $P = 2500\text{ W} = 2.5\text{ kW}$

In $t = 1$ hour, the kettle will use energy:

$$\begin{aligned}E &= Pt\\ &= 2.5 \times 1\\ &= 2.5\text{ kW h}\end{aligned}$$

To calculate in J, recall: 1 kW h = 3.6 MJ

Either convert: $2.5 \times 3.6 = 9$ MJ of energy

OR

Use $E = Pt$ with P in watts and t in seconds:

$$P = 2500\text{ W};\quad t = 1\text{ h} \times 60 \times 60\text{ s}$$

$$\begin{aligned}E &= 2500 \times 1 \times 60 \times 60\\ &= 9 \times 10^6\text{ J or 9 MJ}\end{aligned}$$

b The energy used per hour from part **a** is 2.5 kW h.

In 5 minutes, $\frac{5}{60}$ of this energy is used:

$$\begin{aligned}E_{\text{in 5 min}} &= \frac{5}{60} \times 2.5\\ &= 0.21\text{ kW h}\end{aligned}$$

In J, it's the same proportion:

$$\begin{aligned}E &= \frac{5}{60} \times 9 \times 10^6\\ &= 0.75\text{ MJ}\end{aligned}$$

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Check-in questions – Set 2

1 Why are kilowatt-hours the domestic unit of energy instead of joules?
2 Calculate the total energy used when an induction cooktop using 2 kW of power for 10 minutes and a 1500 W heater is on for 2 hours.

Appliance power ratings

Appliances for use with the mains electrical supply all have their power consumption rating (in watts or kilowatts) on a plate, usually underneath or on the back. More obviously, a star rating system is used on every new appliance sold: the more stars, the more efficient the appliance and the cheaper it will be to run.

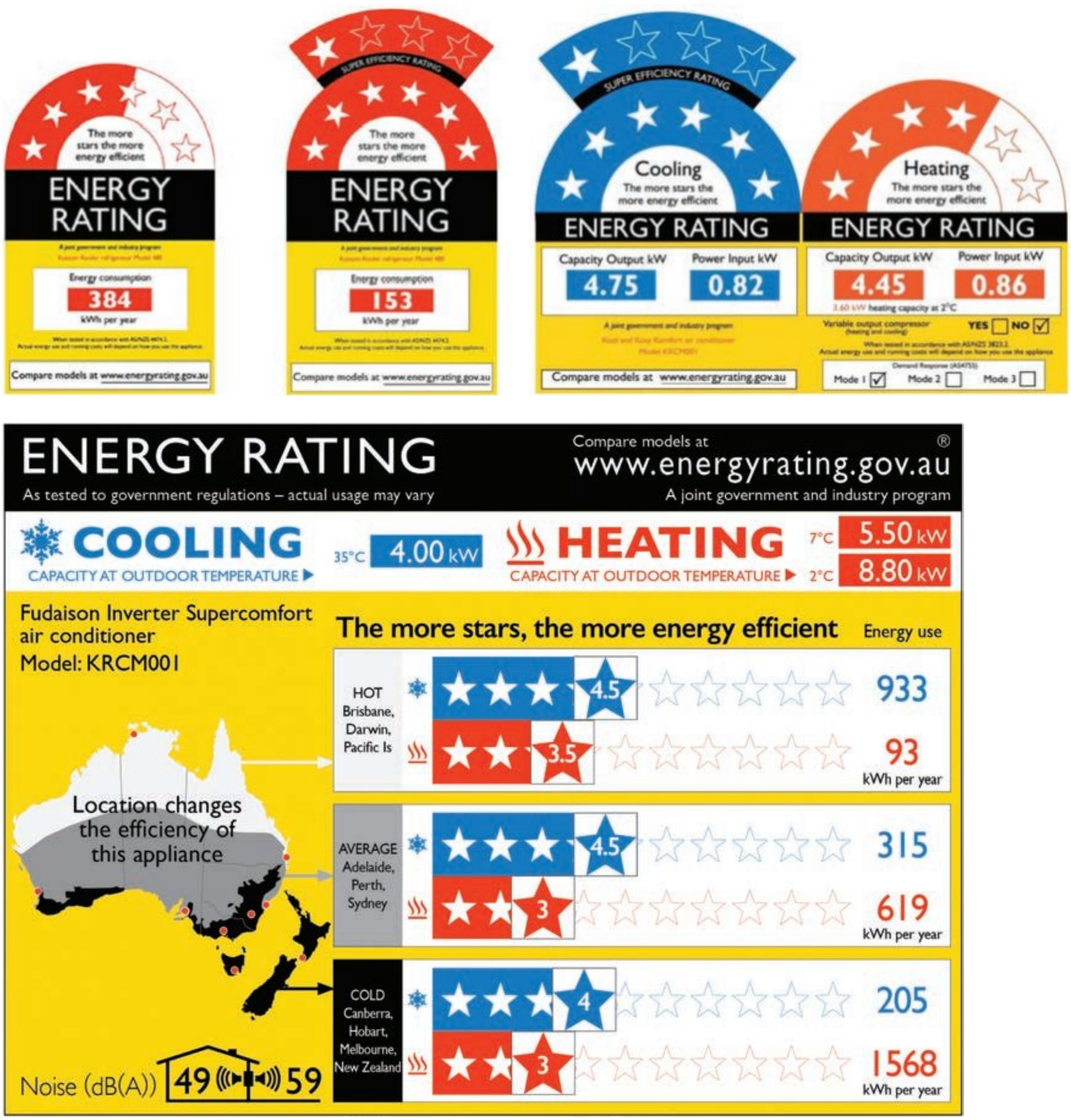

Figure 6B–7 Energy rating labels must meet the Australian standard. You can compare energy efficiency and consumption across a range of appliances and equipment, so you can buy more efficient models, use less energy, save money and reduce greenhouse gas emissions. Air conditioners have a separate rating for each climatic area, because what you need in Darwin is very different from what you need in Melbourne or Hobart. Most of Victoria is in the cold climate zone. The north-western corner is in the mild climate zone. There are also rating systems for gas and water use. In all the star rating systems, the more stars, the better.

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The energy rating label can give you all the information you need to select the most efficient and lowest running cost, but take care to compare the actual figures. A three-star 32-inch TV will use a lot less energy than a 65" TV with five stars.

A typical Australian household spent up to $2000 on electricity in 2021. An estimated breakdown of where energy is used is given in Table 6B–1.

Table 6B–1 Energy usage in Australian households

Appliance type	% of total household electrical energy use	Efficiency – most efficient (cheapest) to run	Energy saving tips
Heating and cooling	40%	Reverse cycle heat pump is the most efficient for heating, as well as cooling. DC ceiling fans are more efficient than others. Space heaters (fan, oil-filled etc.) are the most expensive to run.	Run at the warmest comfortable temperature in summer and coolest comfortable temperature in winter: every 1°C adjustment means a 10% difference in energy consumption
Water heating	23%	Heat pump hot water system is more efficient than gas, especially if run on power from solar panels	Use cold water whenever possible – clothes, dishes, hands, filling the kettle.
Other appliances, e.g. washing machine, clothes dryer, TVs and computers	14%	Be sure to compare similar products and choose the best size for your needs. LCD televisions are far more efficient than plasma televisions. Larger washing machines use more energy even for small washing loads.	Dishwashers are more energy- and water-efficient than hand-washing. Use eco mode, with a full dishwasher. Dry clothes in sunlight.
Fridges and freezers	8%	Bigger units cost more to run due to larger volume to cool. Choose the right size for your needs. An old fridge in the garage could cost $100 or more a year to run.	Adjust temperatures to 3°C (fridge) and –18°C (freezer) for the best balance between food safety and efficiency. Deep freezers use a lot of energy, so may not be worthwhile unless you buy food in bulk.
Lighting	7%	Switching to LED lighting is expensive (although free under a Victorian Government plan in 2022) at the start, but saves a lot of energy.	LED globes running cost is ~10% of that for incandescent globes for the same light output. Halogen globes use nearly double the energy of incandescents.
Cooking	5%	Induction cooktops and microwaves use less energy than a ceramic cooktop or oven.	Boil only the amount of water you need – don't fill the kettle for a single cup.
Standby power	3%	A surprisingly large amount of energy is used when appliances are in standby.	Turn off at the wall when not in use, if possible. This includes phone chargers, appliances with clocks.

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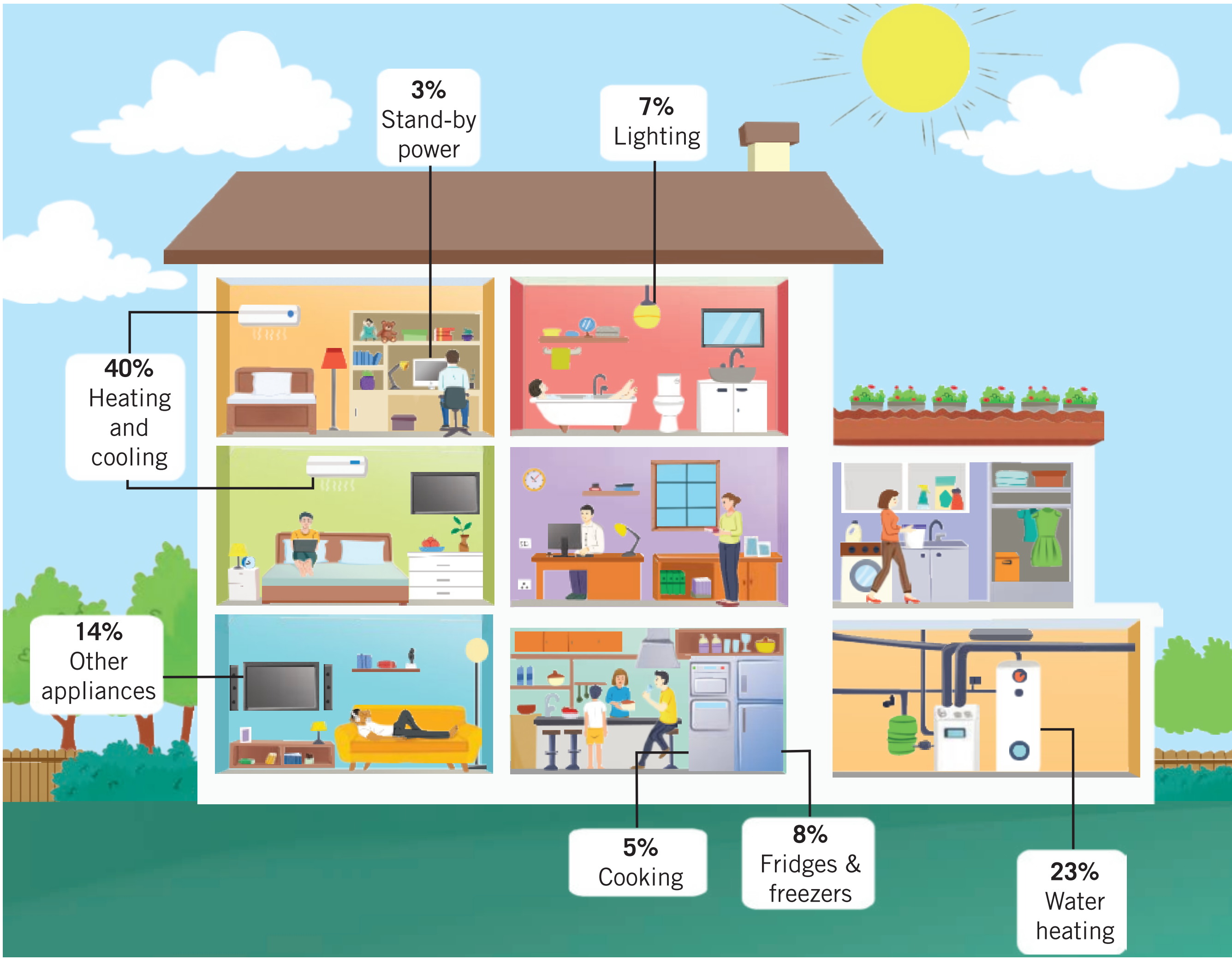

Figure 6B–8 Heating and cooling generally use the most energy in Australian homes, followed by water heating, laundry and entertainment. Food refrigeration and lighting have become more efficient.

Good energy-efficient design, with low-emissivity glass and full wall, floor and ceiling insulation assists with heating and cooling the home efficiently. Not only does this save money, but it also reduces greenhouse emissions from excessive use of electrical energy that may be from non-renewable sources.

There are many devices available to measure the current an appliance draws, either by encircling the power cord, plugging in between the mains and the appliance or even attached to the electricity meter with a Bluetooth readout to a smartphone app. Usually the readout is converted to kW h and shown as energy used.

Many appliances are designed with a standby power mode enabling them to detect remote control devices or to sense movement, when that is used as the cue to activate automatically. Generally, an LED glows constantly to indicate it is in standby and the power is on. Although standby mode and LEDs consume only a small amount of power, over the course of year it may add up to much more than people realise. Figure 6B–9 shows standby and power-on LEDs glowing in a room at night when the lights are off.

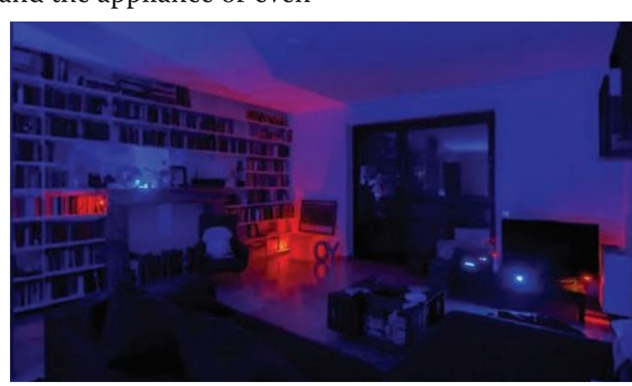

Figure 6B–9 A photo project by Perboni called Stand-by: The Wasted Month, which will highlight the cost of keeping devices on standby instead of switching them off completely.

Power and current rating calculations

It is possible to calculate the current drawn by an appliance using the power equation, $P = VI$, if its normal operating voltage and power are known from its nameplate rating.

Worked example 6B–2 Power consumption in kW h

a A 55-inch 4K television is rated at 80 W. Calculate the current, in mA, that it draws. For ease of calculation, assume the mains supply is 230 V.

b If the same TV is left on standby mode it only draws 2.5 mA of current. Calculate how much power the TV uses when in standby and the energy in kilowatt-hours that the TV will use during a year in standby mode.

Solution

a $P = 80$ W

$V = 240$ V

$I = ?$

Rearrange the equation for power, then substitute:

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

$$= \frac{80}{240}$$

$= 0.333$ A or approximately 330 mA

b Again using the power equation:

$$P = V \times I$$

$$= 240 \times 2.5 \times 10^{-3}$$

$$= 0.6 \text{ W}$$

So, in standby mode, the TV uses 0.6 W (or 6×10^{-4} kW) of power.

To calculate the energy used in a year, use P in kW and convert 1 year to hours:

$E = P$ (in kW) $\times t$ (in h)

$$= 6 \times 10^{-4} \times 1 \times 365 \times 24$$

$= 5.256$ kW h is the energy used by the TV in standby mode for a year.

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Cost of running appliances

To estimate the cost of running an appliance, you first calculate the kW h used, then multiply by the cost of electrical energy per kW h.

Worked example 6B–3 Cost of running appliances

a Using the 55-inch 4K TV from Worked example 6B–2 320, calculate the cost of running the TV for 2 hours in the evening. Assume the electricity costs \$0.30/kW h. Ignore the supply charge.

b Calculate the cost to run the TV for a week if it is on for 2 hours every day. Assume the TV is on standby (as in Worked Example 6B–2) apart from those 2 hours.

c A household battery stores 13.5 kW h of energy. How many days could this power the TV under the conditions in part **b**?

Solution

a $P = 80\text{ W} = 0.08\text{ kW}$

$t = 2$ hours

So,

$$\begin{aligned} E &= P \times t \\ &= 0.08\text{ kW} \times 2 \\ &= 0.16\text{ kW h} \end{aligned}$$

At \$0.30/kW h:

$$\begin{aligned} \text{cost} &= E\text{ (in kW h)} \times \text{price (in \$ per kW h)} \\ &= 0.16 \times 0.30 \\ &= \$0.048 \text{ or } 4.8 \text{ cents} \end{aligned}$$

Note that a shortcut would be:

$$\text{cost} = P\text{ (in kW)} \times t\text{ (in hours)} \times \text{cost (in \$ per kW h)}$$

Notice how the units reduce to \$ when you cancel kW and h:

$$\cancel{\text{kW}} \times \cancel{\text{h}} \times \frac{\$}{\cancel{\text{kW h}}} = \$$$

b For one day:

$$\begin{aligned} \text{cost} &= (\text{energy used in 2 hours 'on'} + \text{energy used in 22 hours 'standby'}) \times \\ &\quad \text{price per kW h} \\ &= (0.16 + 0.6 \times 22) \times 0.30 \\ &= (0.16 + 13.2) \times 0.30 \\ &= 13.36 \times 0.30 \\ &= \$4.008 \approx \$4.01 \text{ per day} \end{aligned}$$

This is a lot to pay for a TV you're not watching!

c The battery can supply $E_{batt} = 13.5$ kW h, and the power used per day (on for 2 hours, standby for 22 hours) $E_{required} = 13.36$ kW h/day, from the calculations in part **b**.

$$\text{time} = \frac{13.5\text{ kW h}}{13.36\text{ kW h/day}} = 1.01 \text{ day or just over 1 day (1 day 14 minutes)}$$

The battery can run the TV (on standby for 22 h and on for 2 h) for 1 day. It would be wise not to leave the TV on standby but to turn it right off! There may also be an issue of the battery not fully returning all the energy that is stored in it, which would shorten the time further.

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ACTIVITY 6B–1 AVERAGE HOUSEHOLD ENERGY USE

Research electrical energy usage in Victoria and find out on average how many units of electricity (kW h) are used in a day by a typical household.

Then answer these questions.

1 Estimate the cost to the household of the electricity consumed. Assume \$0.30/kW h or find out the current price and use that.
2 Discuss ways in which the consumption could be reduced.
3 Is the consumption different on various days of the week?
4 Is the consumption different at various times of the year?

Research how much electrical energy your own household uses and compare this to the average figures. To do this you will need access to recent electricity bills or the energy consumption app, which give the consumption in kW h as well as the cost. Alternatively, record the reading on the electricity meter at home, then again 24 h later. Subtract one reading from the other to find how many kW h of electricity were used that day. Repeat every day for a week. To find the total cost, add in the daily supply charge and other administration fees.

WORKSHEET 6B–1 ELECTRICITY AT HOME

Check-in questions – Set 3

1 Calculate the cost of running an electric jug kettle for 10 minutes, if it has a power rating of 3000 W. Assume the cost of electricity is \$0.30/kW h.
2 Most electric jug kettles will only need to be on for perhaps 2–5 minutes to boil water. How much energy will a 3 kW kettle use if it is on for 5 minutes? What will this cost?

ACTIVITY 6B–2 THE FIRST 'BIG BATTERY' IN VICTORIA

In 2022, the Victorian Big Battery near Geelong was completed. Built next to a substation, with good connections to the national grid, the system charges during the day when electricity from renewable solar and wind energy is cheap. It is able to respond to demand very rapidly ('automatic instant response') to increased demand. It can supply electricity at power 300 MW and store up to 450 MW h of electrical energy.

Research the energy storage capacity of batteries used to power electrical vehicles and households, as well as 'grid-scale' batteries (batteries large enough to supplement the electricity grid for a region). Find answers to these questions.

1 What is the advantage of an electric car using a 100 kW h car battery instead of a 30 kW h battery?
2 What typical storage capacity would be found in a battery to power a household, in kW h? How much power can it supply? Approximately what percentage of the energy put in (for charging) is supplied when discharging (called its efficiency)?

3 What storage capacity is a typical grid connected 'big battery' like the Victorian Big Battery near Geelong? What is it used for?

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6B SKILLS

VIDEO 6B–1
SKILLS: TECHNIQUES FOR SOLVING KW H PROBLEMS

Techniques for solving kW h problems

It is easy to become confused when there are several different units in use for the same quantity. A good technique is to follow these steps.

1. Underline each value given and its unit, and write the symbol for the quantity nearby: *P*, *t*, *E*, $, etc.
2. Write down each useful quantity and the relevant formula for solving the question.
3. Before substituting, convert the quantities into compatible units. For example: hours (× 60 × 60) become seconds for answers in joules, or minutes (÷ 60) to hours for answers in kW h. It's often useful to keep the conversion factors, rather than using a calculator at this point as you may be able to cancel down in the next step, saving time on calculations (and making fewer data-entry errors).
4. Write the equation, and underneath in the next line substitute the quantities and their conversion factors, in the correct units.
5. Cancel wherever possible (but leave your substitutions legible!) and then calculate your answer. Remember to include the correct unit.

Go back to Worked Example 6B–2 to see how these steps apply.

Think ahead when doing these questions and aim to use the simplest method with the fewest calculations, as this will reduce calculator errors. Also, try to get a feel for how big the numbers should be, so you can detect any mistakes in your calculations.

Section 6B questions

Multiple-choice questions

Note that in these calculations, a mains supply at 240 V is used for ease of calculation, even though in Australia the supply is now 230 V (with tolerance +10%, −6%)

1 A fan heater is rated at 2400 W. If it is left on for 5 hours, the energy used would be
  A 1200 kW h. **B** 120 kW h.
  C 12 kW h. **D** 1.2 kW h.

2 What is the current in a 1200 W heater connected to a 240 V mains supply?
  A 0.2 A **B** 5 A
  C 20 A **D** 28 kA

3 A 5 kW water heater takes 3 hours to heat the water it holds. How much will this cost, assuming $0.30/kW h?
  A $0.45 **B** $4.50
  C $45.00 **D** $450.00

4 A 960 W washing machine is connected to a 240 V mains supply in parallel with a 2000 W clothes dryer. The total current drawn when both are operating at the same time is
  A 1.23 A. **B** 4.00 A.
  C 8.33 A. **D** 12.3 A.

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5 The filament globe headlights on a car operate typically at 60 W each and the tail lights at 10 W, while the parking lights usually operate at 5 W each. How long would a 0.32 kW h car battery take to discharge if the lights (all eight of them in parallel) were accidentally left on?
A 1 hour
B 2 hours
C 4.5 hours
D 6 hours

Short-answer questions

6 A 15 W desk lamp made with LEDs is connected to a 240 V mains supply.
a What current does it draw?
b What is the resistance of the lamp?
c How much energy, in kW h, does it draw in 45 minutes?
d What is the cost to run this lamp for 45 minutes if the price of electricity is $0.30/kW h?

7 A washing machine is labelled '240 V, 960 W'.
a Find the current when the machine is operating normally.
b What is the resistance in the circuit when the machine is in use?
c How much does a normal cycle wash cost if it takes 90 minutes and the price of electricity is $0.30/kW h?

8 a Calculate the combined resistance of two filament car headlamps, each rated 20 W, running from a 12 V car battery in:
i series
ii parallel.
b What energy is drawn in an hour by the two headlamps in series?
c What energy is drawn in an hour by the parallel combination?
d Which arrangement, series or parallel, would use less energy from the car battery?
e Which arrangement, series or parallel, would provide the most light?

9 A 6.6 kW solar system in Victoria costs around $8000 to install, after government rebates (in 2022). If the household is able to use *all* the power produced by the panels (in preference to drawing from the mains supply), estimate how many years it would take to pay off the cost of the panel installation. Assume that electricity costs $0.25/kW h and that the panels produce on average 20 kW h per day.

10 An electric oil-filled space heater is rated at 3000 kW.
a How many units (kW h) would be consumed by this electric heater operating for 2 h?
b How much would this cost, assuming $0.30/kW h?
c Compare this to the cost of a reverse-cycle heat pump air conditioner operating in heating mode, rated 2.5 kW, which takes 30 minutes to heat the room to the same temperature due to its superior efficiency (CoP (coefficient of performance, a measure of efficiency) 300 compared to CoP 90).

11 a During what part of the day is most electrical energy used in a house?
b Estimate the maximum value of electrical energy used for a typical household.
c When would the energy use be lowest?
d How low might energy use go for a typical household?
e Suggest strategies that could reduce the energy use at peak times?

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6C Electrical safety

Study Design:

- Model household electricity connections as a simple DC circuit comprising fuses, switches, circuit breakers, loads and earth
- Compare the operation of safety devices including fuses, circuit breakers and residual current devices (RCDs)
- Describe the causes, effects and first aid treatment of electric shock and identify the approximate danger thresholds for current and duration

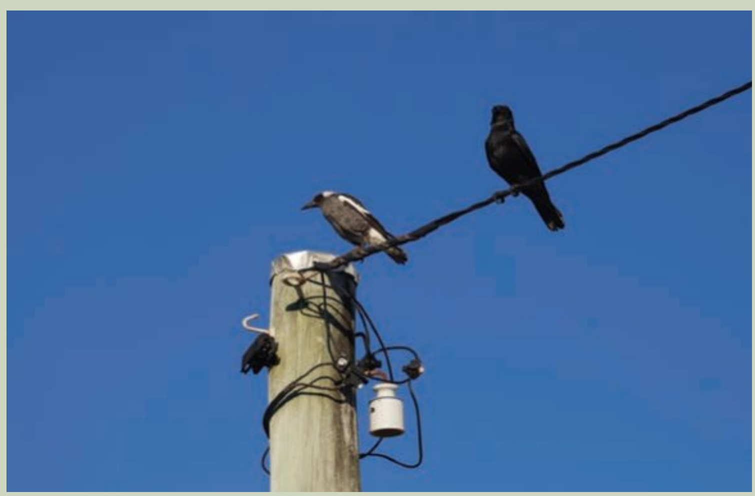
Glossary:

Active
Circuit breaker
Double insulated
Earth
Electromagnetic switch
Fibrillation
Fuse
Neutral
Residual current device (RCD)
Short-circuit
Transformer

ENGAGE

Electrical supply and safety: bird on a wire

We have all seen birds sitting on electricity wires, apparently oblivious to the large energy source their feet are attached to. How is it that birds can do this, but a human can be killed by touching a 230 V socket, especially with wet hands? The clue is in the size of the current that passes through the person or animal, and this in turn depends on both the resistance of the body and the potential difference between the two points of contact (Ohm's law, again!) 'Bug-zappers' have closely-spaced uninsulated wire meshes where a bug can touch both a mesh at one voltage and another mesh at a different voltage, conduct current, and burn. As is often said, it is current that kills, not potential difference.



When a bird is standing on a single-phase power line with both feet, there is a small potential difference between the feet. However, the bird's body is effectively in parallel with the wire of the power line and the resistance of the wire is a lot smaller than that of the bird. So, as in all parallel circuits, the current through the high-resistance bird is a lot smaller than the current in the low-resistance power line.

If the bird is standing on one leg, there isn't a complete circuit so no current at all flows through the bird. But if an unlucky bird touches two wires at once (e.g. with outstretched wings), large currents cause rapid heating and swift death.

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EXPLAIN

Dangers of electricity

Transformer a device that transfers energy via an alternating current (AC) from one circuit to another, usually with an increase or decrease (step-up or -down) in potential difference (voltage)

Power supply authorities use high-voltage transmission lines and **transformers** to distribute electricity efficiently around each state and between states (Figure 6C–1). Transmission voltages may be as high as 500 kV over long distances. For example, from the Snowy Mountains Scheme to Victoria or between Victoria and South Australia or New South Wales, 66 kV lines supply substations, which power groups of suburbs or a whole regional town. However, by the time the electricity is delivered from the street supply to a house, it has been transformed down to the standard supply voltage of 230 V (with a tolerance of −6% and +10%). The reasons for this are explored in detail in Unit 3. For now, note that a higher voltage can cause greater current to flow through anyone who accidentally contacts the high-potential wire while also touching a low potential such as the ground without an insulating barrier in place.

Figure 6C–1 High-voltage transmission lines carry electricity to where it is needed around Victoria and interstate. Transmission can be at 66 kV or up to 500 kV.

VIDEO 6C–1 ELECTRICAL SAFETY

The mains supply presents a potential hazard to life, since a relatively small current passing through the human body can be deadly. Anyone using electricity should be aware of the dangers associated with it, and electrical installation should be carried out only by qualified electricians. People are injured or die every year because of carelessness, negligence or sheer bad luck. With care and common sense, many of these unfortunate incidents could be avoided.

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Effects of electric shock

Potential differences as low as 32 V AC or 115 V DC can cause dangerous currents through the body. There are several identifiable levels of electric shock, as shown in Table 6C–1.

Table 6C–1 The effects of mains electricity (230 V, 50 Hz, AC, 0.5 s) on the human body

Current	Effect on the body
1 mA	Able to be felt
3 mA	Easily felt
10 mA	Painful
16 mA	Maximum current an average person can grasp and 'let go'
20 mA	Respiratory muscles paralysed
50 mA	Severe shock
100 mA	Ventricular fibrillation (heart muscle)
150 mA	Breathing very difficult
200 mA	Death likely
500 mA	Serious burning, breathing stops, death inevitable
15–20 A	Typical current rating for circuit breakers or fuses to disconnect mains

Relatively small currents flowing from one side of the body to the other can be dangerous, depending on the time they flow and the body parts through which they flow. Exposure to electric shock, even for a very short time, can bring about **fibrillation** (rapid and uncontrolled beating of the heart; see Table 6C–1). Fibrillation can starve the brain of oxygen and, in the absence of medical treatment, will cause brain damage and eventually death.

Fibrillation a dangerous state of rapid uncoordinated quivering contractions of heart muscle fibres that fail to pump blood

Table 6C–2 The effect of electric current of 50 mA for various times on the human body (for 230 V 50 Hz mains electricity)

Time of current (ms)	Effects on the body
10–200	Noticeable but usually no dangerous effect
200–400	Significant shock, possibly dangerous
>400	Severe shock, possible death

The size of the current that flows through the body depends on the potential difference of the electricity supply, the path taken by the current and most importantly the skin resistance of the victim. For the average person, resistance between dry hands and arms outstretched is about 100 000 Ω, while the resistance of wet skin is about 1000 Ω. Body tissues below the skin tend to be good conductors due to the presence of water and electrolytes, so skin resistance is the greatest barrier. Insulating shoes can prevent a flow of current to earth. The most dangerous path for current is from one limb to another, across the chest, since this is most likely to affect the heart. The lower the resistance to current flow, the more current will pass through the body and the greater the danger to life. Skin resistance is lower when the skin is wet, or broken by a cut or abrasion, so situations should be avoided in which electricity and water are in close proximity.

First aid for electric high voltage shock

The Australian Government's healthdirect website (https://www.healthdirect.gov.au) provides detailed information on electric shocks and burns, and the following is based on that advice.

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If you are first on the scene of an accident involving an electric shock, there are some basic steps you should take to help the injured person.

1 Assess the scene and call an ambulance on triple zero (000). This is essential if someone has had an electric shock and:
   - they have lost consciousness, even for a second, or
   - they are breathing very fast or very slow, or
   - their heartbeat is very fast, very slow or irregular.

If you do not call an ambulance, the victim should still visit the nearest emergency department or see a doctor as soon as possible, as there may be internal injuries.

2 Look first, don't touch. The person may still be in contact with the source of potential difference, and if you touch them you will also receive an electric shock. Indoors, if possible, turn off the electricity supply at the nearest switch and pull out the plug if the cause of the shock is an appliance. Turn off the mains power if possible. If the supply cannot be turned off, use a wooden broom handle or some other insulating material to lever the casualty away from the source of electricity. Outdoors, keep clear of fallen electricity lines (at least 6 m away) and in the case of a car accident, do not touch the vehicle or occupants if live wires are in contact with the vehicle, until it is declared safe by the electric supply authority. Ask the person not to move.
3 After danger is cleared, check if the person is conscious and breathing. Gently touch and talk to the person. If the person is conscious, reassure them and treat burns with cold running water for at least 20 minutes then cover them with a sterile gauze bandage or a clean cloth. Do not use a blanket, tissue or towel, because loose fibres can stick to the burns.
4 If there is no response, start cardiopulmonary resuscitation (CPR) and continue until the ambulance arrives. Use other bystanders to assist you.

In the emergency department at the hospital, doctors will run tests to check the heart or damage to the soft tissue of the body. They may use pain relief medication. Most people with an electric shock or burn will be able to go home, unless they have heart damage that needs to be treated in hospital. The most common complication of an electrical injury is infection. Some people may have damage to the brain, which can cause seizures, depression, anxiety or personality changes.

Avoiding electric shock

Common causes of electric shock are:
- exposed electrical wires
- water on electrical appliances
- cutting through a live cable; for example, while using a power tool or lawnmower
- old wiring
- faulty appliances.

Electric shocks are occasionally caused by lightning. Do not shelter under trees in a thunder storm. Seek shelter inside, or lie flat on the ground.

You can ensure electrical safety in the home by having safety switches (circuit breakers and RCDs) installed and making sure they are tested regularly. This is a legal requirement for rental properties in Victoria from March 2023. Always use a licensed electrician for electrical work and make sure you have any damaged power points or switches repaired. Never use a power tool, appliance or lead that you know is faulty or has a frayed cord. Make sure no electrical appliances are used in wet areas or near pools.

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Check-in questions – Set 1

1 Consider the information in Table 6C–1. What is the significance of a 10–20 mA current on the human body, compared with 1–10 mA?

2 When administering first aid for an electric shock, why is it important to 'look first, don't touch'?

Active
the 'live' wire in an AC supply; carries potential difference (often called voltage); coloured brown by internationally accepted convention

Neutral
the blue wire in an AC circuit that completes the circuit, providing a close to zero potential for current to flow

Earth
the wire or connection that provides a low resistance path for current to flow into the ground. It is the third wire in a plug or socket, usually green and yellow striped, and is attached to the external metal casing of an appliance for safety.

Domestic connections to mains power

Mains electricity is AC, not DC. The terms 'positive' and 'negative' are not used for AC as they are only relevant for a DC source, such as a battery. The two wires supplying mains electricity are known instead as **active** and **neutral**, and form two of the connections made to a power point. Anything connected to the active wire is 'live' and is particularly dangerous as it carries the potential difference. The third connection to a power point is the **earth** wire, which is connected via a thick cable to an earth stake or electrode driven into the ground. In most cases, the neutral and earth wires are linked together at each consumer's fuse box. The earth wire and the earthed neutral both contribute to the overall safety of the electrical installation. If the active wire accidentally contacts the casing, a large current flows through the low resistance path to earth, causing the circuit breaker to trip and disconnect the active. The earth is taken to be zero electrical potential, as current will flow to it from a positive terminal and from earth to a negative terminal.

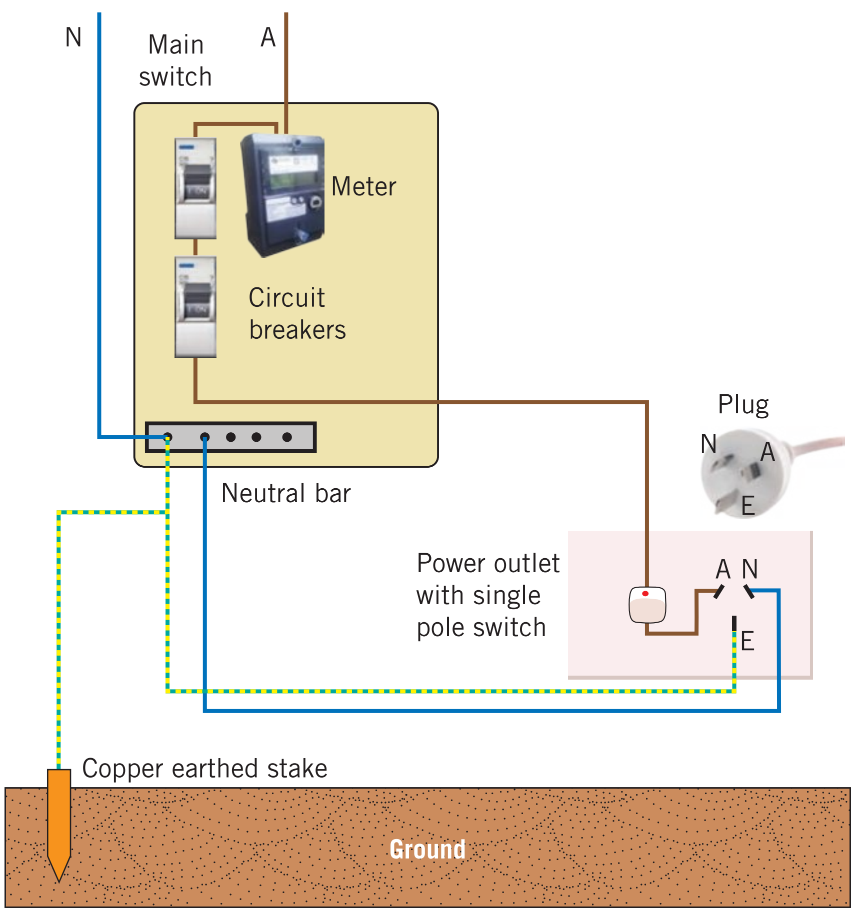

Figure 6C–2 The mains electricity (230 V, 50 Hz) enters the house via the meter and main switch and circuit breaker box. This diagram shows a typical installation for a single power outlet and the way the active, neutral and earth wires are connected to it. Note that the neutral bar is connected to the earthed stake to ensure that the neutral potential difference does not become large. The plug for any appliance with an earth connection has corresponding pins for active, neutral and earth.

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Fuses and circuit breakers

There are several features of a mains installation that contribute to safety.

Short-circuit
an accidental connection in a circuit or an appliance in which a conductor is placed across a potential difference so that an excessive current flows, possibly causing dangerous heating or electric shock

Fuse
a piece of thin wire that acts as a safety device in a circuit by melting when too much current is passed through it, disconnecting the active wire from the circuit and preventing further damage

If a fault occurs in an electrical appliance, a **short-circuit** may develop, causing a very large current to flow. For example, a knife blade may disrupt the fine wires inside a toaster, causing a short circuit. The heating effect of this current can be enough to cause overheating in an appliance or the wall plaster, possibly leading to a fire. To guard against this danger, a fuse or circuit breaker is wired in series with the active wire in each household circuit, as well as in some appliances. A **fuse** is a piece of thin wire, which may be inside a tube, that can conduct a certain amount of current without being affected. If an excessive current flows as a result of a short-circuit, for example, the fuse wire overheats and melts, disconnecting the active wire from the circuit and preventing further damage. The 'blown' fuse is reset after the fault is corrected by replacing the fuse with a new one if it's in the appliance, or in the fuse box the melted wire is replaced with a new length.

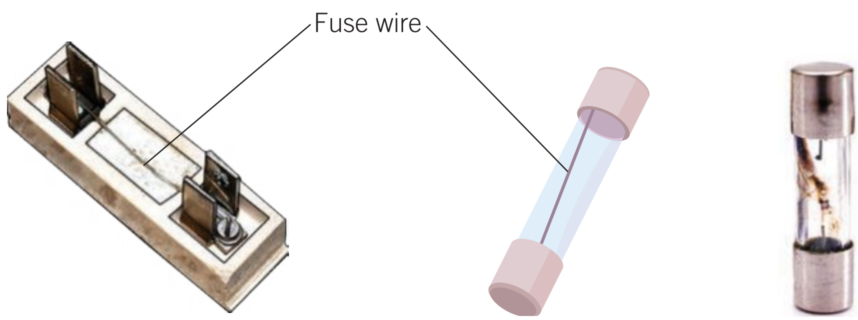

Figure 6C–3 Old-style wire fuses. Left: This type can still be seen in electrical fuse boxes of old houses. The ends of the wire are wrapped around screws to attach it to metal terminals fixed to a non-conducting bar, which is then plugged into a recess in the fuse box so the wire is not exposed. Centre: In this type of fuse, the wire is encased in a glass tube and attached to the metal ends, which fit into metal clips in the circuit. This type is found in some appliances and in cars. Right: a blown fuse. The wire has melted and scorched the inside of the glass tube. It must be replaced by one of the correct rating.

Circuit breaker
a type of automatic switch in which a large current creates an electromagnet, which trips the switch and cuts the supply. It can be turned back on manually after a fault is corrected, without needing to be replaced like a fuse.

Electromagnetic switch
a switch that uses a magnetic field created by an electric current flowing through a coil of wire to move the switch toggle. Unlike a permanent magnet, the magnetic field will cease when the current stops.

In new houses, **circuit breakers** are used instead of fuses. A circuit breaker is an **electromagnetic switch** that automatically turns off when an abnormally high current flows due to a fault in the circuit. It is reset, once the fault is corrected, by moving the switch fully off and then back to the 'on' position. If a circuit breaker continually flips, all appliances connected to the circuit should be disconnected and then tested one at a time to find the faulty one, which should then be repaired or replaced.

Figure 6C–4 A single circuit breaker – for one circuit. A small house or apartment will have six or more of these installed in its circuit breaker box.

Earthing

Many electrical appliances have metal parts. It is possible for a fault to occur that brings an active wire into contact with the metal, so that the metal is 'live' and if touched could lead to an electric shock. Because of this danger, all exposed metal parts in an appliance are 'earthed'. This means they are connected to the earth wire of

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the mains supply. In the event of the metal parts becoming live due to a fault, current will flow harmlessly into the ground (via the earth wire) instead of through the user. Because the path to earth is through a thick copper wire, it has low resistance so a large current will flow, blowing the fuse or triggering the circuit breaker and leaving the appliance safe to handle. The earth may be considered as both a source and a sink of electrons and is by definition a potential of 0 V. The neutral connection is usually wired to the earth at the switchboard, so the potential of the neutral is always close to zero. Recall that the active potential difference alternates 50 times per second +230V to −230V AC and back to +230 V.

LINK UNIT 3

Residual current devices

A further precaution that can be taken with double-insulated equipment is to place a safety switch between the mains power and the equipment casing. The RCD, or **residual current device** operates by comparing the neutral and active currents. If there is an imbalance, it automatically trips within 30 milliseconds (in a similar way to but faster than a circuit breaker) and turns the power off by disconnecting from the active. If there is greater current in the active compared to the neutral, then current must be leaking from the equipment to earth (e.g. via a person!)

Residual current device (RCD) a device in the switchboard that activates circuit breakers when an imbalance between the active–neutral current is detected, protecting against electrocution

Many houses in Victoria are now fitted with an RCD at the switchboard, and it will be illegal for rental properties to not include this safety device from March 2023. From June 2022, rental providers must tha ensure an electrical safety check of all electrical installations and fittings in the premises is conducted every two years by a licensed electrician.

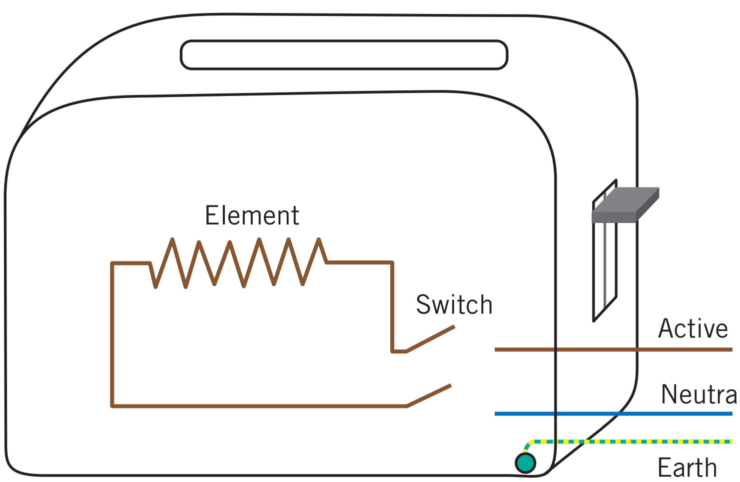

Figure 6C–5 Using a knife to free toast that is stuck can easily dislodge heater wires, which can then connect the active with the case of the toaster. Current enters the body where it comes in contact with the supply, and flows through the lowest resistance path to earth. Don't let that be through your body!

Double insulation

Some appliances are not earthed but instead are **double insulated**. A double-insulated appliance isolates the live parts of the circuit from the user by interposing two separate layers of insulation (the functional insulation and the protective insulation – each rated for 230 V) between the live parts and any external metal. In normal operating situations, both sets of insulation would have to break down to create a hazard. Although this provides a high degree of safety, it is still possible for both sets of insulation to be bypassed; for example, by wetting a drill accidentally with a hose while someone is using it.

Double insulated two layers of insulation are used for added safety, typically on appliances that are not earthed. The layers are placed between the live parts and external metal parts of the appliance.

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Wiring colour code

It is important that mains appliances are connected correctly to the electricity supply. An international colour code has been developed to assist in connecting appliances correctly. The present coding is shown in Figure 6C–6. Older appliances, in which other colour codes were used, may still exist. All mains electrical appliances manufactured in Australia are sold with a moulded plug already fitted to reduce the risk of incorrect wiring of a plug by the user.

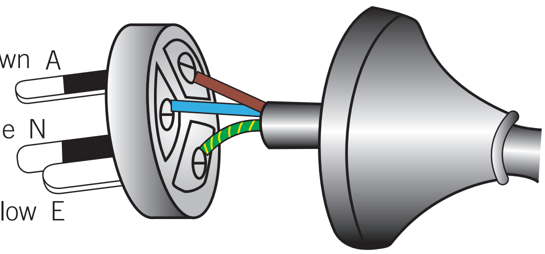

Figure 6C–6 The Australian standard colour coding for electrical wires is brown for active,blue for neutral and green-and-yellow striped for earth. This is also the international code tor electrical wiring. An older version that caused issues for red–blue colour-blind electricians still exists. Note that only a qualified electrician is allowed to connect wiring on mains electrical equipment. Modern electrical plugs cannot be disassembled as shown here; the complete plug body is moulded from one piece of plastic and can't be opened.

WORKSHEET 6C–1 ELECTRICAL SAFETY

Check-in questions – Set 2

1 Which of the three wires in a domestic power socket carries the AC potential difference?
2 What are the other two wires and what is their function?
3 What is the colour code for each of the three wires in an Australian three-pin plug?
4 If an appliance doesn't have an earth pin on its plug, what does this tell you about the structure of the appliance?

VIDEO 6C–2 SKILLS: ELECTRICAL SAFETY CHECK

6C SKILLS

Electrical safety check for appliances in the home

There is a lot of energy associated with mains electricity. Used carefully, this energy provides a comfortable lifestyle, but if safety is ignored it can easily end life. Here are some simple checks to carry out at home. If an appliance fails the check, it should be disposed of or repaired by a qualified person. Do not attempt to repair faulty electrical appliances yourself – only a qualified repair technician or a licensed electrician should repair appliances.

- Discard any appliance that has given anyone a shock or which has overheated or produced fumes.
- Check older appliances for frayed cords, cracked or broken plugs.
- Many old plugs do not have safety barriers between the connections – have them replaced by an electrician with modern plugs or dispose of the appliance.
- All plugs must have insulated active and neutral pins, as shown here.

Insulated pins

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Regulatory compliance mark (RCM)

- All appliances must have a regulatory compliance mark (RCM).
- Do not touch or attempt to repair a loose, cracked or broken power point switch – cover it immediately and arrange for a licensed electrician to replace it.
- Avoid 'piggybacking' adaptors; instead use a power board with a built-in safety device.
- Remove any build-up of materials around the electric motor of exhaust fans, such as fluff, dust and lint.
- Clean the input filters to air conditioners and air filters regularly. This will also help them run more efficiently and prevent overheating of electrical circuits.
- Remove the lint from the filter of tumble dryers every time it is used, as a build-up may cause a fire.
- Clean rangehood filters regularly. Clean ovens and cook tops regularly to prevent the build-up of spilled fats and burned foods.
- Do not spray household cleaners, detergents and insecticides on electrical accessories – they may cause cracking and create an electrical hazard.

Water and electricity do not mix. Follow these simple tips to ensure the safe use of electrical appliances near water.

- Never use any electrical appliance near water.
- Never touch anything electrical with wet hands or bare feet.
- Never leave an electrical appliance where it can fall into the bath or basin.
- Never leave an electrical appliance unattended around children.
- Switch off and unplug all portable electric appliances (e.g. hairdryers, hair straighteners and shavers) after use.
- Do not use portable heaters in bathroom areas – use a strip heater installed high on the wall or a ceiling unit installed by a registered electrical contractor.
- Take extreme care when using electrical appliances near sinks, baths or swimming pools.
- Immediately dispose of an electrical appliance that has been immersed in water.
- Do not use extension leads or power leads in wet areas – unless they are specifically designed for that purpose.
- Wear rubber or plastic-soled shoes when using electrical appliances in laundries, on concrete floors or outdoors – many victims of serious and fatal electrical accidents are barefooted.

Electricity near swimming pools can be lethal

Electric shocks received in the vicinity of a swimming pool are more likely to be fatal than those received in other locations, because bare feet, minimum clothing and wet skin reduce your body's insulation and resistance.

Never use a portable electrical appliance or place an extension cord where it could be splashed or fall into the pool.

Recreation activities near powerlines

Recreation activities, such as sailing, flying a kite or model aeroplane or climbing trees can also be a hazard around powerlines. **Do not fly kites, drones or model aeroplanes anywhere near overhead powerlines.**

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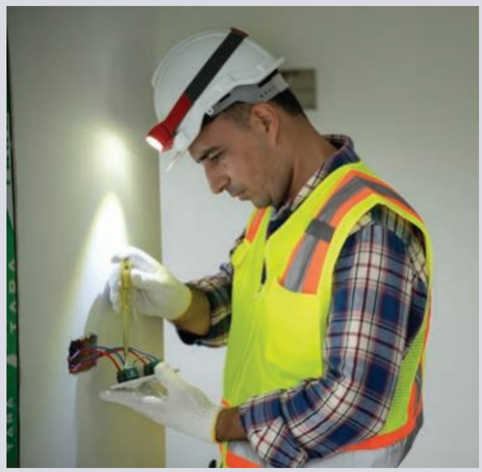
Electrical system maintenance
In addition to taking care when using electricity, regular maintenance is also required. From March 2021 in Victoria, residential rental providers (landlords) must ensure that an electrical safety check of all electrical installations and fittings in the premises is conducted every two years by a licensed electrician. If an electrical safety check has not been conducted within the last two years at the time the renter occupies the premises, the rental provider must arrange an electrical safety check as soon as practicable.

If the safety check shows electrical repairs are needed to make the property safe, the rental provider should employ a licensed electrician to do the repair work.



Section 6C questions

Multiple-choice questions

1 The smallest current that can be felt on the skin is
- A 0.1 mA
- B 0.5 mA
- C 1 mA
- D 3 mA

2 The smallest current that can kill a person if it passes through the heart is about
- A 0.5 mA
- B 5 mA
- C 10 mA
- D 16 mA

3 The reason for an earth wire connecting to the casing of an electrical appliance is to
- A supply extra electrons from the earth to neutralise the current.
- B provide a low-resistance path for high current to flow to earth, tripping the circuit breaker or fuse.
- C provide a high-resistance path to stop the current to flowing to earth.
- D bypass the fuse or circuit breaker.

4 When a large current flows through a fuse, the
- A thin, high-resistance wire melts, breaking the circuit.
- B thin, high-resistance wire melts, creating a short circuit.
- C thick, low-resistance wire melts, breaking the circuit.
- D thick, low-resistance wire melts, creating a short circuit.

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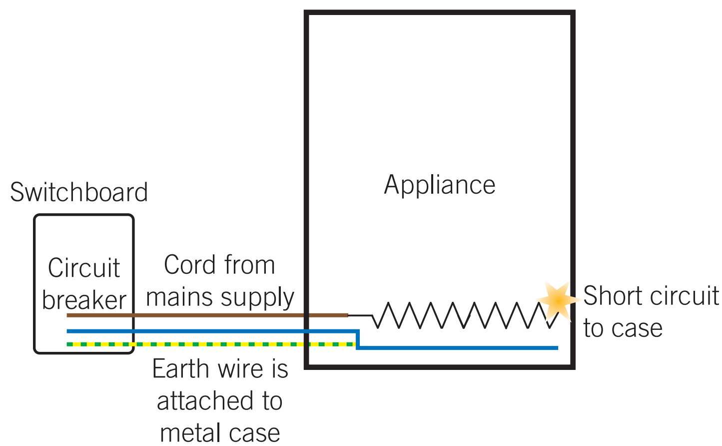
5 In Australia, the switch and the fuse or circuit breaker are always in the
- **A** neutral wire.
- **B** live wire.
- **C** earth wire.
- **D** appliance plug.

Short-answer questions

6 **a** Why was a low voltage, typically 12 V, chosen for use in car electrical circuits?
b What would be the current in your body if you touched the terminals of a 12 V battery and if the contact resistance of dry skin was 100 000 Ω?
c If your skin became wet, and the contact resistance dropped to only 1000 Ω, what would be the current in your body? Is this current potentially dangerous?

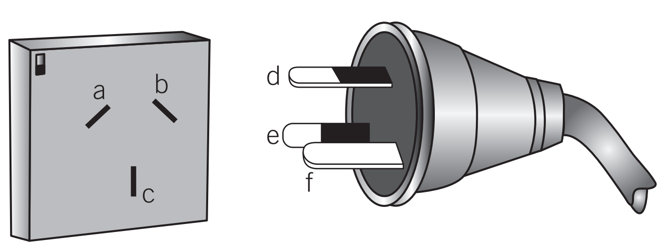
7 If a fault develops in an appliance as shown, explain how the earth wire and the circuit breaker help to prevent injuries. Why must the circuit breaker be in the active wire?



8 A fuse rating is the maximum current that the fuse can carry without melting. Only certain values are available: 3 A, 5 A, 10 A, 13 A. Circuit breakers are also rated in a similar way: 3 A, 10 A, 15 A, 32 A. A vacuum cleaner with a power rating of 720 W is plugged into a mains power point.
a What fuse rating should be on that circuit for the vacuum to operate without blowing the fuse? Explain.
b What circuit breaker rating would be best for the vacuum? Explain.
c What circuit breaker rating would you choose for a lighting circuit with ten 9 W LEDs and a 200 W ceiling fan in parallel?
d What circuit breaker rating would you choose for an induction cooktop circuit that requires 28 A maximum current when all the hotplates are on the boost setting?

9 Explain why it is extremely dangerous to replace thin fuse wire with thicker wire, or with a nail. (This is one of the reasons fuses have been replaced with circuit breakers.)

10 Identify the holes of this electric socket and the pins of the electric plug.



11 State three things you should do before touching someone you fear may have been electrocuted. Explain why it is important to do these first.

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Chapter 6 review

Summary

Create your own set of summary notes for this chapter on paper or in a digital document. A model summary is provided in the Teacher Resources, which can be used to compare with yours.

Checklist

In the Interactive Textbook, the success criteria are linked from the review questions and will be automatically ticked when answers are correct. Alternatively, print or photocopy this page and tick the boxes when you have answered the corresponding questions correctly.

Success criteria – I am now able to:		Linked questions
6A.1	Recognise the way a diode behaves in a circuit and relate this to its I–V characteristic (graph)	11☐
6A.2	Recognise the way an LED behaves in a circuit and relate this to its I–V characteristic (graph); compare this to the characteristic for a diode, and relate it to the uses for each	1☐, 13☐
6A.3	Recognise a variable resistor (or potentiometer) as a long high-resistance wire of which a selected section is used; apply this to use in a volume control or dimmer, or in a circuit where current is to be varied	13☐
6A.4	Recognise the way an LDR behaves in a circuit and relate this to its resistance vs light level graph	3☐, 13☐, 16☐
6A.5	Recognise the way a thermistor behaves in a circuit and relate this to its resistance vs temperature graph	2☐, 12☐,14☐
6A.6	Calculate the potential difference output of a potential divider given the ratio of resistances used and the supply potential difference	12☐, 13☐
6A.7	Predict and analyse the behaviour of potential divider circuits using resistors, LDRs, thermistors, and LEDs; understand some of the uses for these non-ohmic components	12☐, 13☐, 14☐, 16☐
6A.8	Predict and analyse the behaviour of other components in a circuit where variation is created using potentiometers, diodes, LEDs and switches	11☐, 12☐, 16☐
6B.1	Re-draw a picture of a circuit as the equivalent circuit diagram for series, parallel and complex	20☐
6B.2	Identify household electrical systems as mostly parallel circuits, with AC supplied in Australia at 230 V 50 Hz	19☐, 20☐, 22☐
6B.3	Calculate the power and energy supplied to household appliances in a parallel circuit	6☐, 7☐, 19☐, 20☐, 22☐
6B.4	Justify the use of series or parallel circuits for household circuits using the characteristics of each type of circuit	19☐, 20☐, 29☐

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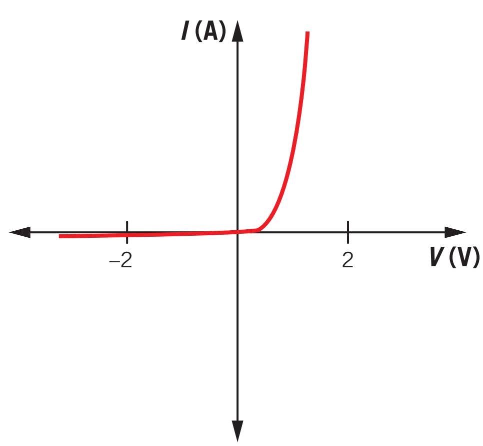
Success criteria – I am now able to:		Linked questions
6B.5	Consider the energy used in a household (and other applications) and apply the kilowatt-hour (kW h) as a unit of energy; for example, as it relates to cost and to battery storage	4☐, 5☐, 15☐, 17☐, 18☐, 20☐, 21☐
6C.1	Describe the causes, effects and first aid treatment of electric shock	27☐, 28☐
6C.2	Identify and recall the approximate danger thresholds for current and duration passing through a human body	24☐
6C.3	Recall that the mains supply in Australia is 230 V 50 Hz; recognise the need for safety devices such as fuses, switches and circuit breakers to make a circuit safe	23☐, 24☐
6C.4	Recognise the Australian standard three-pin plug with active, neutral and earth connections; relate this to a model of an AC circuit compared with DC	28☐
6C.5	Understand the earth connection as a low-resistance path to 0 V, hence as a safety connection; also as a zero of potential; recall the conditions under which double-insulated devices do not require an earth connection	24☐, 26☐
6C.6	Describe the operation of these safety devices in Australia: switch, fuse, circuit breaker, residual current device (RCD)	8☐, 9☐, 10☐, 24☐, 25☐

Multiple-choice questions

1 Consider the following graph.



Which of the following components is most likely to have the *I*–*V* characteristic shown in the graph?

A thermistor
B LED
C LDR
D 5 kΩ ohmic resistor

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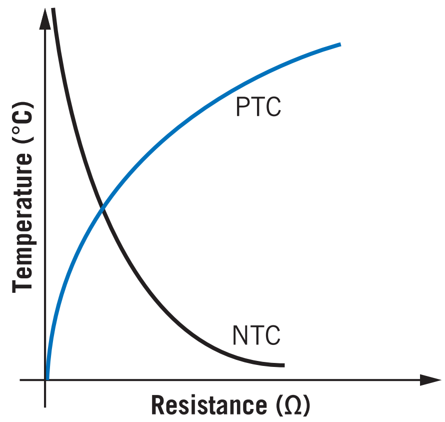
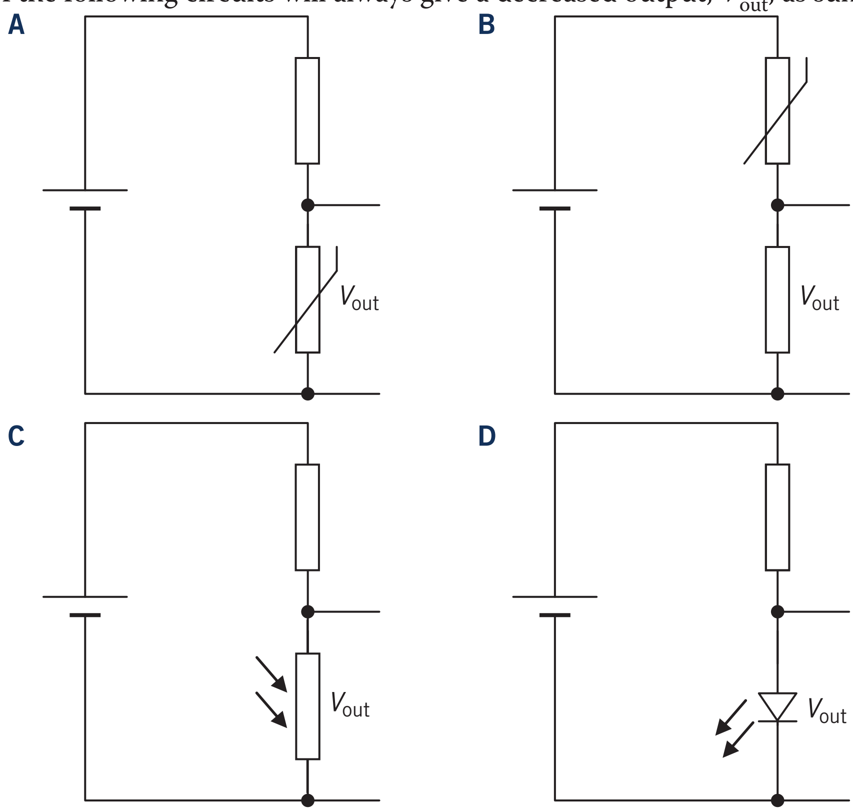
2 Consider the following graphs.



The graphs represent the behaviour of

A two thermistors that increase their resistance as temperature increases.
B two thermistors that decrease their resistance as temperature increases.
C a thermistor that increases its resistance as temperature decreases and another thermistor that increases its resistance as temperature increases.
D LDR that decreases its resistance as temperature decreases and another LDR that decreases its resistance as temperature increases.

3 Which of the following circuits will always give a decreased output, V_{out}, as sunlight falls on it?



4 It takes 5 min to heat water in a 2.5 kW kettle to boiling point. How much does the electricity cost to do this? Assume \$0.30/kW h.

A 62.5 cents
B 15 cents
C 20.8 cents
D \$2.25

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5 Approximately how much would it cost to heat half the amount of water in the kettle in Question 4?

A 30 cents

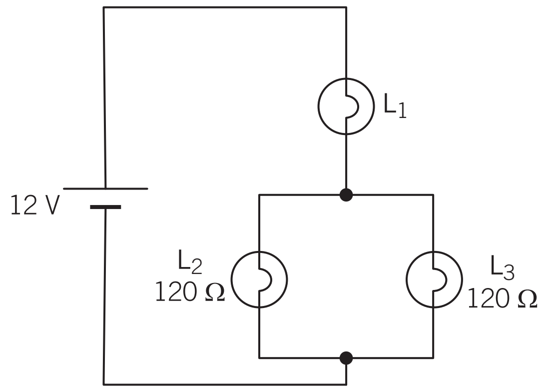
B 60 cents

C 12 cents

D $1.10

Use the following information to answer Questions 6 and 7.

Three light globes are placed in a circuit as shown. L_2 and L_3 are identical but L_1 is different.



6 Calculate the equivalent resistance of the parallel L_2 and L_3 combination.

A 60 Ω

B 90 Ω

C 120 Ω

D 240 Ω

7 In the circuit above, if the current through L_1 is 0.12 A, how much energy is dissipated in lamp L_2 in 10 s?

A 0.432 J

B 4.32 J

C 7.2 J

D 24 J

8 What is the current in a 3000 W heater connected to a 240 V mains supply?

A 1.25 A

B 12.5 A

C 125 A

D 800 A

9 Could two of the same heaters from Question 8 be used safely in a circuit protected by a 15 A circuit breaker?

A yes, if they were in series, but not in parallel or the circuit breaker would trip

B yes, if they were in parallel, but not in series or the circuit breaker would trip

C no, the current would be too large, whether they were in series or parallel

D yes, no problem

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10 In an overseas country, the mains supply is 120 V. Could two of the 3000 W heaters in Question 8 be used safely in a 15 A circuit there?

A yes, no problem

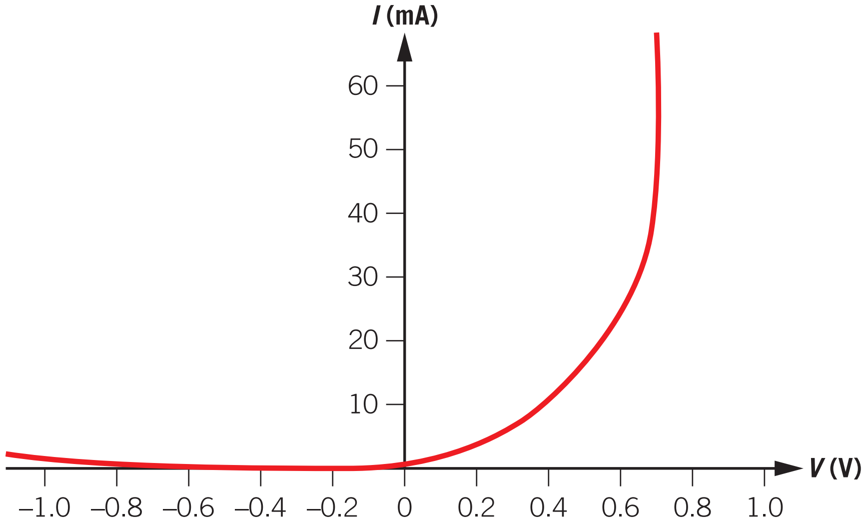
B yes, if they were in series but not in parallel or the circuit breaker would trip

C yes, if they were in parallel but not in series or the circuit breaker would trip

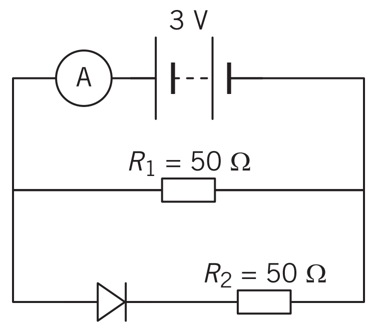
D no, even one heater would draw more than 15 A

Short-answer questions

11 The *I*–*V* characteristic of a particular diode is shown below.



The diode is connected in the circuit as shown.



a Calculate the current through the resistor parallel with the diode, R_1. (1 mark)

b From the graph, what is the potential difference across the diode? (1 mark)

c Calculate the potential difference across the resistor in series with the diode, R_2. (1 mark)

d Calculate the current flowing through the ammeter, A. (1 mark)

12 A thermistor that has a current running through it will be warmed up by the current.

a What energy transformation is taking place in the thermistor? (1 mark)

b If the thermistor is placed in a pipe that has gas flowing through it, the gas flow will cool the thermistor down. The speed of gas flow in the pipe can be measured by the changes of resistance produced. Draw a circuit diagram to model this gas flow meter. (3 marks)

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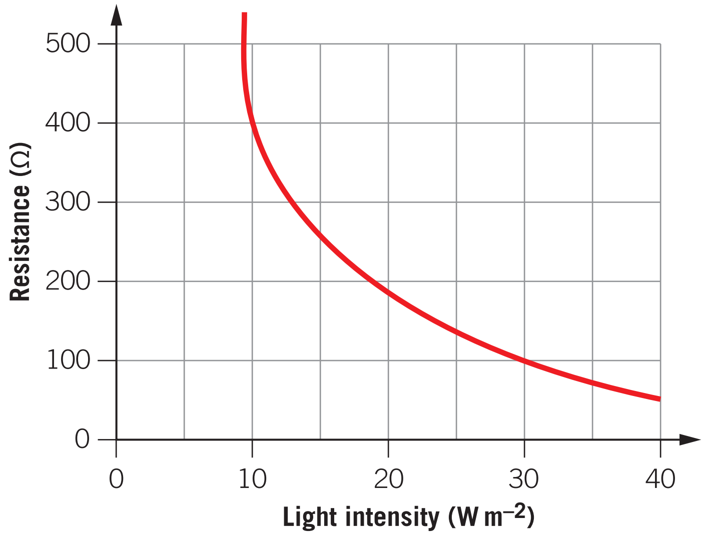
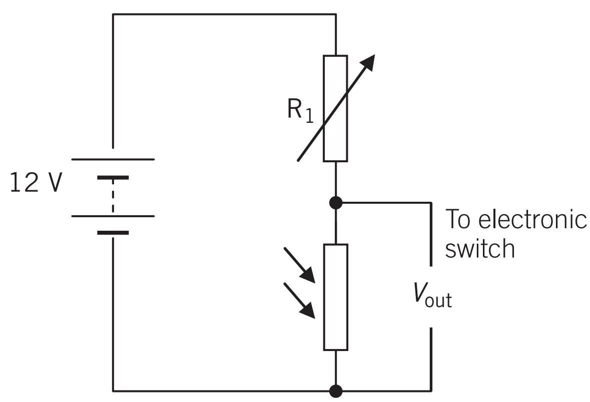
13 The graph of the resistance of an LDR with respect to the light intensity is shown below.



a What is the resistance of the LDR when the light intensity is 10 W m^{-2}? (1 mark)

The LDR is used in the circuit shown to automatically turn on the lights in a classroom when the intensity drops to 30 W m^{-2}.

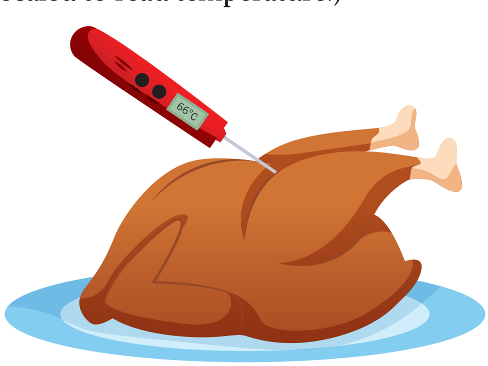


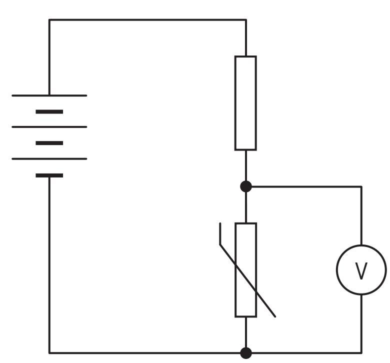
b What is the resistance of the LDR when the light intensity is 30 W m^{-2}? (1 mark)

c What is the value of the variable resistor, R_1, if the required value of V_{out} is 8 V when the light intensity is 30 W m^{-2}? (1 mark)

d Can you anticipate any problems with this circuit, or any adjustment that may need to be made once the lights are on? (2 marks)

14 A digital thermometer can be made using a thermistor (NTC type). What would be the limitation to this thermometer if it worked according to the circuit shown? (The voltmeter can be scaled to read temperature.) (2 marks)





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15 A car battery operates at 12 V.

a How much charge leaves a car battery each second if it supplies current to four headlights in parallel, each of which draws a current of 4 A? (1 mark)

b Extension: If the battery is rated at 40 A h, how long before it runs flat? (Batteries are sometimes rated on how long they can supply current for, in amp-hours, A h, which is similar to power ratings in watt-hours W h or kilowatt-hours kW h.) (1 mark)

16 Design a circuit to sound an alarm inside a reversing car when it approaches the white wall at the end of the garage. Assume an electronic switch will be used to turn on the alarm. (3 marks)

17 A resistive hot water system is rated at 4000 W.

a What current does it draw from the mains supply? (1 mark)

b How much energy, in kW h, does it consume if it heats for 6 hours? (1 mark)

c What would this cost, if it runs on an off-peak tariff of 15 c/kW h? (1 mark)

18 A heat pump hot water system is rated at 900 W.

a What current does it draw from the mains supply? (1 mark)

b How much energy, in kW h, does it consume if it heats for 6 hours? (1 mark)

c What would this cost, if it runs on an off-peak tariff of 15 c/kW h? (1 mark)

d What would this cost, if it runs on solar power produced from the photovoltaic panels installed on the roof? (1 mark)

e It is sometimes useful to calculate the income foregone by using solar electricity that could otherwise have been sold to the grid. If the solar feed-in tariff is 5.20 c/kW h, how much income could have been gained from the electricity used by the

i resistive hot water system in Question 17 (1 mark)

ii heat pump hot water system above. (1 mark)

19 This question concerns a household circuit where several downlights are connected in a kitchen.

a What would happen to the current in the other lamps if one lamp in a series-connected set of kitchen downlights lights burned out? (1 mark)

b After replacing the burned-out light, what would happen to the brightness of each lamp if more lamps were connected in series? (1 mark)

c What would happen to the current in the other lamps if one lamp in a parallel-connected lighting circuit burned out? (1 mark)

d After replacing the burned-out light, what would happen to the brightness of each lamp if more lamps were connected in parallel? (1 mark)

e Which would be cheaper to run, five lights in series or the same five lights in parallel? Explain your reasoning. (1 mark)

f Which would provide the most light: five lights in series or the same five lights in parallel? (1 mark)

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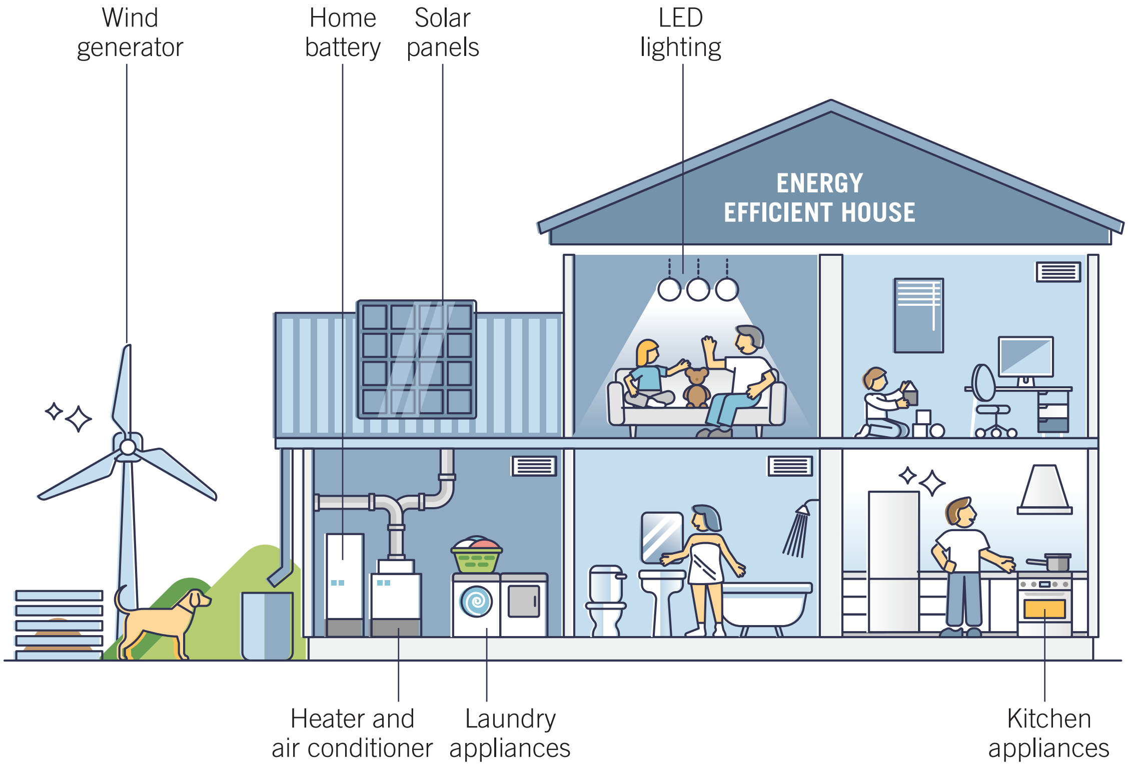
20 The house shown below is in a remote area and has no connection to the mains grid.



A typical 12 V DC installation for such a house uses a rechargeable home battery to supply lighting and some appliances like refrigerators and televisions. The battery can be recharged by a number of methods including solar cells or wind generators. Assume this one can store 20 kW h. Some appliances need a 230 V AC supply that can be generated from the battery with a device called an inverter. A diesel generator may be installed into the same system to supply power when the battery runs down.

a Draw a possible circuit diagram for a 12 V lighting circuit in the house. (3 marks)

b How many 7 W LEDs could be on at the same time if the battery supplies 25 kW? (1 mark)

c The diesel generator supplies 20 kW. How long must it run to resupply the battery from empty? (1 mark)

d If the solar system supplies a maximum of 20 kW, on a sunny day, how long will it take to resupply the battery from empty on a sunny day? (1 mark)

e If the wind generator supplies a maximum of 15 kW, on a windy day, how long will it take to resupply the battery from empty on a windy day? (1 mark)

f Discuss whether it is likely that this household in northern Victoria could manage without using fossil fuel (diesel) for electricity throughout the year. How would this affect their lifestyle, if at all? (2 marks)

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21 A refrigerator does not run continuously because it is controlled by a thermostat. For example, it may be running for a quarter of the time. Estimate how many kW h are used each day by a typical refrigerator that operates at 250 W. (2 marks)

22 Should an iron (1000 W), a clothes dryer (2400 W) and a washing machine (900 W) be operated from the same 15 A power point? Explain your answer. (2 marks)

23 What would happen if:

a a kitchen appliance in the United States, designed for a 120 V mains supply, was connected to the 230 V mains supply in Australia? (1 mark)

b an Australian appliance was used in the United States? (1 mark)

24 Would accidental contact with the live wire in a mains-operated appliance necessarily be fatal? Explain why or why not. (2 marks)

25 How can the danger of electric shock in a home be reduced? List at least three safety measures. (3 marks)

26 **a** Explain how the earth connection to a toaster could save your life if one of the heating wires inside the toaster was broken and short-circuited the control lever. (2 marks)

b A hairdryer also has heating wires inside it, but usually does not require an earth connection. Explain why not. (1 mark)

27 Explain how the first aid procedures for an electric shock patient correspond to the DRS ABC mnemonic (Danger, Response, Send for help, Airway, Breathing, CPR). (6 marks)

28 Design a typical domestic lighting circuit. (4 marks)

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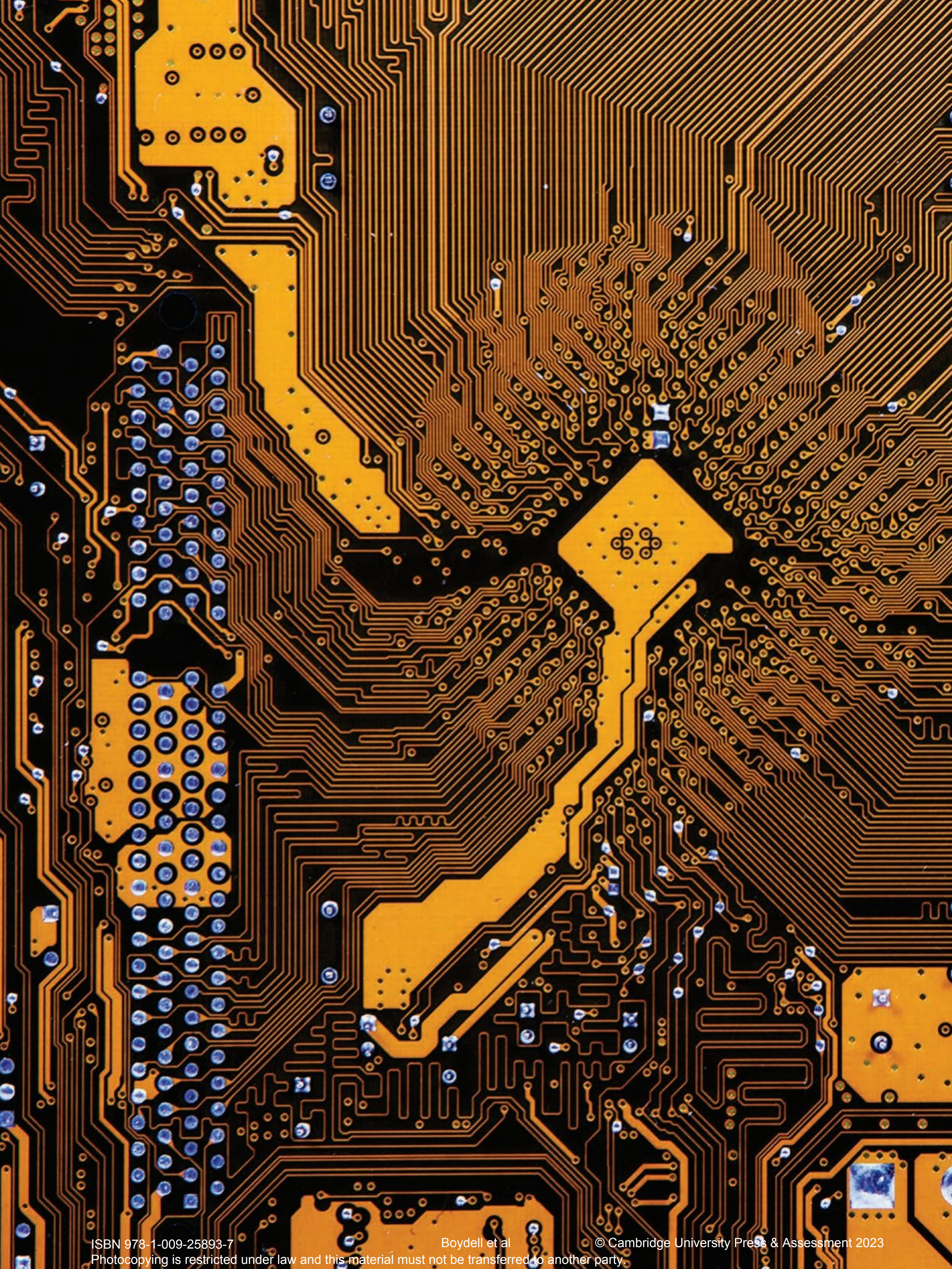

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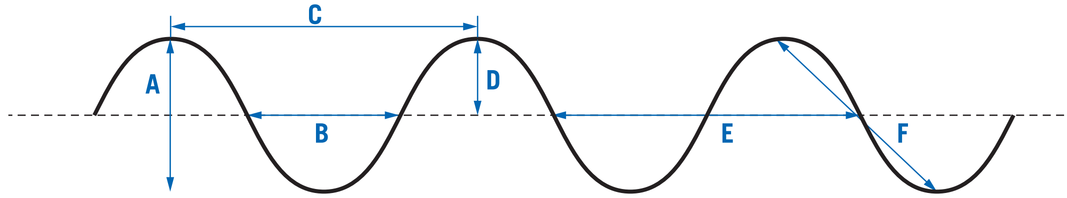
Unit 1 Revision exercise

Multiple-choice questions

1 An example of a travelling wave motion is

A a mass on the end of a spring moving regularly up and down.
B light travelling from the Sun to Earth.
C the motion of a skipping rope.
D a vibrating guitar string.

2 The diagram shows a snapshot of a transverse wave.



Which pair of letters shows the correct labels for the *amplitude* and *wavelength*?

A A and C
B D and B
C F and C
D D and E

3 A blackbody is an object that

A reflects as much black radiation as it receives.
B is a perfect absorber of all wavelengths.
C appears black to all visible wavelengths.
D is any object painted with pure black paint.

4 Earth receives electromagnetic radiation from the Sun and re-radiates electromagnetic radiation back into space. Which of the following statements best describes the key reason for current global warming?

A Greenhouse gases contribute more infrared radiation than other gases.
B The oceans store more thermal energy than the land masses.
C The polar icecaps are melting at an increasing rate.
D The difference between the incoming and outgoing radiation.

5 Isotopes of an element have the same number of

A nucleons.
B neutrons.
C neutrons but a different number of protons.
D protons but a different number of neutrons.

6 An alpha particle is also known as

A an electron.
B a positron.
C a helium nucleus.
D a photon.

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7 A radioactive sample has a half-life of 5.0 minutes. What fraction of the sample is left after 20 minutes?

A $\frac{1}{2}$

B $\frac{1}{4}$

C $\frac{1}{8}$

D $\frac{1}{16}$

8 What is the mass of the products of a nuclear fission reaction compared to the mass of the original nuclei before fission?

A less
B same
C more
D sometimes less and sometimes more

9 Which type of substance is best described as 'a sea of free electrons moving randomly in a lattice of positive nuclei'?

A an insulator
B a metal
C a semiconductor
D a non-metal

10 The potential difference across a resistor, R, is 9.0 V and the current through it is 0.3 A. What is the value of the resistance, *R*?

A 0.03 Ω
B 3.0 Ω
C 30 Ω
D 300 Ω

11 Which of the following is the best component to use in a circuit to control the temperature in a refrigerator?

A LED
B LDR
C thermistor
D potentiometer

12 Which of the following is the component most likely to change its resistance with the intensity of light falling on it?

A LED
B LDR
C thermistor
D potentiometer

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Short-answer questions

13 A TV transmission link operates at a frequency of 56 MHz.

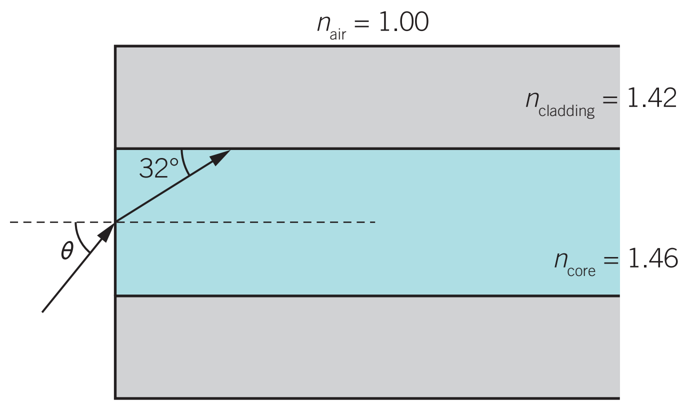
a Calculate the wavelength of this radiation. (1 mark)

b Calculate the period of this radiation. (1 mark)

c State the region of the electromagnetic spectrum that this belongs to. (1 mark)

d Describe the nature of this radiation. (2 marks)

14 The transmission of light within an optical fibre is shown below. The fibre has an inner core of refractive index 1.46 and an outer cladding of refractive index 1.42. A single monochromatic light ray is incident on the core as shown.



a Calculate the angle, θ, at the air–core boundary. (2 marks)

b Will any of the initial light ray be transmitted into the cladding? Explain your answer. (3 marks)

15 100 g of ice at a temperature of 0°C is added to 400 g of water at 25°C in a perfectly insulated container. The mixture is left until all the ice has melted and the water is at a uniform temperature. Take $c_{water} = 4.2\ kJ\,kg^{-1}\,K^{-1}$ and $L_{fusion(water)} = 334\ kJ\,kg^{-1}$.

a Describe the energy transfers that will occur in the ice and the water. (2 marks)

b Calculate the final temperature of the water. (3 marks)

16 Steam burns are known to be potentially far more damaging than hot water burns, even when the water is at 100°C. Suggest why this might be the case. (3 marks)

17 Explain why it is possible to have two different elements with the same number of nucleons. (2 marks)

18 **a** Complete the nuclear transformation equation of magnesium-24.

$^{24}_{12}Mg^* \rightarrow ?$ (1 mark)

b What is the name of the emission? (1 mark)

c What does the asterisk(*) stand for? (1 mark)

19 A patient has a 20 g cancerous tumour, which absorbs 0.004 J of energy from an external cobalt-60 gamma emitter radiotherapy unit. Use a weighting factor of 1.0 for the gamma radiation.

a Calculate the absorbed dose for this tumour. (2 marks)

b Calculate the dose equivalent of the source. (2 marks)

Another patient with advanced prostate cancer has a 60 g cancerous tumour, which absorbs 0.006 J of energy from internally implanted radium-223 alpha emitting pellets.

Use a weighting factor of 20 for the alpha radiation.

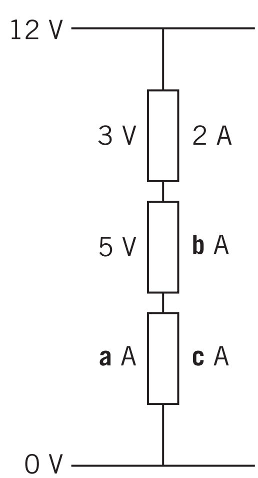
c Calculate the absorbed dose for this tumour. (2 marks)

d Calculate the dose equivalent of the source. (2 marks)

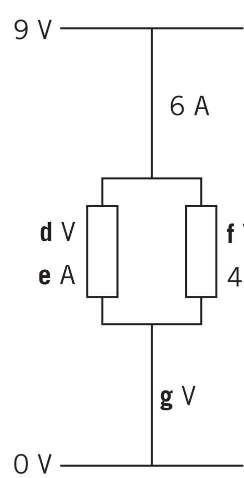
20 The core of a nuclear reactor contains fuel rods, a moderator and control rods. Explain the function of each component. (6 marks)

21 Given the information on each of these four potential divider circuits, find the potential difference or current for the labels **a** to **m**. (13 marks)

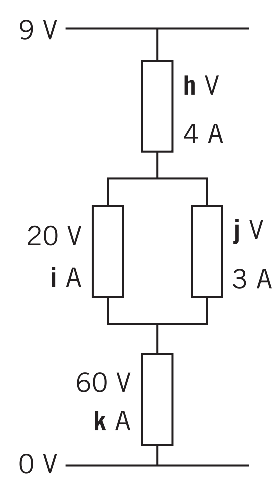
Circuit 1



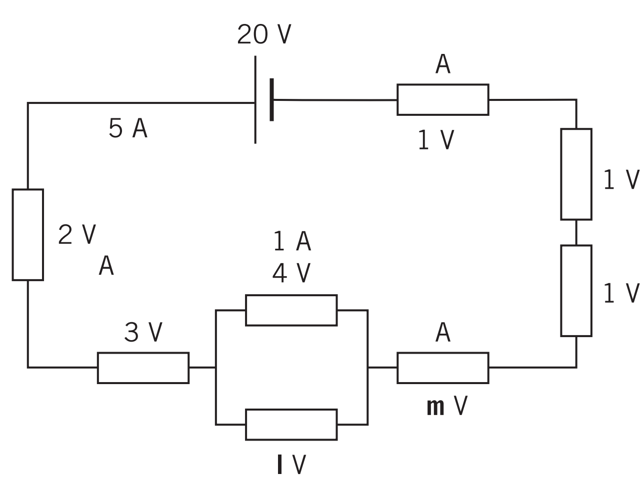
Circuit 1



Circuit 1



Circuit 4



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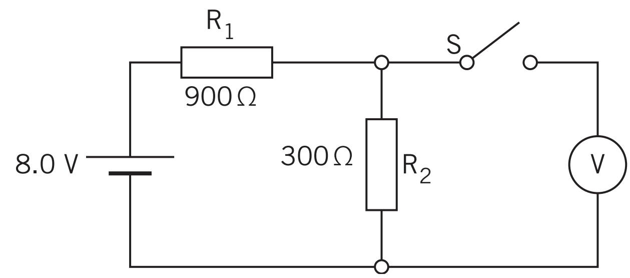
22 Students in a physics classroom construct the following circuit.



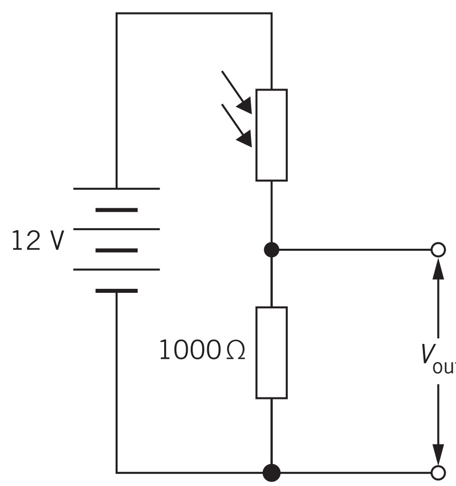
The battery potential difference is 8.0 V, and the values of the resistors are 900 Ω (R_1) and 300 Ω (R_2).

a What is the expected reading on the voltmeter in the circuit when the switch, S, remains open? (1 mark)

The students now close the switch S.

b What is the potential difference that should now be measured by the voltmeter? (2 marks)

23 The light sensor in the figure below has to detect light and dark.



a At a particular light level the resistance of the LDR is 600 Ω. What is V_{out}? (2 marks)

b What is the potential difference across the LDR? (1 mark)

c In the dark, the resistance of the LDR is 10 kΩ. What is V_{out}? (2 marks)

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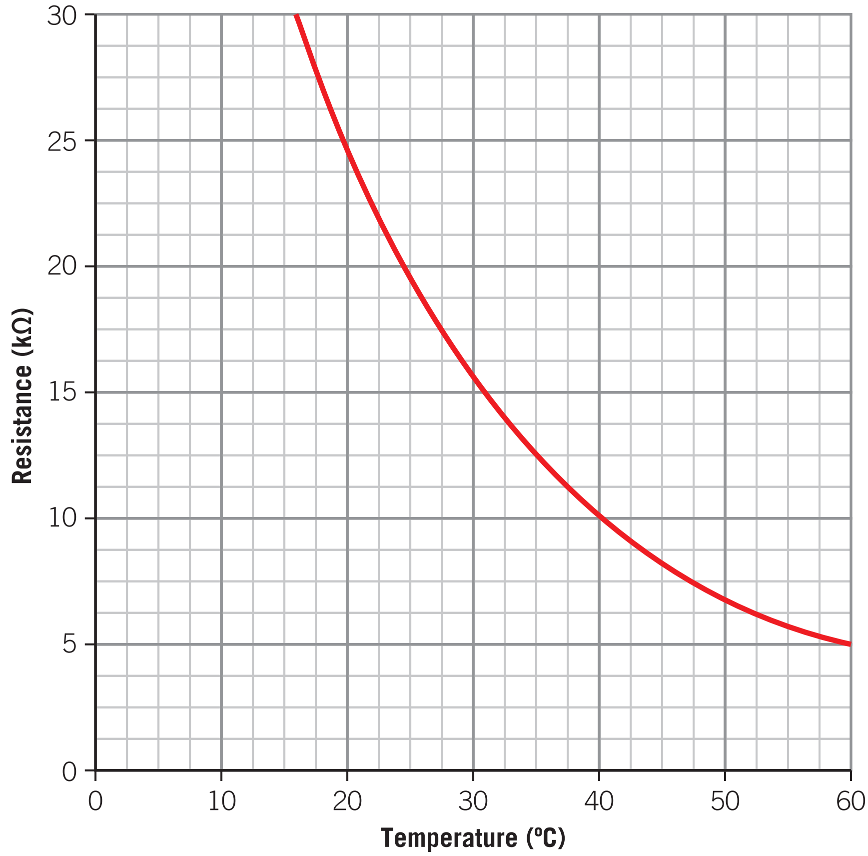
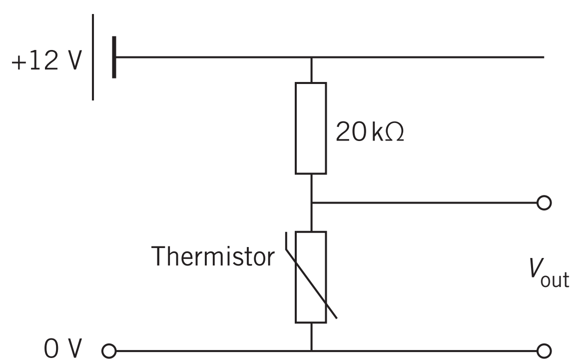
24 A thermistor has the following characteristic curve.



a What is the approximate resistance of the thermistor at 25°C? (1 mark)

The thermistor is used in a thermostat circuit with a 20 kΩ resistor, as shown below.



b What is the value of V_{out} at 25°C? (2 marks)

c Describe the variation of V_{out} as the temperature varies between 25°C and 40°C. Include any necessary calculations in your answer. (2 marks)

d What current flows through the thermistor at 40°C? (2 marks)

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UNIT 2 HOW DOES PHYSICS HELP US TO UNDERSTAND THE WORLD?

CHAPTER 7 MODELLING MOTION

Introduction

On 20 July 1969, an estimated 650 million people crowded around their fuzzy black and white television screens and heard the distorted voice of Neil Armstrong proclaim:

> 'this is one small step for man, one giant leap for mankind'

In that moment, the human race's collective dream of touching the Moon was realised, and across the world people dared to dream a little bolder. Now, more than 50 years after the event, the Moon landing remains an enduring symbol of what humanity can achieve when we unite our efforts.

People were only able to reach the Moon through an understanding of motion. This understanding of motion has progressed throughout human history. Aristotle, Galileo, Newton and Einstein are some of the people who have fundamentally changed the way we understand motion. This understanding has led us to accomplish many great things. As we pursue a more complete understanding of motion it will no doubt continue to push the frontier of humankind.

This chapter explores how to model motion. It first looks at vectors and scalars, which are used to quantify motion. The chapter then moves on to explore how motion can be displayed graphically and highlights the interconnectedness of displacement–time, velocity–time and acceleration–time graphs. The last section of this chapter examines how bodies with straight-line motion undergoing constant acceleration will move. This analysis is done by applying the equations of straight-line motion.

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Curriculum

Area of Study 1 Outcome 1
How is motion understood?

Study Design	Learning objectives – at the end of this chapter I will be able to:
Concepts used to model motion • Identify parameters of motion as vectors or scalars **Forces and motion** • Apply the vector model of forces, including vector addition and components of forces, to readily observable forces including the force due to gravity, friction and normal forces	**7A Concepts used to model motion** **7A.1** Recall that a vector requires a magnitude and direction while a scalar only needs a magnitude **7A.2** Recall common types of vectors and scalars **7A.3** Perform basic straight-line addition of vectors **7A.4** Determine the components of vectors **7A.5** Determine an unknown vector when when given the initial vector and the resultant vector
Concepts used to model motion • Analyse graphically, numerically and algebraically, straight-line motion under constant acceleration • Analyse, graphically, non-uniform motion in a straight line	**7B Analysing motion through graphs** **7B.1** Interpret a displacement–time graph **7B.2** Apply the knowledge that the gradient of a displacement–time graph is the velocity **7B.3** Interpret a velocity–time graph **7B.4** Apply the knowledge that the gradient of a velocity–time graph is the acceleration **7B.5** Apply the knowledge that the area under a velocity–time graph is the total displacement and the absolute values of the area under the graph is the total distance travelled **7B.6** Interpret an acceleration–time graph **7B.7** Apply the knowledge that the area under an acceleration–time graph is the change in velocity
• Analyse graphically, numerically and algebraically, straight-line motion under constant acceleration $v = u + at$, $v^2 = u^2 + 2as$, $s = \frac{1}{2}(u + v)t$, $s = ut + \frac{1}{2}at^2$, $s = vt - \frac{1}{2}at^2$	**7C Analysing straight-line motion with uniform acceleration** **7C.1** Analyse numerically and algebraically, straight-line motion under constant acceleration using the formulas $v = u + at$, $v^2 = u^2 + 2as$ and $s = \frac{1}{2}(u + v)t = ut + \frac{1}{2}at^2 = vt - \frac{1}{2}at^2$

Glossary

Acceleration
Displacement
Free-falling
Friction
Gradient
Magnitude
Net force
Origin
Parabolic path
Quantitative
Resultant vector
Scalar
Vector
Velocity

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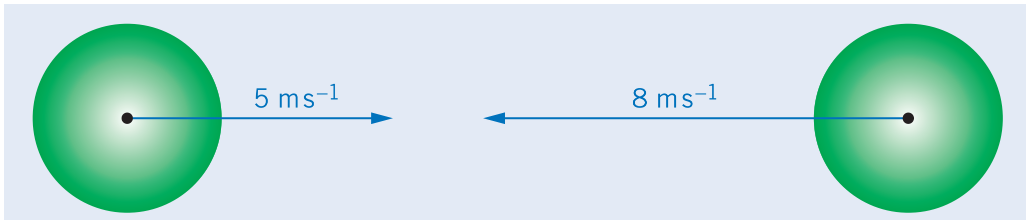
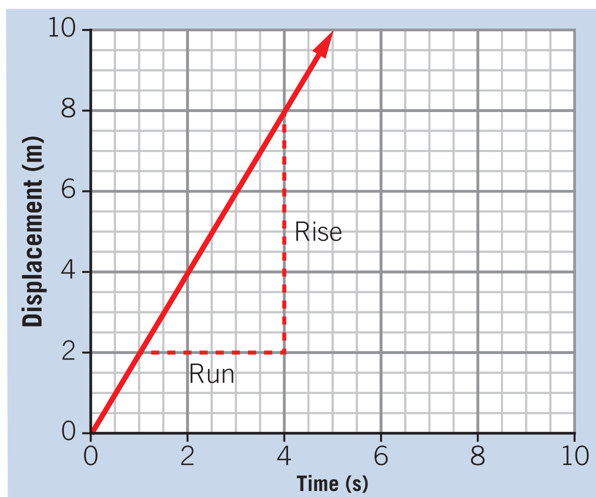
Concept map

7A Concepts used to model motion



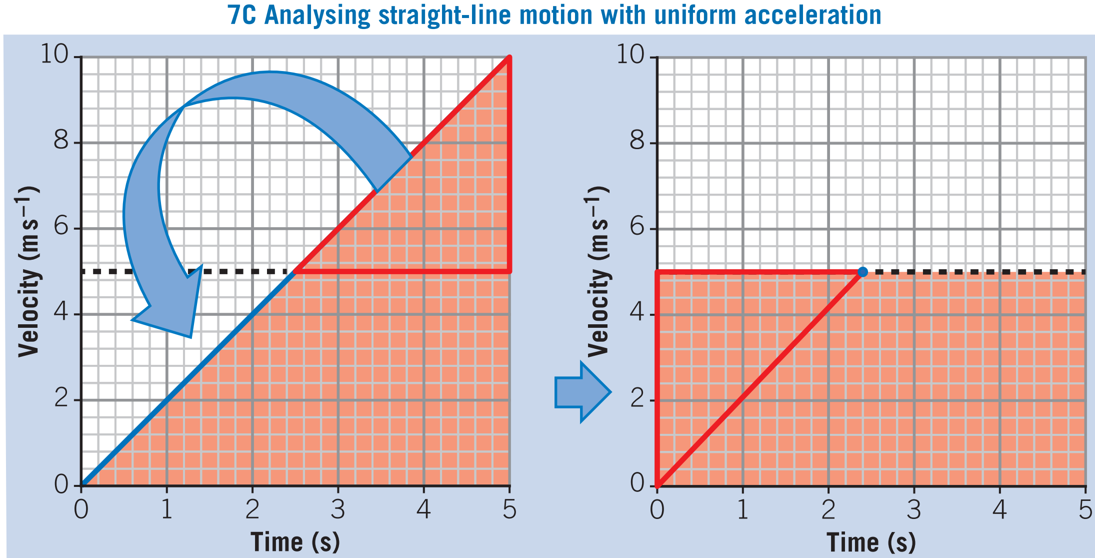
Vectors and scalars are used to understand and quantify motion

7B Analysing motion through graphs



Graphs are used to derive the equations of straight-line motion with uniform acceleration

7C Analysing straight-line motion with uniform acceleration



See the Interactive Textbook for an interactive version of this concept map interlinked with all concept maps for the course.

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7A Concepts used to model motion

Study Design:
- Identify parameters of motion as vectors or scalars
- Apply the vector model of forces, including vector addition and components of forces, to readily observable forces including the force due to gravity, friction and normal forces

Glossary:
Displacement
Friction
Magnitude
Quantitative
Resultant vector
Scalar
Vector
Velocity

ENGAGE

The shortest way isn't always the quickest

Mountaineering was first popularised by the scientist Horace-Bénédict de Saussure following his visit to Mont Blanc in 1760. At 4807 m tall, Mont Blanc is one or the tallest peaks in Europe and the young scientist was determined that the mountain would be conquered. Therefore, he offered a prize for anyone who was able to ascend Mont Blanc. It would take 26 years before the prize money was claimed by an unassuming doctor and his porter.

In 1854, mountaineering took off. This was an era that would become known as the golden age of mountaineering. Predominately British climbers, with Italian, French and Swiss guides, began ascending the high peaks of the Swiss alps for no other reason than the satisfaction of getting to the top. Mountaineering involves monitoring weather conditions, hiking challenging terrain, including steep rocks, snow and ice. The shortest way to the top of the mountains is rarely the best and the first mountaineers would carefully record their winding path to the top so that others could follow. In such hostile conditions, knowing where one camp was relative to another became a matter of life and death.

The climax of the golden era of mountaineering was when a British team of mountaineers, led by Edward Whyper, first scaled the Matterhorn on 14 July 1865.

Figure 7A–1 One route up the Matterhorn, a mountain in the Swiss and Italian Alps

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VIDEO 7A–1
CONCEPTS USED TO MODEL MOTION

EXPLAIN

Vectors and scalars

In science, all **quantitative** measurements are either **vectors** or **scalars**. A vector is a quantity that requires both a **magnitude** (size) and direction. For example, if you give someone directions to a shop, you would not say it is 500 m away, you would include a direction and say it is 500 m to the north, for example. A scalar quantity only requires a magnitude; no direction is needed. For example, if someone asks you to pour 500 mL of milk to make a cake, it would not make sense to give a direction for the the 500 mL, the action of pouring has an implicit direction.

Table 7A–1 shows a list of examples of vector and scalar quantities.

Table 7A–1 Examples of vector and scalar quantities

Vector	Scalar
Displacement	Distance
Velocity	Speed
Acceleration	Mass
Force	Volume
Momentum	Area
Impulse	Energy
Torque	Power
Electrical field	Temperature
Magnetic field	Time

Quantitative
data that can be measured by the quantity

Vector
a quantity that is described by both a magnitude (how big it is) and a direction

Scalar
a quantity that is fully described by a magnitude (it doesn't need a direction)

Magnitude
a number the defines only the size of a quantity

Check-in questions – Set 1

1 List four vector quantities and four scalar quantities.
2 What is the difference between a vector and a scalar?

Vector addition

When adding any vector, you must remember that only the same types of vectors can be added. For example, you can add two velocity vectors but you cannot add a velocity vector to an acceleration vector. Vectors are often represented by arrows. The direction of the arrow indicates the direction of the vector, and the length of the arrow represents the magnitude of the vector.

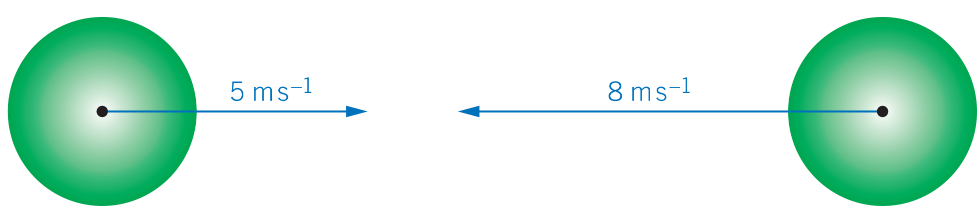

Figure 7A–2 Two balls moving towards each other. The arrows indicate the magnitude and direction of the balls' velocity.

When objects are moving in one dimension, the direction of the vector can be represented by either a positive or negative sign. In Figure 7A–2, you can represent the vectors on the balls as 5 $m\,s^{-1}$ and –8 $m\,s^{-1}$, in this case the direction right is positive. It is important to note you could also represent the vectors on the balls as –5 $m\,s^{-1}$ and 8 $m\,s^{-1}$; in this case the direction left is positive.

Vector addition in one dimension

When adding two or more of the same type of vector, the vectors must be added head-to-tail; the vector being added should start where the previous vector finished. The **resultant vector** is then drawn from the tail of the first vector to the head of the final vector. The order in which you add the vectors does not affect the resultant vector.

Resultant vector
a single vector that is equivalent to the sum of two or more vectors

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Worked example 7A–1 Vector addition in 1D

A person walks 200 m east and then turns around and walks 50 m west.

a Draw a vector diagram for this situation.

b Calculate how far the person is away from the origin at the end of their journey.

Solution

a Let east be to the right. The 200 m east vector is draw to the right. The 50 m west vector then starts at the end (tail) of the previous vector and points to the left indicating the direction, west.

b This question is asking you to find the sum of the two displacement vectors. To find this, the vectors are added head-to-tail and the resultant vector runs from the start of the first vector to the head of the final vector, as shown below.

The magnitude of the resultant vector is found by 200 – 50 = 150 m, where the positive indicated the direction east. Therefore, the final answer is 150 m to the east.

Vector addition in two dimensions

When an aircraft is flying through the air, the pilot must consider the direction of the wind and which way to point the nose of the plane in order to fly straight. This is one of many examples where finding the resultant vector acting on a body is needed.

The same set of principles apply when adding vectors in one dimension to adding vectors in two dimensions. This means that vectors are added head-to-tail, and the resultant vector extends from the start of the first vector drawn to the head of the last vector drawn.

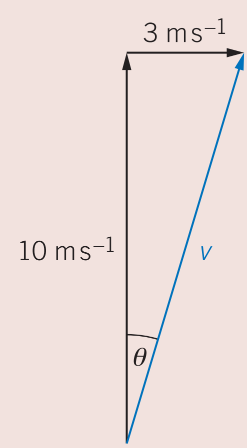
Worked example 7A–2 Vector addition in 2D

A boat is moving north at $10\ \text{m s}^{-1}$ through a lake that has a current of $3\ \text{m s}^{-1}$ east. Calculate the net **velocity**, v, of the boat. Ensure that you include a direction for the velocity.

Velocity the rate of change of displacement

Solution

First, draw a vector diagram of this situation.



Rearrange Pythagoras' theorem, $a^2 = b^2 + c^2$, to determine the magnitude of the velocity.

$$v = \sqrt{10^2 + 3^2} = 10.4\ \text{m s}^{-1}$$

Determine the angle by using a trigonometric function (sin, cos or tan):

$$\tan\theta = \frac{3}{10}$$

$$\theta = \tan^{-1}\frac{3}{10} = 16.7°$$

Note that the angle is measured from the north and the angle moved towards the east. Hence, the angle is written as N16.7°E, which means 16.7° from the north towards the east. Therefore, the final velocity is $10.4\ \text{m s}^{-1}$ N16.7°E.

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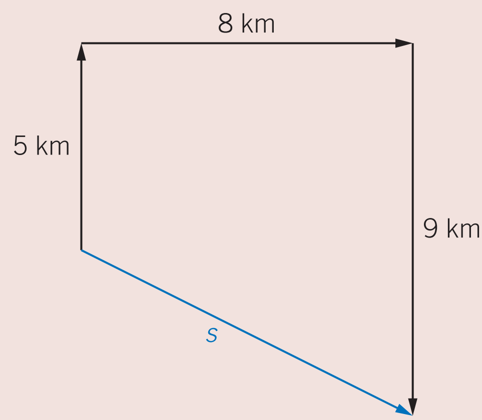
Worked example 7A–3 Finding total displacement

A hiker walks 5 km north, then 8 km east and finally 9 km south. What is the **displacement** of the hiker from their starting point? Include a direction in your answer.

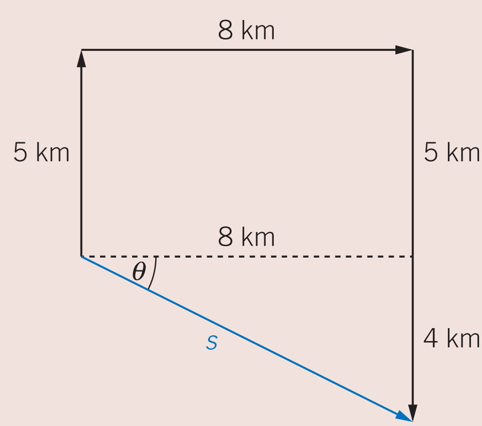
Displacement the shortest distance from one point to another

Solution

First, draw a vector diagram of the situation.



From the diagram, you should be able to see that the north vector will partially cancel out the south vector. This will leave a right-angled triangle that has a length of 8 km one side, 4 km on the other and the hypotenuse will be the net displacement as shown below.



Rearrange Pythagoras' theorem, $a^2 = b^2 + c^2$, to determine the magnitude of the displacement.

$$v = \sqrt{8^2 + 4^2}$$
$$= 8.94 \text{ km}$$

Determine the angle by using a trigonometric function (sin, cos or tan):

$$\tan\theta = \frac{4}{8}$$
$$\theta = \tan^{-1}\frac{4}{8}$$
$$= 26.6°$$

The displacement is 8.94 km at E26.6°S.

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Friction

Friction is a force that resists the relative motion of solid surfaces and fluid layers sliding against each other. The force of friction always acts parallel to the surface. There are two main types of friction: static friction and kinetic friction.

Friction
a force that resists the relative motion of solid surfaces and fluid layers sliding against each other

Static friction is the force that resists the initiation of movement. Static friction helps you to push off the ground and walk, and is also why cars are able to move forwards. The static friction between your foot and the road or the tyre and the road pushes in the direction of travel, producing forwards motion. If you were to try and walk on ice, you would probably slip, and if you tried to drive on ice, the wheels would just spin. This is because there is insufficient static friction to cause forward motion.

Figure 7A–3 The chains on a car's tyre increase the friction between the wheels and the icy road so that forward motion of the car can be generated.

Kinetic friction resists the motion of one object moving over another. This friction always opposes the direction of relative motion. If you push a flat box over the ground, it requires effort as you need to overcome the kinetic frictional force.

Frictional forces are also present when an object moves through a fluid (liquids and gases). These kinds of frictional forces are called drag forces. The mechanism of these frictional forces is different from solid on solid frictional force.

Check-in questions – Set 2

1 If a runner runs at 9.65 $\mathrm{m\,s^{-1}}$ into a 2 $\mathrm{m\,s^{-1}}$ headwind (a headwind blows against the direction of travel), calculate the net velocity of the runner relative to the ground.

2 A hiker starts from their camp and walks 40 km south, stops and walks 10 km north and then walks another 9 km south. What is the displacement of the hiker relative to the camp? Include a direction in your answer.

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Component vectors

In many cases it is useful to break up vector into their components. For example, when a projectile is launched at an angle, it is useful to determine the horizontal and vertical components of the projectile's velocity. This is because, if air resistance is ignored, the horizontal component of the velocity will not change but the vertical velocity will be constantly changing because it is acted upon by the force of gravity throughout its flight.

Figure 7A–4 When the javelin is released its velocity can be broken up into horizontal and vertical components. The magnitude of these two components affects how far the javelin will travel. Therefore, a javelin thrower must consider the launch angle of their javelin to maximise the distance that the javelin travels.

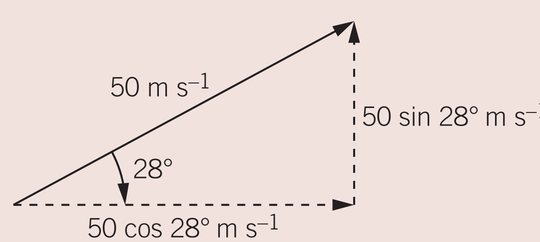
Any vector can be broken up into its component vectors by forming a right-angled triangle and then using a trigonometric function to solve for the components.

Worked example 7A–4 Finding vector components

A cannon fires a cannonball at an angle of 28° up to the horizontal at an initial velocity of 50 m s^{-1}. Calculate the horizontal and vertical components of the cannonball's initial velocity.

Solution

Draw the velocity vector and then apply appropriate trigonometric functions to determine the components.



$$\text{horizontal component} = 50 \cos 28° = 44.1\ \text{m s}^{-1}$$

$$\text{vertical component} = 50 \sin 28° = 23.5\ \text{m s}^{-1}$$

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Check-in questions – Set 3

1 A cannonball is launched with a velocity of 15 m s^{-1} at an angle of 23.5° from the horizontal. Calculate the horizontal and vertical components of the cannonball's initial velocity.

2 An aircraft has an air speed of 40.9 m s^{-1} at an angle of S12°W. Calculate the magnitude of the aircraft's velocity, if it was flying through still air, as well as the crosswind velocity. It is given that a crosswind blows perpendicular to the aircraft and that the nose of the plane is pointing in the south direction.

Solving for unknown vectors

There will be situations where you will be given the resultant vector and will have to solve for an unknown vector. In these situations you can determine the unknown vector by either drawing a vector diagram or determining an equation to solve the unknown vector. The unknown vector will add to the initial vector to cause a change and produce the resultant vector. A general equation to solve for an unknown vector is shown below.

Formula 7A–1 Solving for an unknown vector

$$\Delta V = V_{\text{final}} - V_{\text{initial}}$$

Where:

ΔV = Unknown vector, also called the change in the initial vector

V_{final} = Final vector

V_{initial} = Initial vector

Worked example 7A–5 Change in velocity

A ball is thrown north against a wall with a velocity of 5 m s^{-1}. The ball then hits the wall and rebounds at a velocity of 3 m s^{-1} south. Calculate the magnitude and direction of the change in velocity of the ball.

Solution

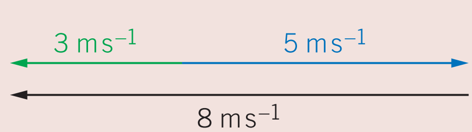
Let north be positive:

$$\Delta v = v_{\text{final}} - v_{\text{initial}} = (-3) - (5) = -8 \text{ m s}^{-1}$$

The negative sign indicates the direction: south.

This can also be solved by drawing a vector diagram. Because 3 m s^{-1} south is the resultant vector, it must be drawn from the tail of the first vector, as shown below.

The unknown vector is then drawn from the end of the first vector to the end of the resultant vector, as shown below.



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WORKSHEET 7A–1
CONCEPTS USED TO MODEL MOTION

Check-in questions – Set 4

1 A car travels 200 km east in 2 hours then 150 km west in 2 hours before finally turning around and travelling 50 km east in 1 hour.
   a Calculate the average velocity of the car in the first 2 hours.
   b Calculate the total distance covered by the car in the 5-hour journey.
   c Calculate the net displacement of the car in the 5-hour journey.
   d Calculate the magnitude of the average velocity of the car for the 5-hour journey.
   e Calculate the average speed of the car in the 5-hour journey.

VIDEO 7A–2
SKILLS: USING DIRECTION IN AN EQUATION

7A SKILLS

Using direction in an equation

In any question that involves a vector quantity, the direction of the vector must be considered and incorporated into your equation. Direction can be incorporated into an equation with a positive and negative sign representing different directions. This means that whenever you encounter a problem involving vectors, one of the first things you must do is determine which direction will be positive and which direction will be negative. Once you have made this decision, write it down on the page as this will allow you to keep track of the meaning of a negative or positive answer. For example:

Question

A jet plane is moving through the air with a velocity of 150 $m\,s^{-1}$ south when it encounters a headwind blowing 25 $m\,s^{-1}$ northerly (a northerly wind blows from the north towards the south). What is the velocity of the jet plane relative to the ground?

Solution

Determine which direction is positive.

positive direction = south

Add the vectors:

$$v = 150 + (-25)$$
$$= 125\ m\,s^{-1}\text{ south}$$

Note that the positive answer gave the direction south.

We could also let south be negative and the solution would still be the same:

$$v = -150 + 25$$
$$= -125\ m\,s^{-1}$$

The negative indicates the direction: south.

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Section 7A questions

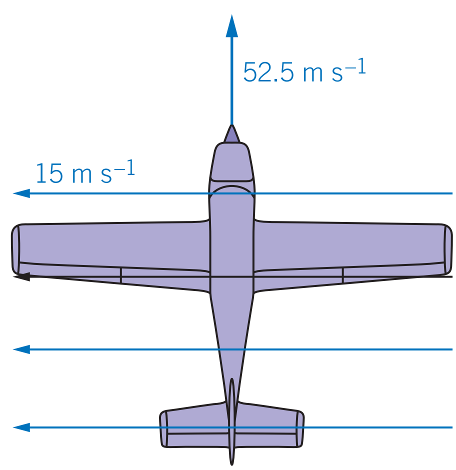
Multiple-choice questions

1 Which of the following is not a vector quantity?
- **A** velocity
- **B** force
- **C** distance
- **D** acceleration

2 A 50 kg cannon ball is launched from a cannon with a velocity of 20 $\mathrm{m\,s^{-1}}$ at an angle of inclination of 30° from the horizontal. What is the horizontal component of the cannon ball's velocity?
- **A** 20.0 $\mathrm{m\,s^{-1}}$
- **B** 17.3 $\mathrm{m\,s^{-1}}$
- **C** 11.5 $\mathrm{m\,s^{-1}}$
- **D** 10.0 $\mathrm{m\,s^{-1}}$

3 A vector requires
- **A** a magnitude.
- **B** a direction.
- **C** an unbalanced force.
- **D** both A and B.

4 A light aircraft is travelling through a storm, due north, with an air speed of 52.5 $\mathrm{m\,s^{-1}}$ (the speed if there was no wind). A cross wind is blowing towards the east with a velocity of 15 $\mathrm{m\,s^{-1}}$. This situation is shown below.



The magnitude of the net velocity of the aircraft relative to the ground is:
- **A** 54.6 $\mathrm{m\,s^{-1}}$
- **B** 67.5 $\mathrm{m\,s^{-1}}$
- **C** 72.4 $\mathrm{m\,s^{-1}}$
- **D** 2.98×10^3 $\mathrm{m\,s^{-1}}$

5 A ball is thrown east at a wall with a speed of 10 $\mathrm{m\,s^{-1}}$, the ball rebounds and travels west at a speed of 5 $\mathrm{m\,s^{-1}}$. The change in velocity of the ball is
- **A** 5 $\mathrm{m\,s^{-1}}$ west
- **B** 5 $\mathrm{m\,s^{-1}}$ east
- **C** 15 $\mathrm{m\,s^{-1}}$ west
- **D** 15 $\mathrm{m\,s^{-1}}$ east

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Short-answer questions

6 What is the difference between a vector and a scalar? Your answer must include an example to demonstrate your point.

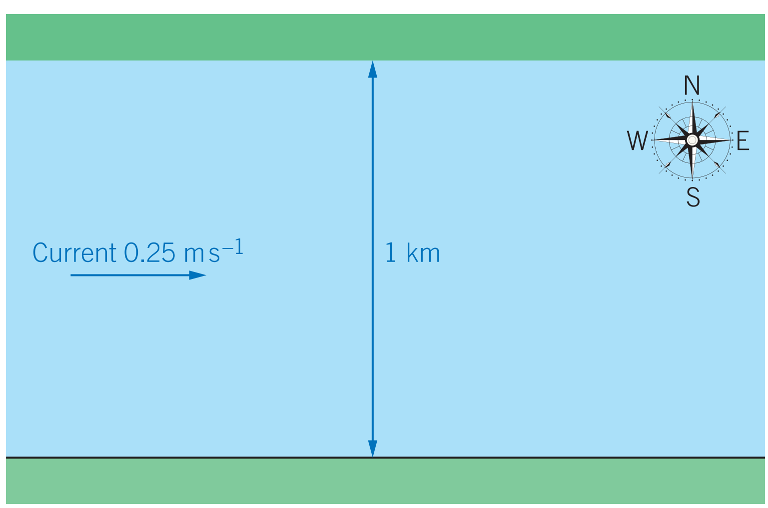
7 A ball is thrown with a velocity of 18.1 $m\,s^{-1}$ south at an angle of 15.0° to the horizontal. Calculate the magnitude of the horizontal and vertical components of the ball's velocity.

8 A car is travelling along a straight road at a constant velocity of 80 $km\,h^{-1}$ south.
  a The driver then accelerates, which increases the thrust force to 2250 N and increases the frictional force to 1750 N. What is the net force on the car, given that the net force is the sum of all of the forces acting on the body?
  b The driver then approaches a pedestrian crossing and slows down to 40 $km\,h^{-1}$ south. What is the magnitude and direction of the change in the car's velocity?

9 An aircraft is attempting to travel north towards its landing strip. The aircraft has an air speed of 42 $m\,s^{-1}$ (speed when there is no wind present). While the aircraft is trying to land, a 5.55 $m\,s^{-1}$ wind blows from the west towards the east.
  a What is the final velocity of the aircraft?
  b In order to fly straight, the pilot angles the aircraft into the wind. Explain how this enables the aircraft to fly straight. Draw a diagram to aid your answer.

10 During the Australian Open a tennis ball is travelling west towards a player at 25 $m\,s^{-1}$. The player strikes the tennis ball and sends the ball back east towards their opponent at 19.5 $m\,s^{-1}$. What was the change in velocity of the tennis ball? Include a direction in your answer.

11 A swimmer intends to cross a river that is 1 km wide. The river has a current of 0.25 $m\,s^{-1}$ east and the swimmer swims with a speed of 1.43 $m\,s^{-1}$ in still water.



  a On the diagram above, trace the path that the swimmer would take.
  b Calculate how much extra distance the swimmer would travel due to the current.
  c Suggest a way that the swimmer could swim directly north. Justify your answer.

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7B Analysing motion through graphs

Study Design:
- Analyse graphically, numerically and algebraically, straight-line motion under constant acceleration
- Analyse, graphically, non-uniform motion in a straight line

Glossary:
Acceleration
Gradient
Origin

ENGAGE

How to accelerate as fast as a Formula 1 car

BASE jumping, cliff diving, helicopter skiing and the luge are some of the most dangerous sports in the world. They involve high speed, high acceleration and high risk. Yet in all of these sports there are no motors, no gears, no jets or rockets. In fact, the only form of propulsion used by people participating in these sports is the acceleration due to gravity. Which raises the question, how big is the acceleration due to gravity?

Figure 7B–1 A group of BASE jumpers look over the cliff that they are about to jump off in Norway.

The acceleration due to gravity is 9.8 $m\,s^{-2}$ down; this is equal to an object increasing its speed by 35.3 $km\,h^{-1}$ every second. So how does this compare to the acceleration of other things? If it is assumed the acceleration of other objects is linear, the graph in Figure 7B–1 can be derived, which shows the acceleration due to gravity compared to other objects.

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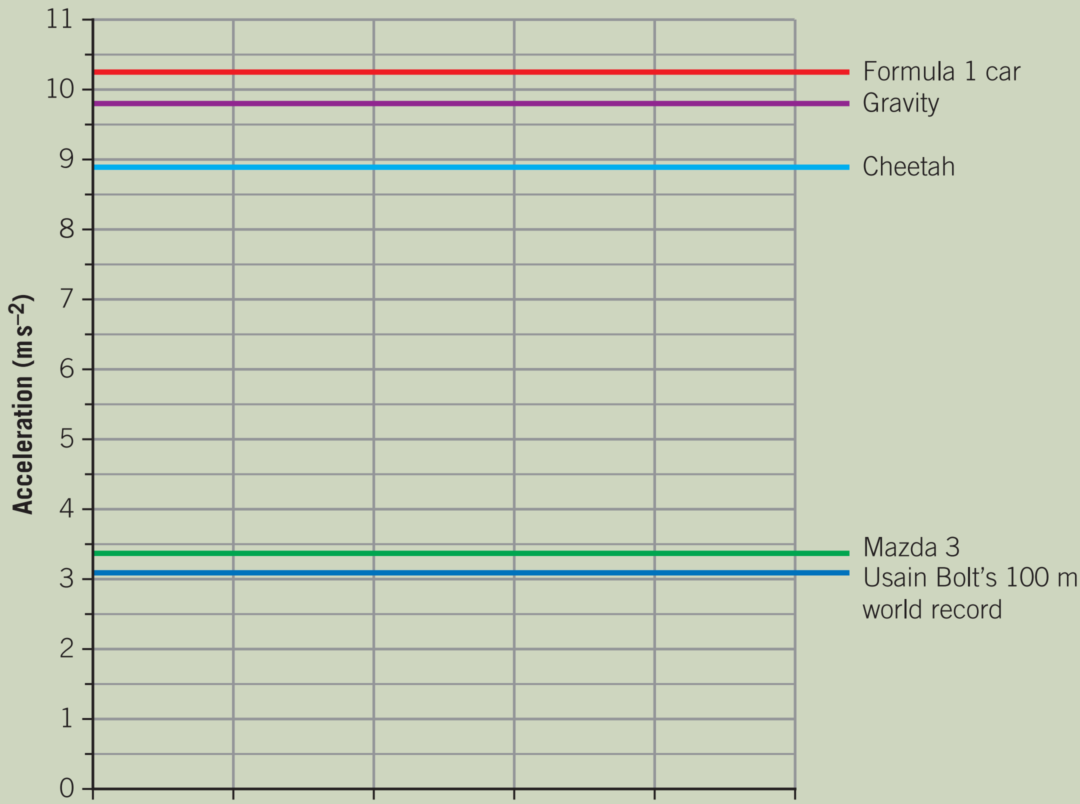

Figure 7B–2 The above shows that the acceleration due to gravity is significant. It is about one-quarter of the maximum acceleration of the Saturn V rocket (38.4 ms^{-2}) that launched the Apollo space shuttles destined for the Moon.

The acceleration due to gravity is very significant. This is why free-falling under the influence of gravity in sports such as BASE jumping and cliff diving is so dangerous. Because your speed increases so rapidly as you fall if you hit something solid you will decelerated even faster which will subject your body to large damaging forces. The velocity–time graph in Figure 7B–3 shows how the velocity of a free-falling object increases with time if air resistance is ignored.

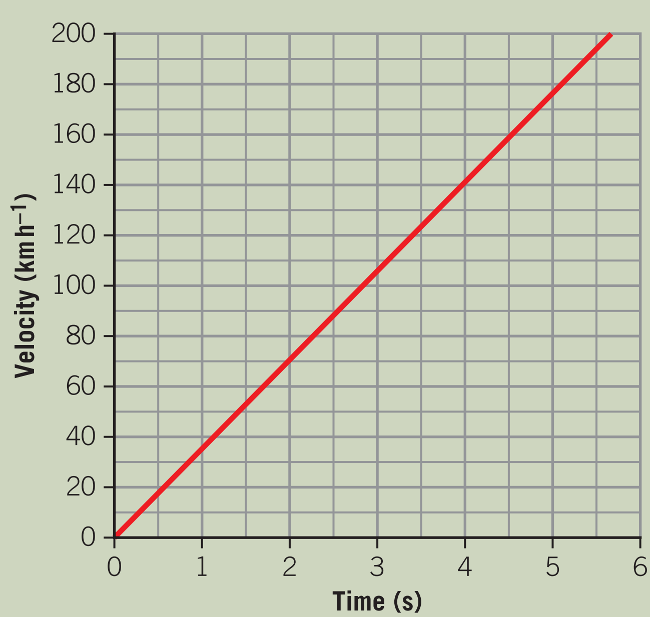

Figure 7B–3 This velocity–time graph shows how the velocity of a free-falling object increases with time if air resistance is ignored.

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From the graph in Figure 7B–3, the free-falling object would take just over 5.5 s to reach 195 $km\,h^{-1}$. The displacement–time graph in Figure 7B–4 shows how much distance an object would cover as time passes, if the object was initially at rest and accelerated by gravity.

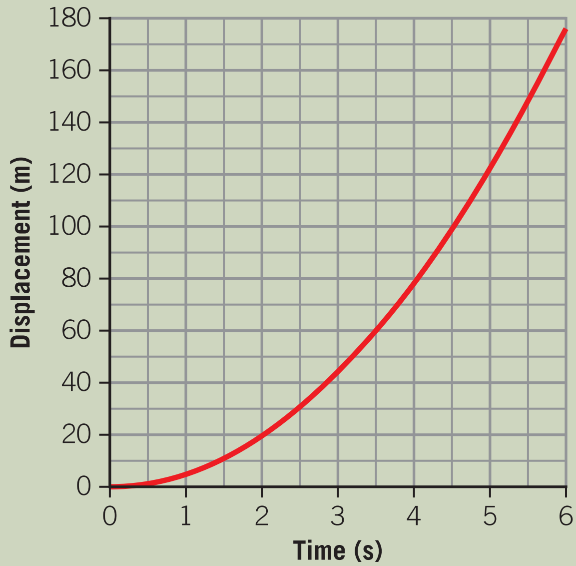

Figure 7B–4 The displacement–time graph shows the distance an object would travel as time passes, if the object was initially at rest and free-falling under gravity. This graph ignores the effect of air resistance.

This graph then demonstrates that if air resistance was ignored, you would only need to fall for about 150 m before you reached a velocity of 195 $km\,h^{-1}$. In reality, air resistance reduces the final velocity. There is even a limit to how fast things can fall called 'terminal velocity', where the force due to gravity is balanced by the force of the air pushing up on the falling object. Since the overall force on the body is zero, the body will no longer accelerate but will maintain its velocity. For humans, terminal velocity is about 195 $km\,h^{-1}$, which takes about 12 seconds to reach and requires an individual to fall for 450 m. Gravity accelerates BASE jumpers to speeds in excess of 180 $km\,h^{-1}$, cliff divers will hit the water with speeds greater than 80 $km\,h^{-1}$, skiers will travel downhill with speeds greater than 96 $km\,h^{-1}$, and luge competitors reach speeds of about 140 $km\,h^{-1}$.

Figure 7B–5 A helicopter drops off skiers on a steep mountain. The skiers will descend the mountain with velocities similar to a that of high-performance car.

So, if you want to accelerate close to the speed of a Formula 1 car, just jump and you'll accelerate towards Earth at about the same rate (if you ignore air resistance).

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EXPLAIN

The vector quantities of motion

Understanding how to analyse motion in a straight line is the starting point for analysing all motion. The analysis of motion is extensively used in a range of different fields such as flight, racing car driving and even for video umpires in sports.

Figure 7B–6 When hiking, the distance travelled and displacement are usually very different.

Distance versus displacement

Imagine a hiker who walks from camp A to camp B. The camps are separated by a distance of 10 km when you travel directly east. However, it is impossible for the hiker to go directly east, as a steep mountain blocks the path. Therefore, to get to camp B, the hiker must walk a distance of 11.7 km around the mountain.

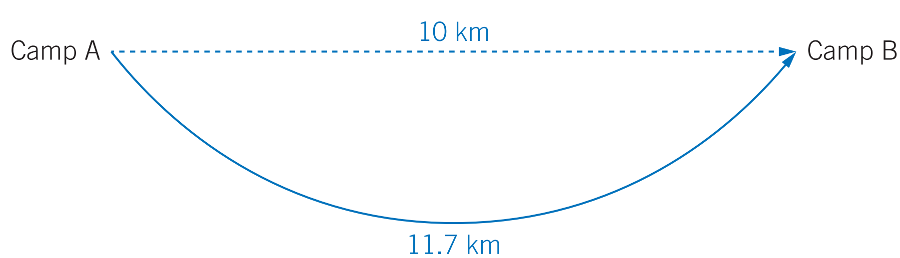

Figure 7B–7 Example of a hike with a displacement of 10 km and a distance of 11.7 km

This example highlights the difference between distance and displacement. Displacement is the direct distance from one point to another. Displacement is a vector quantity and therefore requires both a magnitude and a direction. When the hiker has reached camp B, their displacement from the **origin** (starting position) is 10 km east. You know that the hiker actually travelled 11.7 km in order to reach camp B; which is a measure of distance and is a scalar quantity so it requires a magnitude only.

Origin
the initial point from where a body moves

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Worked example 7B–1 Distance and displacement

A track runner is running around a circular track that has a circumference of 500 m. The runner does exactly four laps, finishing where they started.

a Calculate the distance travelled by the runner.
b Calculate the displacement of the runner once they complete one full lap.

Solution

a $500 \times 4 = 2000$ m
b Since the runner finishes where they start, they will have zero net displacement because they have not moved relative to the origin.

Speed versus velocity

Velocity is the rate of change of displacement. It is a vector quantity because it requires both a magnitude and direction. The direction of the velocity is the same as the direction of the change in displacement. In motion, the velocity can be either positive or negative. For example, if a velocity of 10 m s^{-1} north means that every second you are moving 10 m further north away from your starting position. The greater the velocity, the faster you are moving from the starting position. Speed is the rate of change of distance. This is a scalar quantity and therefore only requires a magnitude. The formula for speed is very similar to the formula for velocity, the two are shown side by side for comparison below.

Formula 7B–1 Average velocity

$$v_{av} = \frac{\Delta s}{\Delta t}$$

Where:

v_{av} = Average velocity (m s^{-1})
Δs = Change in displacement (m)
Δt = Change in time (s)

Formula 7B–2 Average speed

$$\text{average speed} = \frac{\Delta d}{\Delta t}$$

Where:

Δd = Change in distance (m)
Δt = Change in time (s)

Speed is often given in terms of kilometres per hour (km h^{-1}) as many vehicles use this as a measure of their speed. When given a value of speed or velocity in terms of kilometres per hour, it is useful to convert it immediately into metres per second. This can be done by dividing the km h^{-1} value by 3.6. So, to convert from m s^{-1} to km h^{-1}, multiply the m s^{-1} value by 3.6 as shown in the figure below.

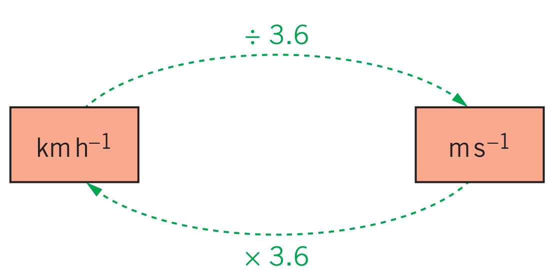

Figure 7B–8 Conversion between kilometres per hour and metres per second

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Acceleration the rate of change of velocity

Acceleration

Acceleration is the rate of change of velocity. It is given the symbol a. The SI unit for acceleration is metres per second per second ($m\,s^{-2}$). Imagine a car, starting from rest and travelling in a straight line, that is accelerating at 4 $m\,s^{-2}$; by the end of the first second that car will be travelling with a velocity of 4 $m\,s^{-1}$. When 2 seconds have passed, the car would have gained another 4 $m\,s^{-1}$ to its velocity and will be travelling at 8 $m\,s^{-1}$.

Formula 7B–3 Acceleration

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

Where:

a = Acceleration ($m\,s^{-2}$)
Δv = Change in velocity ($m\,s^{-1}$)
v = Final velocity ($m\,s^{-1}$)
u = Initial velocity ($m\,s^{-1}$)
t = Time (s)

Figure 7B–9 As a raft moves into water that is moving more quickly, it will begin to accelerate in the direction of flow.

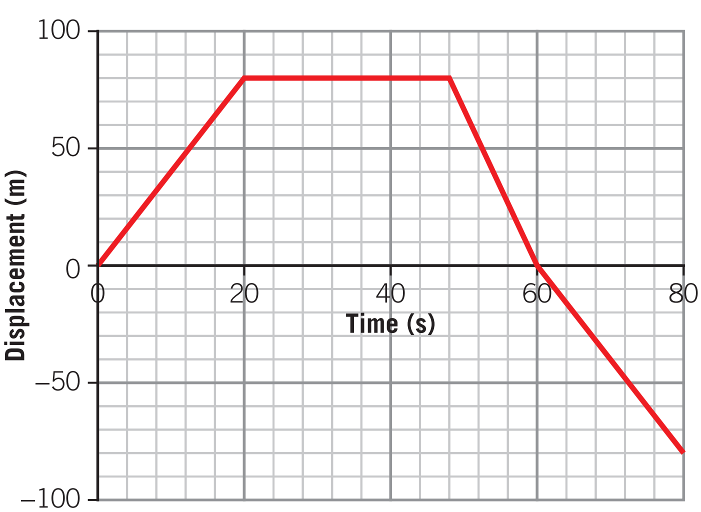

Figure 7B–10 The displacement–time graph of a jogger

Displacement–time graphs

Displacement–time graphs display how far an object is away from its origin at a given point in time. This can be shown by the displacement–time graph of a person going for a jog in Figure 7B–10.

The jogger leaves their origin, their house, and runs away from their house for 20 s, covering a distance of 80 m. The jogger then stops and rests for 24 s before turning around and running the 80 m back towards their house in 12 s. The jogger then continues to run in the opposite direction, away from their house, and covers another 80 m in 20 s.

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Gradient of a displacement–time graph

There are a few useful principles that can be applied to all graphs. Many questions will ask about the gradient of the line of best fit. The **gradient** of the graph is given by:

$$\text{gradient} = \frac{\text{rise}}{\text{run}}$$

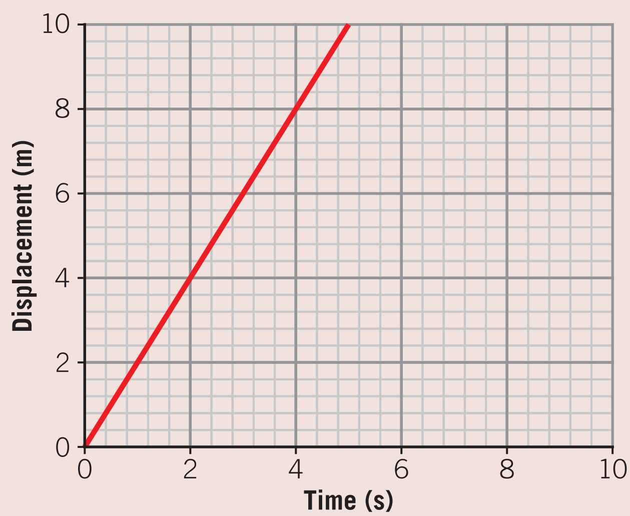
The gradient gives useful information; for example, the gradient of a displacement–time graph gives the velocity of the object.

Gradient the slope of a graph. The gradient of a straight line can be calculated as the rise divided by the run.

Worked example 7B–2 Displacement–time graph gradient

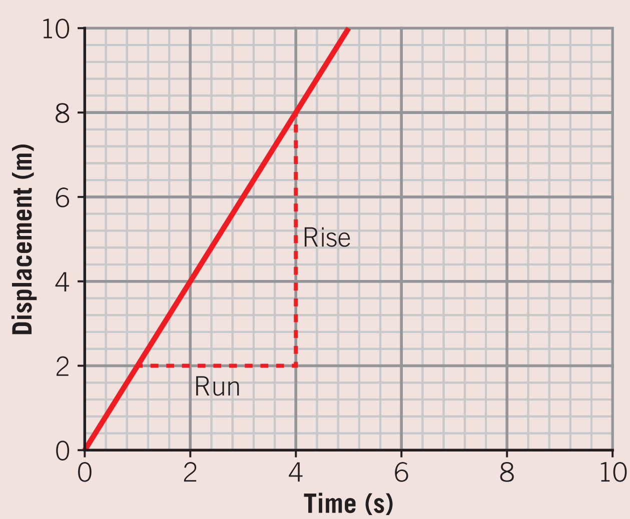
A body moves from rest in a straight line. Its motion is displayed in the displacement–time graph (right).

What is the gradient of the graph? Include a unit in your answer and state what the gradient represents.



Solution

The first step in determining the gradient of a graph is to take two clear points from the line, determine the rise and the run and then divide the rise by the run.



$$\begin{aligned}\text{gradient} &= \frac{\text{rise}}{\text{run}}\\ &= \frac{8-2}{4-1}\\ &= 2\end{aligned}$$

As you are dividing the values on the y-axis (rise) by the values of the x-axis (run), the gradient represents the velocity as $v = \frac{\Delta d}{\Delta t}$. The unit for this graph is $\frac{\text{m}}{\text{s}} = \text{m s}^{-1}$.

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Displacement–time and velocity–time graphs compared

The gradient of the graph can be thought of as the steepness of the graph, it is often important to be able to quickly assess the gradient of any graph. Consider the motion of a body displayed on the displacement–time graph in Figure 7B–11 on the next page.

1 From A to B, the steepness is positive and constant, giving a constant positive gradient and therefore velocity.
2 The section B to C is steeper than the previous section (A–B), but it is still constant and positive, giving a constant positive gradient (velocity).
3 Section C to D is flat and as it has no incline, the gradient and therefore the velocity is zero during this time.
4 The steepness of the segment D to E is negative, quite steep and constant. This gives a large, constant, negative gradient (velocity).

To graph the velocity–time graph of the body, we would have to graph the value of the gradient of the displacement–time graph at each point. This is shown in Figure 7B–12. The two graphs are positioned so the points A–E are vertically aligned in both graphs.

1 From A to B the gradient in the top graph is 1 ms^{-1}, as shown in the bottom graph. The dashed vertical line in the bottom graph indicates that the velocity change was instant. With most physical objects this is unrealistic but that can be ignored here.
2 From B to C the gradient in the top graph is 2 ms^{-1}.
3 From C to D the gradient in the top graph is 0 ms^{-1}, so the body is stationary.
4 From D to E the gradient is –3, and the negative sign indicates the body has changed direction and is returning to its starting position. Its final displacement is zero..

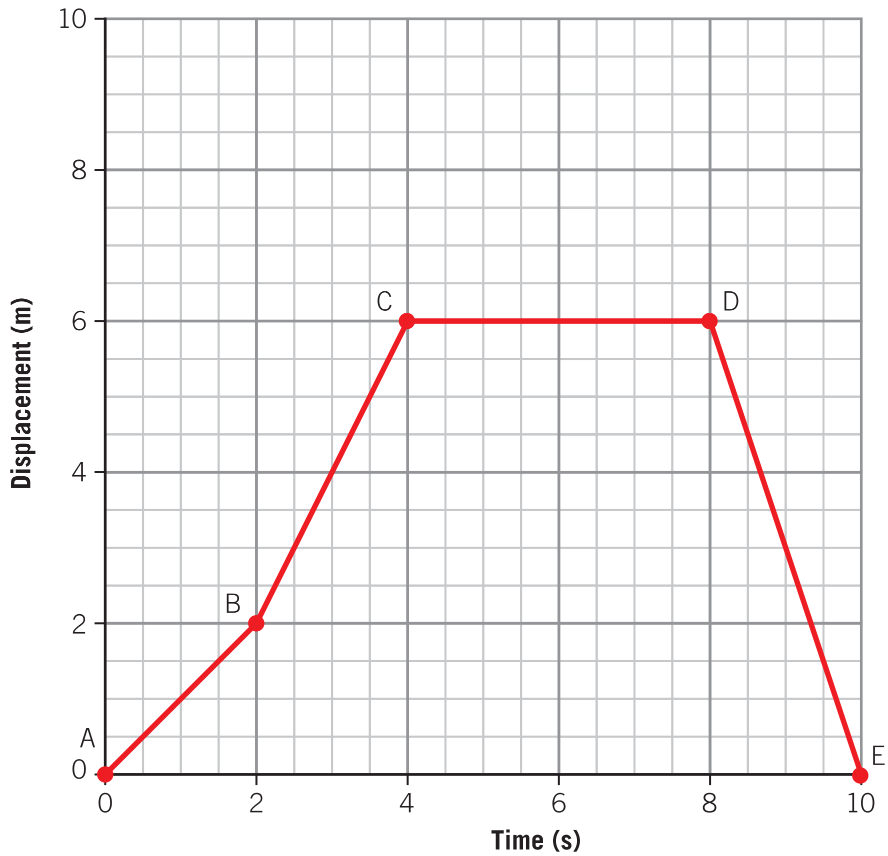


Figure 7B–11 The displacement–time graph of a body moving in a straight line with a variety of different velocities

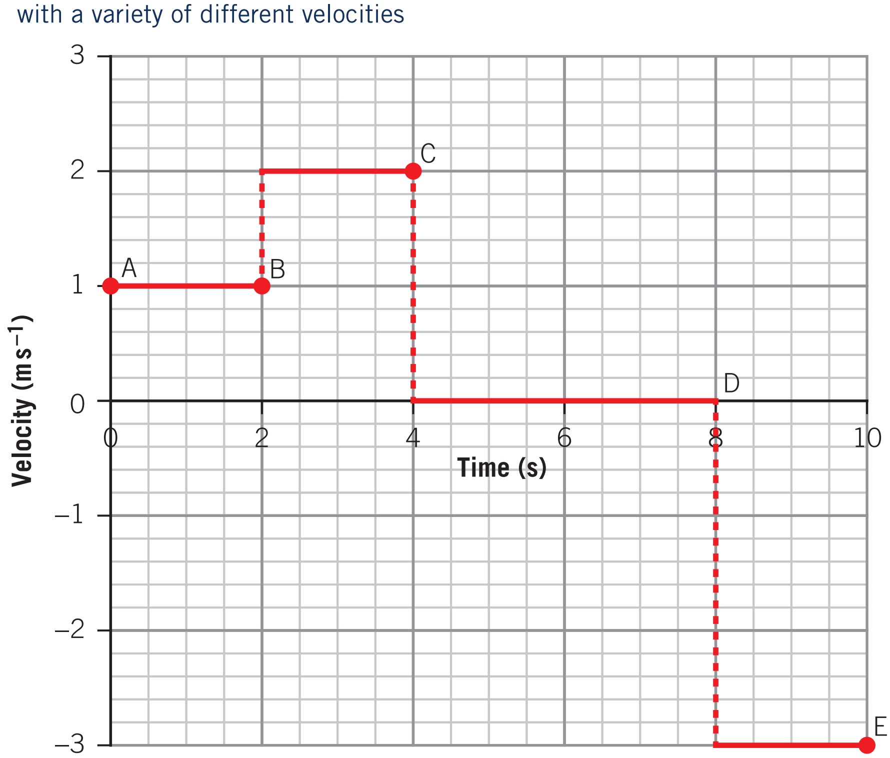


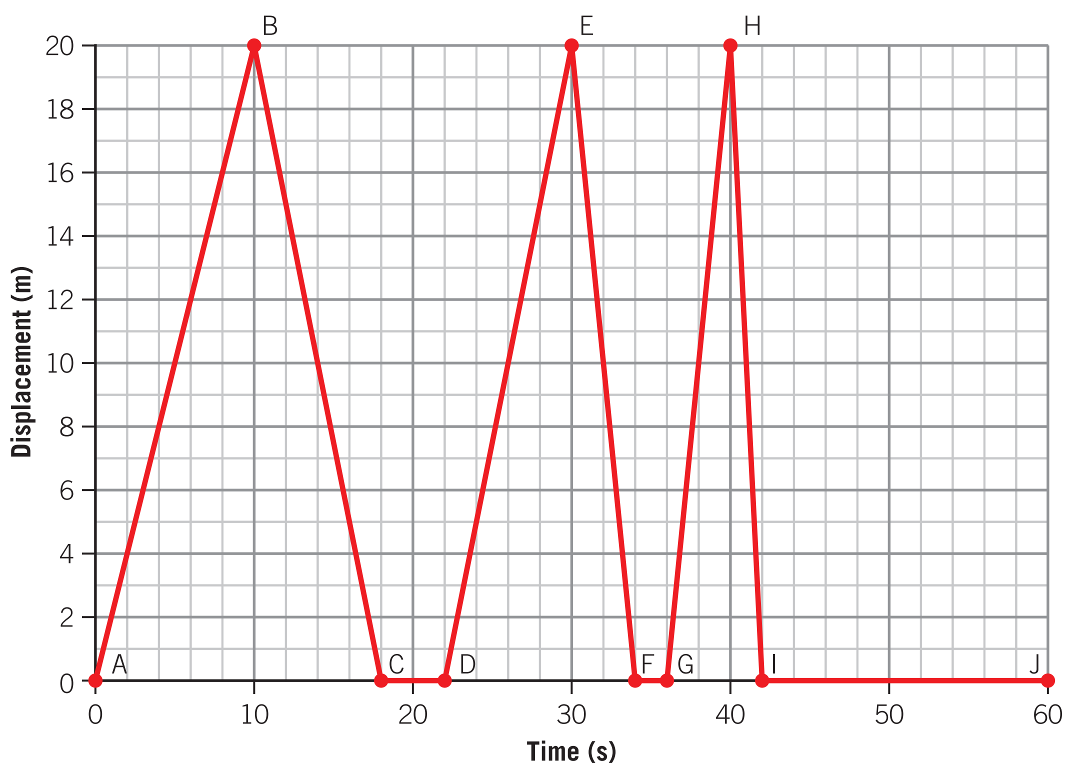
Figure 7B–12 The velocity–time graph of the body in Figure 7B–11 displays information about how the gradient of its displacement–time graph changes with time.

Check-in questions – Set 1

1 Convert the following from $m\,s^{-1}$ to $km\,h^{-1}$.
  a $32.5\ m\,s^{-1}$
  b $25\ m\,s^{-1}$
  c $12.5\ m\,s^{-1}$
  d $50\ m\,s^{-1}$

2 Convert the following from $km\,h^{-1}$ to $m\,s^{-1}$.
  a $9\ km\,h^{-1}$
  b $81\ km\,h^{-1}$
  c $99\ km\,h^{-1}$
  d $54\ km\,h^{-1}$

3 A football team is doing pre-season running training. They are performing 20 m sprints to a cone and then back again. A displacement–time graph of one runner is shown below.



  a What is the magnitude of the velocity of the runner from G to H?
  b What is the displacement of the runner after 50 s?
  c What is the speed of the runner over the 60-second time period?
  d During which segments was the runner stationary?

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Velocity–time graphs

Velocity–time graphs display the velocity of an object at a given point in time. This can be demonstrated by the velocity–time graph in below for a car doing a U-turn at a set of traffic lights.

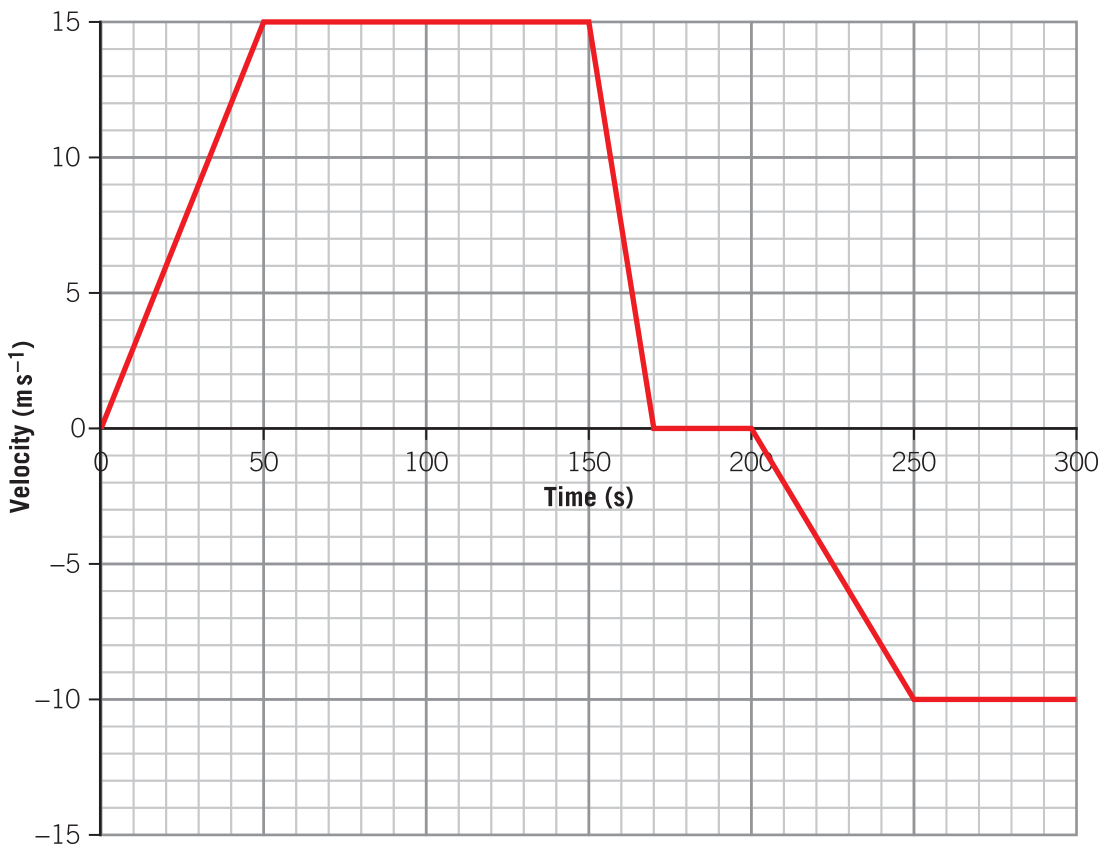

Figure 7B–13 The velocity–time graph of a car doing a U-turn at a set of traffic lights on a straight stretch of road

The car takes 50 s to uniformly accelerate to a speed of 15 m s^{-1}. The car then travels at a constant velocity of 15 m s^{-1} for 100 s. The driver, seeing the traffic lights on red, brakes and the car takes 20 s to decelerate to a velocity of zero. The car remains stationary at the lights for 30 s. Then the light turns green and the car does a U-turn and accelerates for 50 s in the opposite direction to which it was originally travelling. This is why the velocity has become negative. The car then maintains a constant velocity of 10 m s^{-1} for 50 s.

Gradient of a velocity–time graph

On a velocity–time graph, the velocity is on the *y*-axis and time is on the *x*-axis.

The gradient of the line represents the acceleration because gradient $= \frac{\text{rise}}{\text{run}} = \frac{\Delta v}{\Delta t} = a$.

Dividing m s^{-1} by seconds, you get the unit $\frac{\text{m s}^{-1}}{\text{s}} = \text{m s}^{-2}$. You may hear this spoken as 'metres per second per second'.

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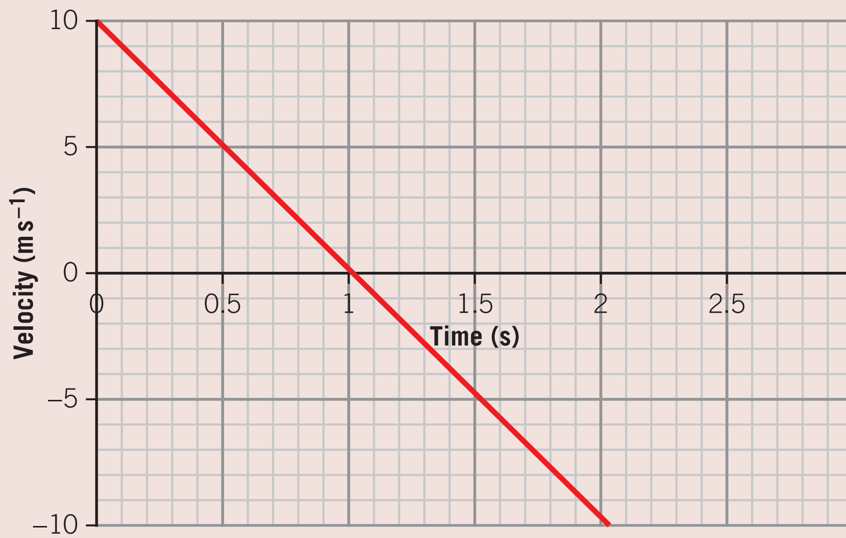
Worked example 7B–3 Reading a velocity–time graph

A ball is thrown vertically into the air and it leaves the thrower's hand at an initial velocity of 10 m s^{-1}. The velocity–time graph of the ball from the moment it leaves the thrower's hand is shown below (air resistance is ignored).



a When the velocity of the ball is zero, the time is 1.02 s. In terms of the ball's height, what is the significance of when the velocity is zero?

b Calculate the gradient of the line and comment on the significance of this gradient.

Solution

a When the velocity of the ball is zero, the ball will be at its maximum height.

b
$$\text{gradient} = \frac{\text{rise}}{\text{run}}$$
$$= \frac{0-10}{1.02-0}$$
$$= -9.8\ \text{m s}^{-2}$$

This gradient is the acceleration due to gravity.

Note that the acceleration is changing the velocity. As seen above, the velocity has gone from being positive to zero to negative.

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The area under a velocity–time graph

The area under a velocity–time graph represents the change in displacement. Consider the velocity–time graph of a hiker, walking with a constant straight-line velocity of 1 m s^{-1} for 5 seconds (Figure 7B–14).

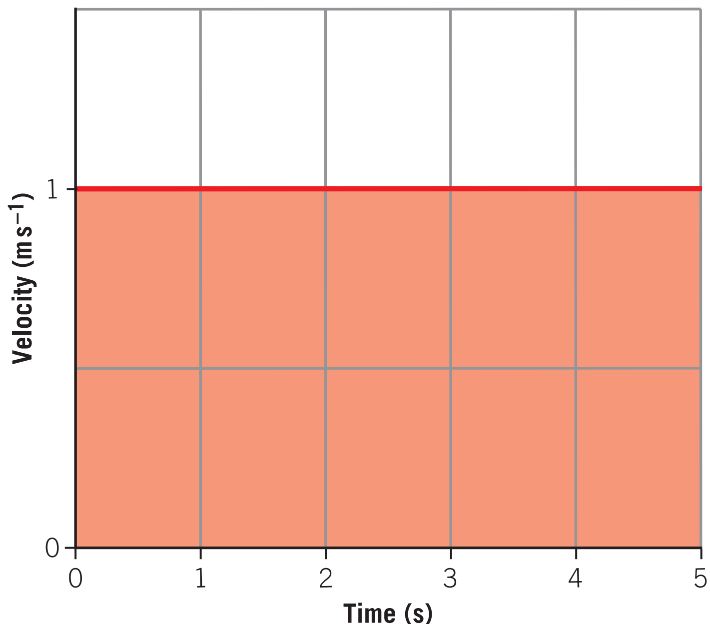

Figure 7B–14 The velocity–time graph of a hiker walking at 1 m s^{-1} for 5 seconds

The change in displacement of the hiker after 5 seconds can be determined by finding the area under the graph:

$$\text{area} = s = vt = (1)(5) = 5 \text{ m}$$

For non-constant velocity, the change in displacement is still found using the area under the velocity–time graph, as shown in Figure 7B–15.

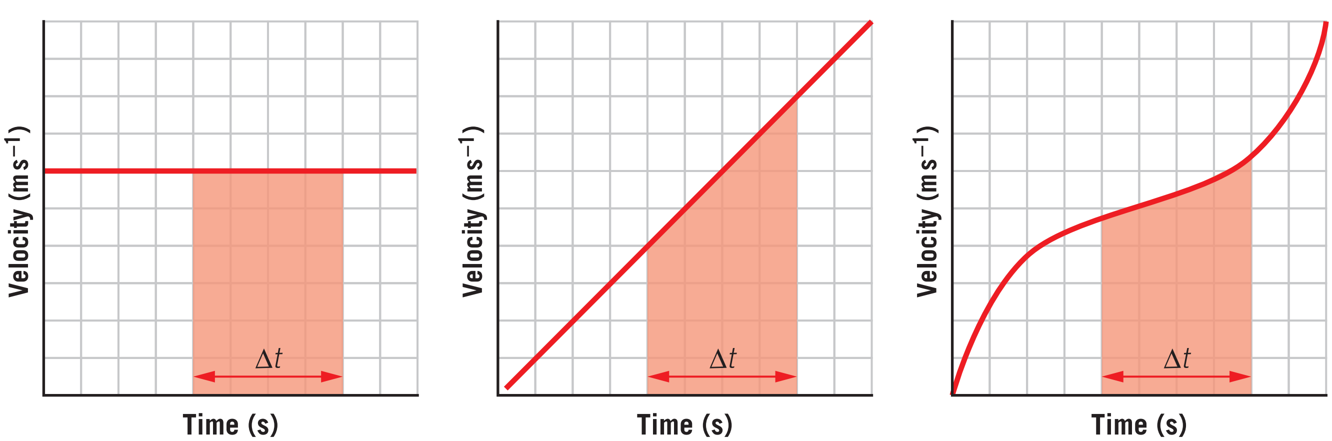

Figure 7B–15 The area under a velocity–time graph gives the change is displacement, even if the velocity changes with time.

The unit is given by multiplying the x-axis unit with the y-axis unit as shown, m × s^{-1} × s = m.

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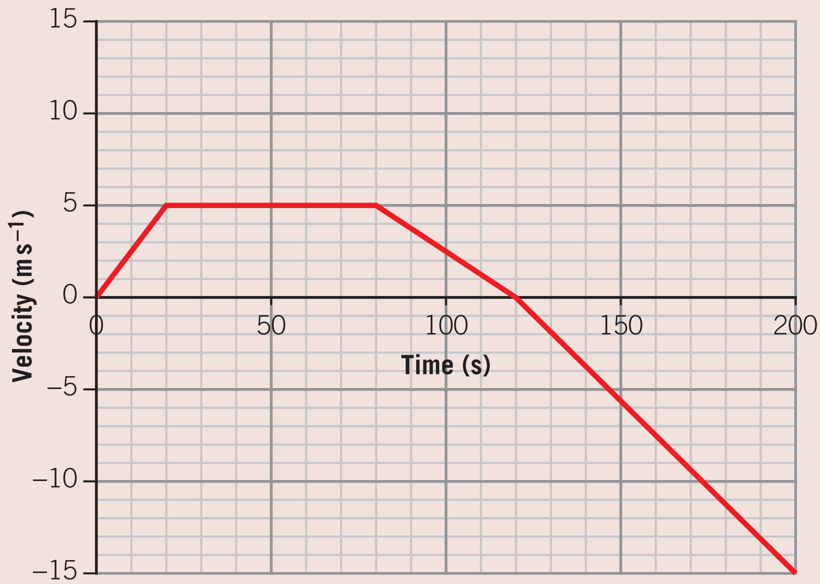
Worked example 7B–4 Area under a velocity–time graph

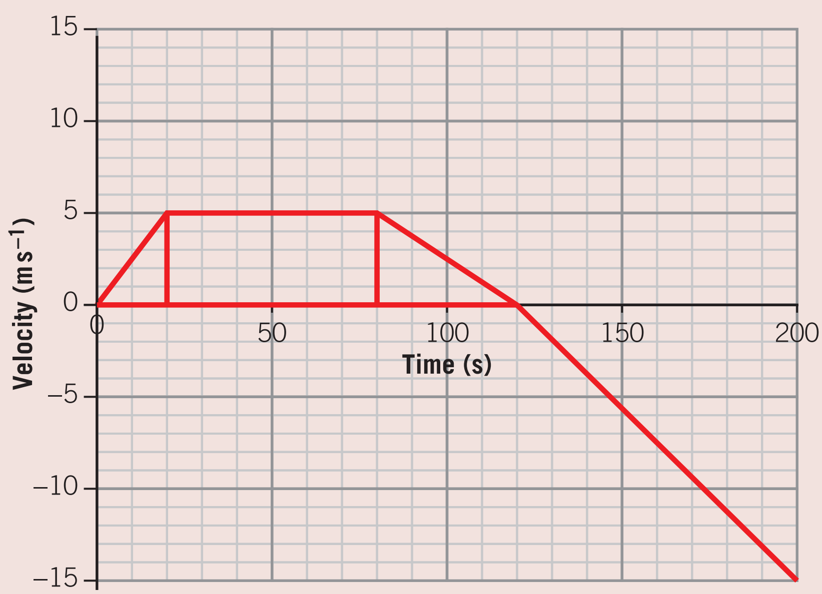
A cyclist rides north up a straight road, turns around and then returns to where they started. A velocity–time graph of this situation is shown below.



a Find the displacement of the cyclist once they have travelled for 120 s.
b What is the displacement after 180 s?
c What is the total distance covered after 180 s?

Solution

a The displacement is the area under the graph. To find the area under the graph, divide the graph into a series of triangles and rectangles as shown on the next page.



The area under the graph up to 120 s, and therefore the displacement, can then be found by adding the area of all the shapes:

$$\frac{1}{2}(20)(5)+(60)(5)+\frac{1}{2}(40)(5)=450\text{ m}$$

As this question asked for displacement (a vector quantity), a direction is required. The direction is north.

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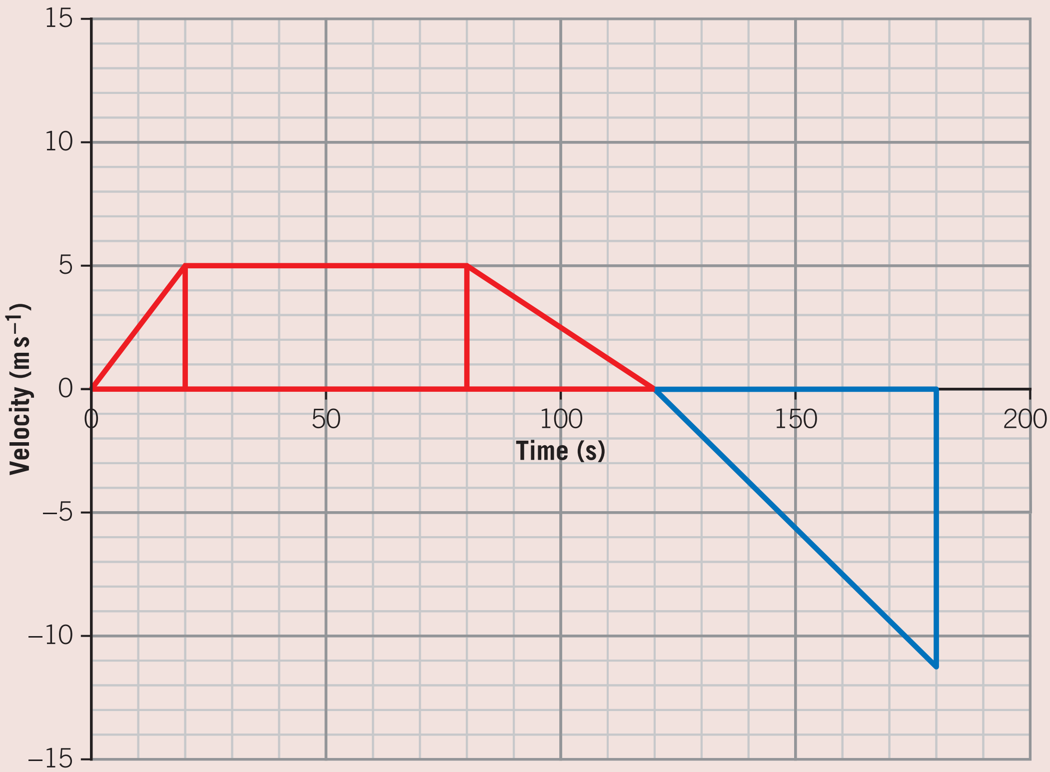
b Note that this graph has a negative value for velocity; this indicates that the cyclist is travelling south. To calculate the displacement after 180 s, the graph needs to be divided into a rectangle and triangles as shown below.



The important point to remember is that when calculating the displacement, the negative value for velocity needs to be considered. Therefore, the area for the blue triangle is:

$$\text{area} = \frac{1}{2}(60)(-15)$$

$$= -450 \text{ m}$$

The negative does not indicate negative area but rather the direction travelled: south. Therefore, the total displacement of the bike after 180 s is:

$$450 + -450 = 0 \text{ m}$$

c Distance is a scalar quantity. Therefore, no direction is required. This means that any negative velocities must be turned into positive values. This is because in the first 120 s the cyclist travels 450 m, and from 120 s to 180 s the cyclist travels another 450 m. This gives a total distance covered of 900 m.

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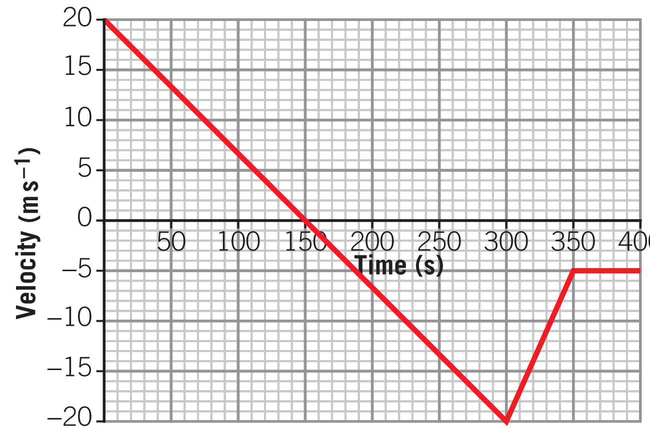
Check-in questions – Set 2

1 The velocity–time graph on the right shows the motion of a car that is initially moving north along a straight road of a testing facility.



a What is the acceleration of the car in the first 300 s? Include a direction in your answer.

b When was the car stationary?

c Describe the motion of the car in the first 300 s of its journey.

d If the car started at its origin, what is the displacement of the car after its 400 second journey. Include a direction in your answer.

Acceleration–time graphs

Acceleration-time graphs display the acceleration of an object at a given point in time. This can be demonstrated by the acceleration–time graph of a car travelling east that is braking as it comes up to a stop sign.

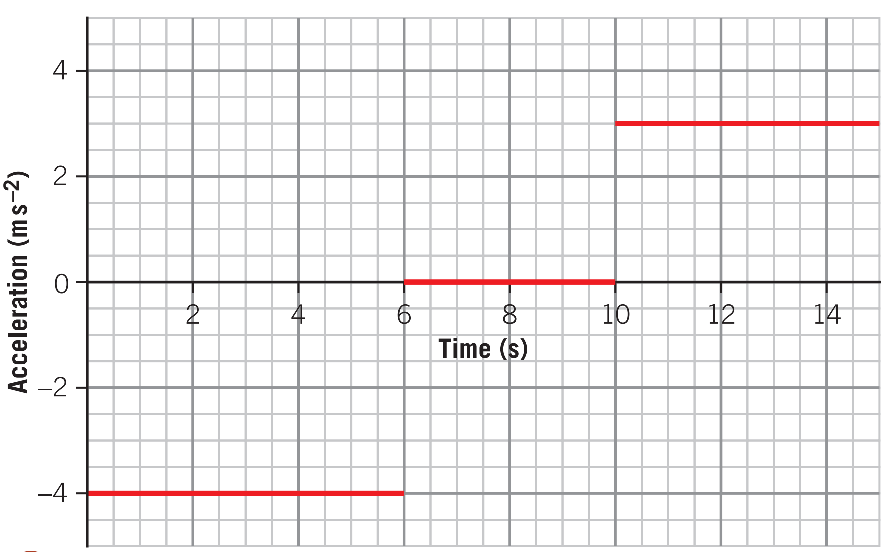


Figure 7B–16 Acceleration–time graph of a car braking as it approaches a stop sign

As seen in the acceleration–time graph in Figure 7B–16, when the car brakes, it accelerates at a constant rate of $-4\ \text{m s}^{-2}$ for 6 s. The negative value means that the car is accelerating in the west direction and therefore the velocity of the car is being reduced. The car then remains stationary at the lights for 4 s before accelerating uniformly by $3\ \text{m s}^{-2}$. Even though the car's acceleration was directed west for the first 6 seconds, the car did not travel west through its entire journey.

The area under an acceleration–time graph

In an acceleration–time graph, acceleration, a, is on the y-axis and time, t, is on the x-axis. The area under an acceleration–time graph is the change in velocity as:

$$\text{area} = \Delta v = at$$

For non-constant acceleration, the change in velocity is still found using the area under the acceleration–time graph. The unit is given by multiplying the units on the x and y-axis together to give $\text{m s}^{-2} \times \text{s} = \text{m s}^{-1}$.

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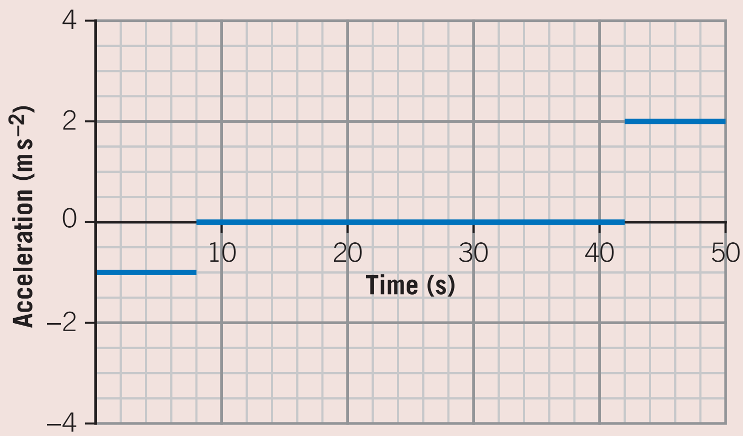
Worked example 7B–5 Area under an acceleration–time graph

A car, initially travelling at 72 km h^{-1}, is travelling on a straight road when it approaches to some roadworks. The car slows to the new speed limit and then accelerates again once it has passed the roadworks. The acceleration–time graph of the car's journey is shown below.



a Calculate the speed that the car travelled past the roadworks in kilometres per hour.

b Calculate the speed, in km h^{1}, of the car at the end of the 50 s.

Solution

a The first step is to interpret this diagram. The car is accelerating at a rate of –1 m s^{-2} for 8 s as it approaches the roadworks. The car is passing through the roadworks at a constant velocity (as there is no acceleration) from 8 s to 42 s. After 42 s, the car has left the roadworks and accelerates. Therefore:

$$\text{initial velocity of the car} = \frac{72}{3.6} = 20 \text{ m s}^{-1}$$

$$\text{change in velocity} = \text{area under the graph} = (-1)(8) = -8 \text{ m s}^{-1}$$

$$\text{final velocity} = 20 - 8 = 12 \text{ m s}^{-1}$$

$$\text{convert m s}^{-1} \text{ to km h}^{-1} = (12)(3.6) = 43.2 \text{ km h}^{-1}$$

b Since you know from part **a** that the car will be travelling at 12 m s^{-1} after 42 s, you only need to consider the change in velocity after this point.

$$\text{change in velocity of the car} = \text{area under the graph} = (2)(8) = 16 \text{ m s}^{-1}$$

$$\text{final velocity} = 12 + 16 = 28 \text{ m s}^{-1}$$

$$\text{convert m s}^{-1} \text{ to km h}^{-1} = (28)(3.6) = 101 \text{ km h}^{-1}$$

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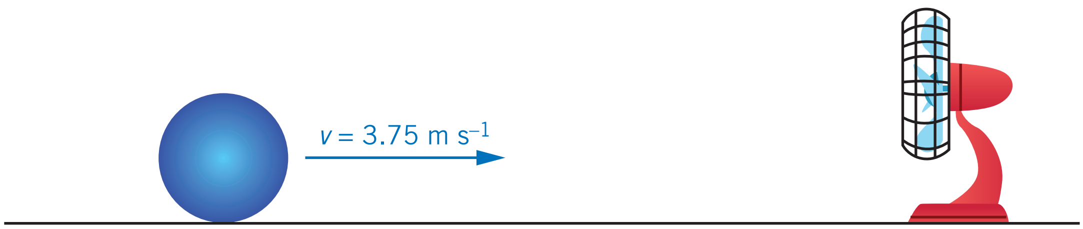
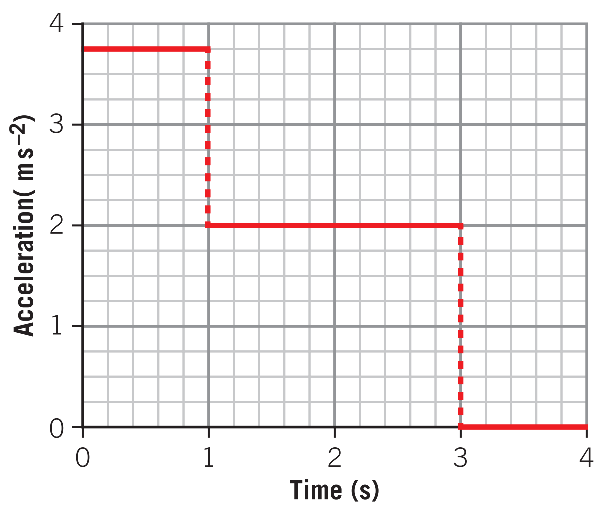
WORKSHEET 7B–1 ANALYSING MOTION THROUGH GRAPHS

Check-in questions – Set 3

1 A ball is initially travelling at 3.75 m s^{-1} east. A fan applies a near constant westward force on the ball until it changes direction. After 1 second, the velocity of the fan's blades is lowered, which reduces the constant force on the ball. Soon after, the fan is turned off. A diagram of this situation is shown below.



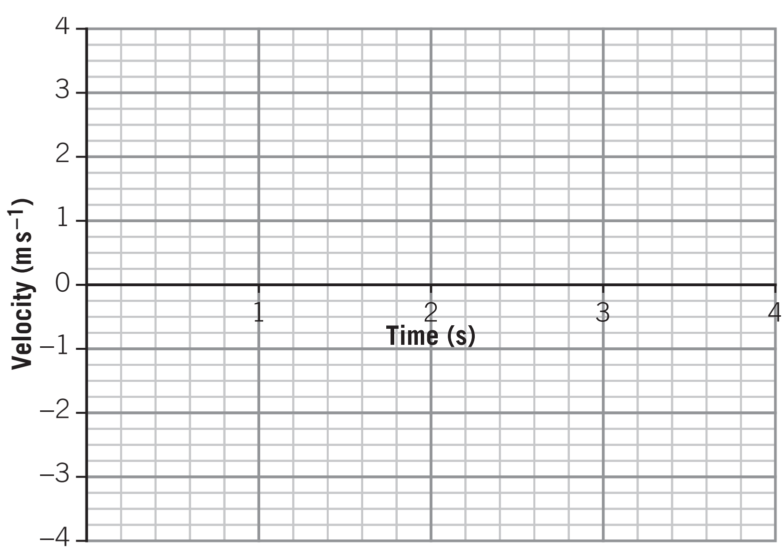
The acceleration–time graph of the ball is shown below.



a How long does it take before the ball is momentarily stationary?

b During what time period is the ball moving west?

c Copy the graph grid below and plot the velocity–time graph of the ball on it.



d Use the graph to calculate the change in velocity of the ball over the 4 s.

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Instantaneous velocity versus average velocity

Speed and velocity can be either instantaneous or average. Imagine a truck is moving down a straight road. A displacement–time graph of the truck's motion is shown in Figure 7B–17.

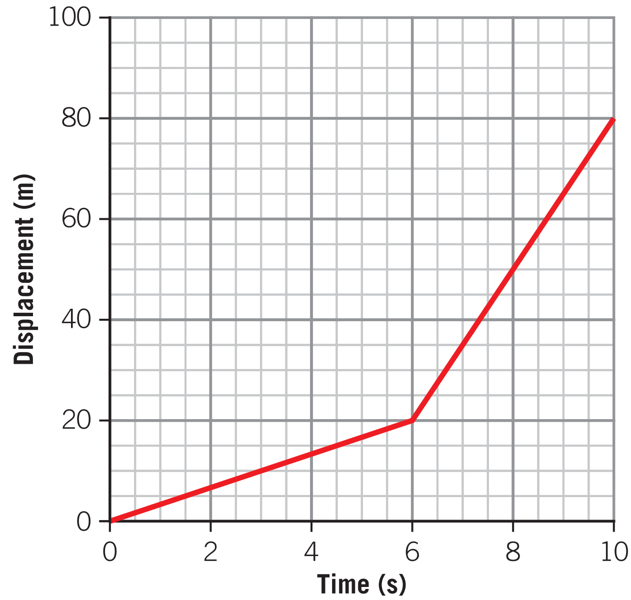

Figure 7B–17 Displacement–time graph of a truck driving along a road

The gradient of this line will be the velocity because:

$$\text{gradient} = \frac{\text{rise}}{\text{run}} = \frac{\Delta s}{\Delta t} = v$$

But the gradient changes after 6 seconds and the line becomes steeper, indicating an increase in velocity. This means that the velocity for the first 6 seconds is:

$$v_{av} = \frac{\Delta s}{\Delta t} = \frac{20-0}{6-0} = 3.33 \text{ m s}^{-1}$$

The velocity for the next 4 seconds is:

$$v_{av} = \frac{\Delta s}{\Delta t} = \frac{80-20}{10-6} = 15 \text{ m s}^{-1}$$

The average velocity for the whole 10-second trip is:

$$v_{av} = \frac{\Delta s}{\Delta t} = \frac{80-0}{10-0} = 8 \text{ m s}^{-1}$$

The formula for average speed and velocity must be used with care. As you can see from Figure 7B–17, considering different parts of the graph will give different results as the velocity of the object changes. You should remember that this formula gives the average velocity of a body and should not be confused with a formula that gives the final velocity.

Measuring instantaneous velocity is much more difficult. In fact, any real-world measurement of velocity will always be an average because it is calculated by dividing the distance travelled by the time that it took the body to travel that distance. As the time interval approaches zero, the velocity becomes closer to the instantaneous velocity.

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For example, imagine a car that is accelerating and therefore its velocity is constantly increasing. The displacement–time graph for the accelerating car is shown in Figure 7B–18.

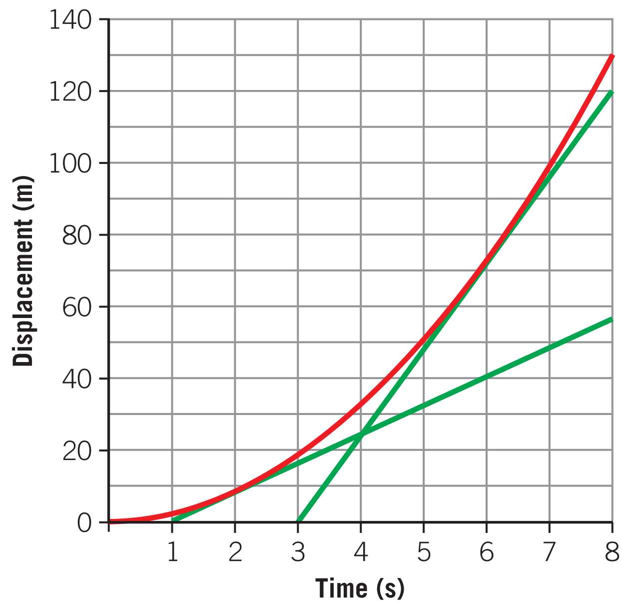

Figure 7B–18 Displacement–time graph of an accelerating car. The value of the instantaneous speed is given by the gradient of the tangent at that point in time. As time passes, the gradient of the tangent increases, showing that the instantaneous velocity is also increasing.

As the gradient is constantly changing, the velocity is also constantly changing.

Worked example 7B–6 Average velocity and the instantaneous velocity

What is the difference between the average velocity and the instantaneous velocity? Use Figure 7B–18 to help answer your question.

Solution

The average velocity of an object is the change in the displacement of an object divided by the time. The instantaneous velocity of an object is the velocity of an object at a specific point in time.

In Figure 7B–18 the average velocity is:

$$v = \frac{\Delta s}{\Delta t} = \frac{128 - 0}{8 - 0} = 16 \text{ m s}^{-1}$$

The instantaneous velocity when t = 2 and when t = 6 is:

$$v_{t=2} = \frac{40 - 0}{6 - 1} = 8 \text{ m s}^{-1}$$

$$v_{t=6} = \frac{120 - 0}{8 - 3} = 24 \text{ m s}^{-1}$$

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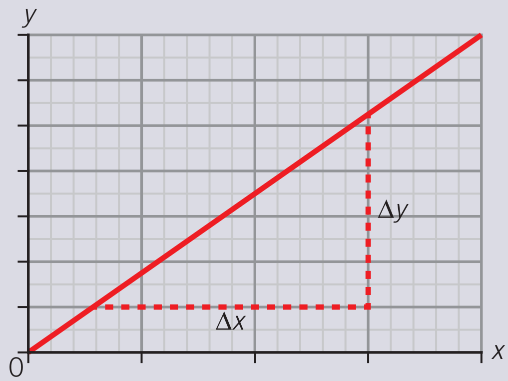
7B SKILLS

VIDEO 7B–1
SKILLS: UNDERSTANDING THE GRADIENT OF A GRAPH

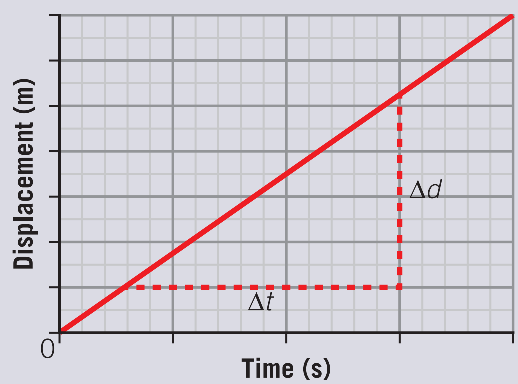
Understanding the gradient of a graph and how to use it

The gradient of a graph tells you how steep the graph is. It is calculated by the change in the y-value, Δy, and divided by the change in the x-value, Δx.



$$\text{gradient} = \frac{\Delta y}{\Delta x} = \frac{\text{rise}}{\text{run}}$$

This means that the unit for the gradient will always be the y-axis unit divided by the x-axis unit. Using this principle, we can derive the unit for the gradient of the distance–time graph.



This means the unit for this graph is $\frac{\text{m}}{\text{s}} = \text{m s}^{-1}$. The gradient of the displacement–time graph is the velocity:

$$\text{gradient} = \frac{\Delta d}{\Delta t} = v$$

Understanding how to derive the unit for the gradient and how to interpret the meaning of the gradient is an essential skill in physics.

Question

A group of students set up an experiment to test the acceleration due to gravity. They drop a ball, initially at rest, from different heights and use an accurate device that can measure the instantaneous velocity of the ball. The students then record the final velocity at which the ball strikes the ground. The students aim to test the acceleration due to gravity by using the following equation:

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

Since the initial velocity is zero, the students rearrange the equation to:

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

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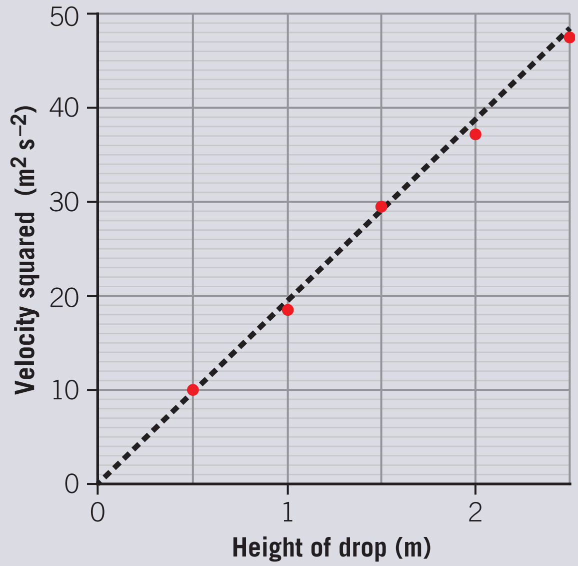
The students gain a set of results and then graph the height of the ball drop, s, on the x-axis and the velocity squared, v^2, on the y-axis.



a Determine the gradient of the graph. Include the unit for the gradient in your answer.

b Use the gradient of the graph to determine the acceleration due to gravity, as measured by the students' experiment.

Solution

a Take two clear points, which are well separated from the line of best fit:

$$\text{gradient} = \frac{\text{rise}}{\text{run}} = \frac{48-0}{2.5-0} = 18$$

$$\text{unit} = \frac{\text{m}^2}{\text{m}} = \text{m s}^{-2}$$

Therefore, the gradient of the line of best fit is 19.2 m s^{-2}

b This question requires you to recognise that the gradient represents the following:

$$\text{gradient} = \frac{v^2}{s} = \frac{\text{rise}}{\text{run}} = v^2$$

Once you recognises the significance of the gradient, you can then substitute it into the formula from the question and solve the acceleration due to gravity as follows:

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

Therefore:

$$a = \frac{1}{2} \times \text{gradient} = \frac{1}{2} \times 19.2 = 9.6 \text{ m s}^{-2}$$

This means the students' data revealed that the acceleration due to gravity is 9.6 m s^{-2}.

Note that this value is below the real acceleration due to gravity. This is not uncommon and you should not get discouraged if the value you have calculated does not match the accepted value. This is because this experiment may have had measurement uncertainties such as air resistance that decreased the final velocity of the ball and gave an acceleration due to gravity that was consistently lower than expected.

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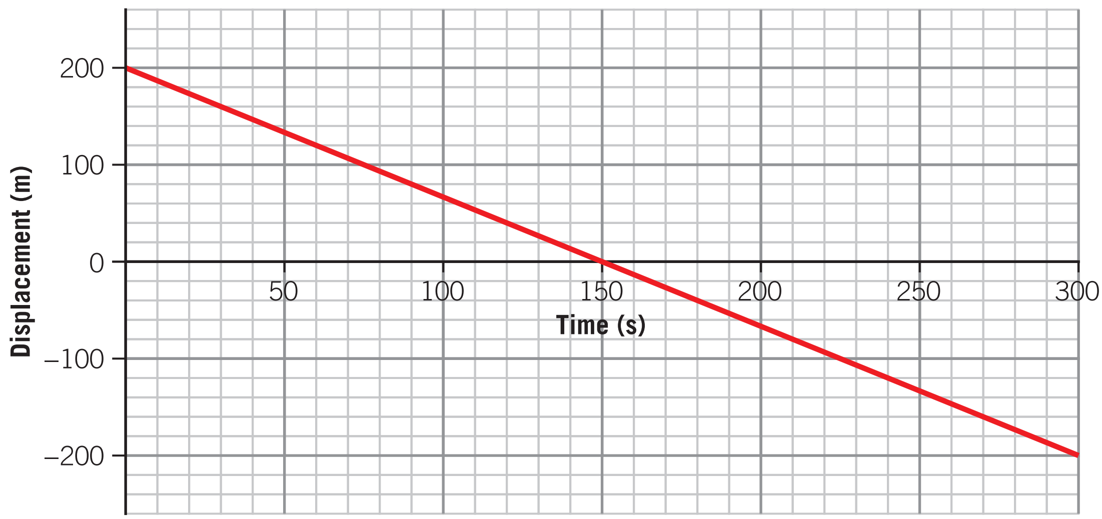
Section 7B questions

Multiple-choice questions

1 A hiker starts 200 m due east of their camp. A displacement–time graph of their hike is shown below.



Which of the following statements is the best description of the hiker's motion?

A The hiker walks east for 150 s before turning around and travelling west back to their camp.

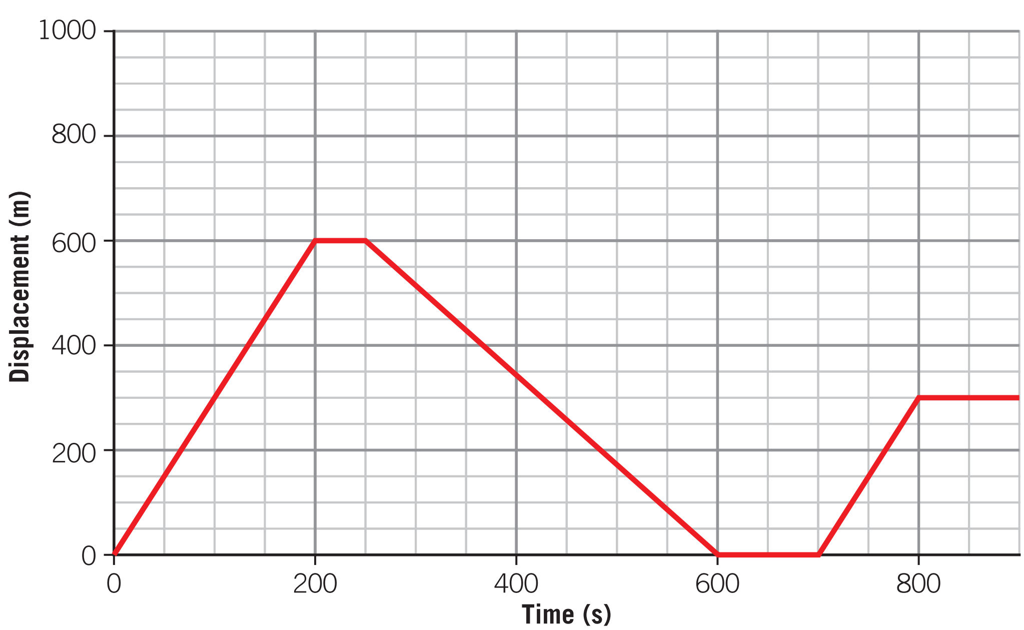
B The hiker's velocity is becoming smaller and smaller until, at 150 s, the hiker's velocity becomes momentarily zero and then becomes increasingly negative.

C The net displacement of the hiker after their journey is zero.

D The hiker walks west with a constant velocity.

Use the following information to answer Questions 2 and 3.

A runner goes out for a training session. A displacement–time graph of the runner's session is shown below.



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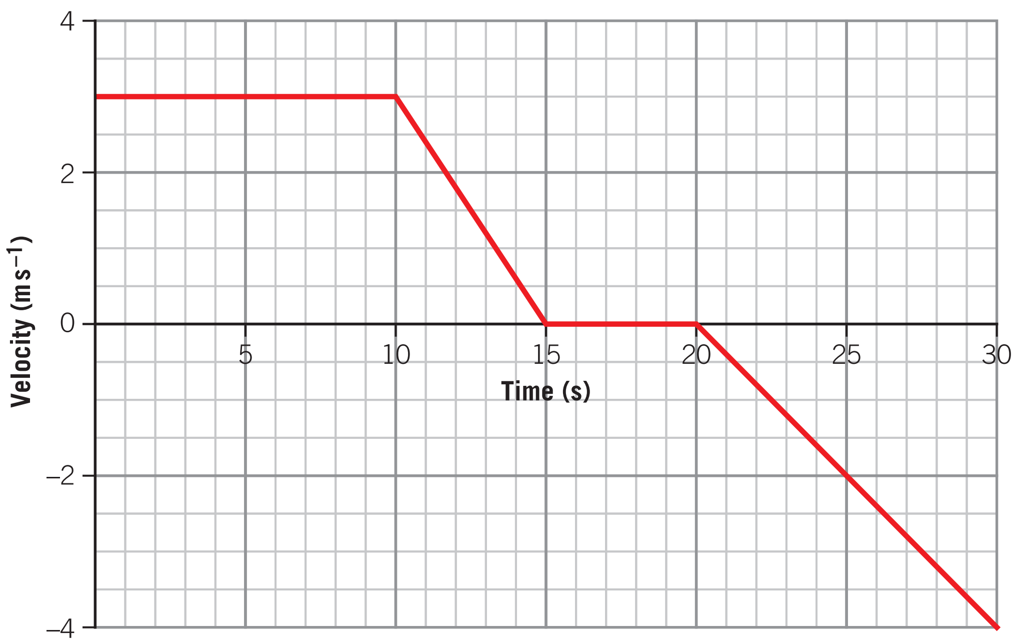
2 In which time interval(s) was the runner stationary?
A 250 to 600 s
B 200 to 250 s, 600 to 700 s and 800 to 900 s
C 0 to 200 s and 700 to 800 s
D 0 to 600 s only

3 What is the maximum speed of the runner during the running session?
A $3.00\ \text{m}\,\text{s}^{-1}$
B $1.71\ \text{m}\,\text{s}^{-1}$
C $0.583\ \text{m}\,\text{s}^{-1}$
D $0.333\ \text{m}\,\text{s}^{-1}$

Use the following information to answer Questions 4 and 5.

A runner completes a 30-minute running session on a straight road. The runner starts at their house and immediately travels north. The velocity–time graph of the runner's session is shown below.



4 Which of the following statements is not true?
A From 10 to 15 minutes, the runner is running back towards the origin.
B The runner does not finish their run back at their house.
C The runner stops running for 5 minutes once 15 minutes passes.
D The runner is travelling south in the last 10 minutes.

5 What is the acceleration of the runner in the last 10 minutes?
A $6.67 \times 10^{-3}\ \text{m}\,\text{s}^{-2}$ north
B $6.67 \times 10^{-3}\ \text{m}\,\text{s}^{-2}$ south
C $0.400\ \text{m}\,\text{s}^{-2}$ north
D $0.400\ \text{m}\,\text{s}^{-2}$ south

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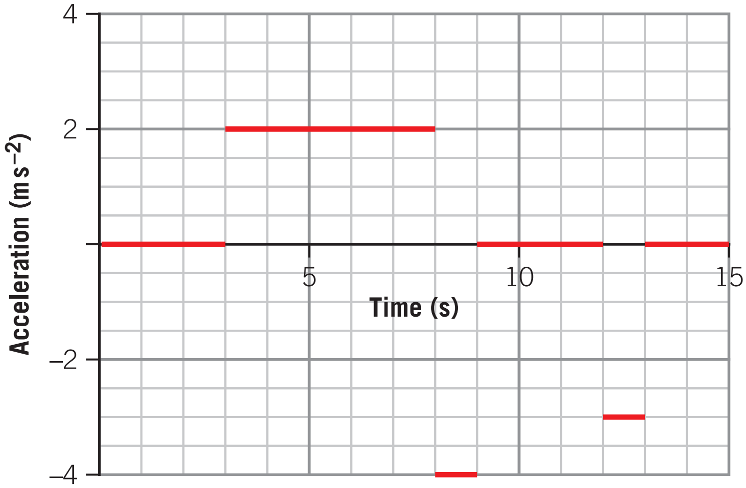
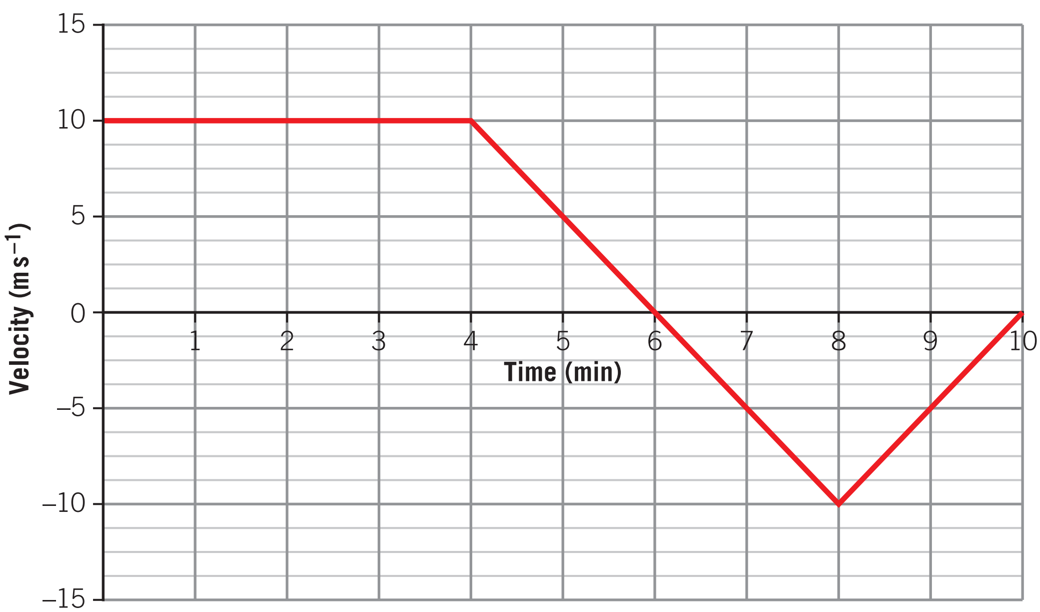
Short-answer questions

6 A car is travelling initially at 13 m s^{-1} in heavy traffic. An acceleration–time graph of part of the car's journey is shown below.



a List all of the times that the car is braking.
b What is the maximum velocity of the car?
c Calculate the final velocity of the car.

7 A cyclist is initially travelling north with a velocity of 10 m s^{-1}. The cyclist travels for 10 minutes and a velocity–time graph of the journey is shown below.



a Describe how the velocity and acceleration of the cyclist changes with time throughout the 10-minute journey. No exact values for acceleration are required.
b What is the cyclist's velocity after 7 minutes?
c If the cyclist starts from the origin, how far from the origin are they after 10 minutes?
d What is the total distance the cyclist covered in the journey?
e Use the graph to calculate the cyclist's acceleration between 4 and 8 minutes. Include a direction in your answer.

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8 A ball is thrown straight up in the air at 9.8 $m\,s^{-1}$; once 2 seconds have passed the ball is caught at the same height that the ball was released from. Assume that the ball reaches a maximum height of 4.90 m above its origin.

- **a** Draw a displacement–time graph of the motion of the ball. An appropriate scale, units, and x- and y-axis labels should be included.
- **b** Draw a velocity–time graph of the motion of the ball. An appropriate scale, units, and x- and y-axis labels should be included.
- **c** Draw an acceleration–time graph of the motion of the ball. An appropriate scale, units, and x- and y-axis labels should be included.

9 Some hikers start walking from a point 200 m north of their camp, which is considered the origin. They walk north at a constant velocity for 200 m over 100 seconds. They then stop and rest for 20 seconds before taking 200 seconds to walk back to their camp. The hikers rest at camp for 80 seconds and then travel 400 m south in 100 seconds.

- **a** Draw a displacement–time graph of the motion of the hikers. An appropriate scale, units, and x- and y-axis labels should be included.
- **b** During which time interval is the hikers' speed the greatest?
- **c** What is the average speed in the first 110 s?

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10 A banker accidently dropped a one-dollar coin, initially at rest, off a building. The building is 70.8 m tall and it takes the coin 3.80 s to fall. The displacement–time graph of the coin's velocity is shown below.

a Explain how the velocity of the coin changes with time.

b Calculate the average velocity for the coin for its 3.80-second fall and comment on how this would differ from the instantaneous velocity of the coin at this point.

c Which of the following is the velocity–time graph that matches the motion of the coin? Explain your choice.

A

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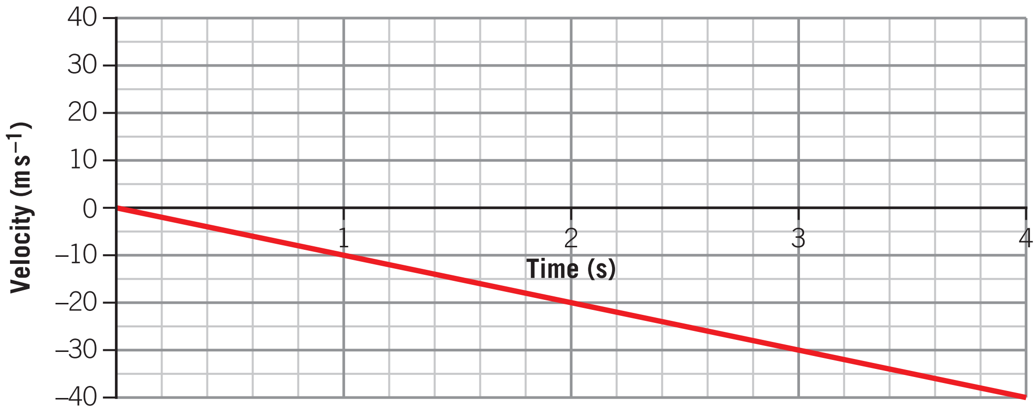
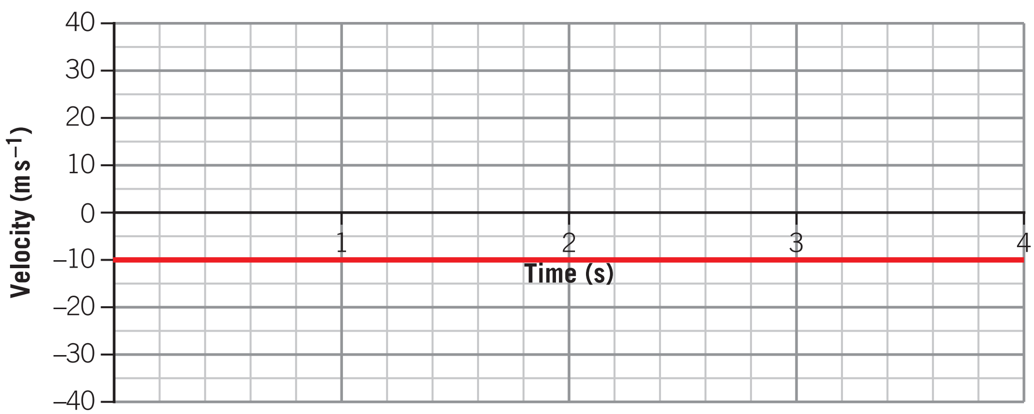
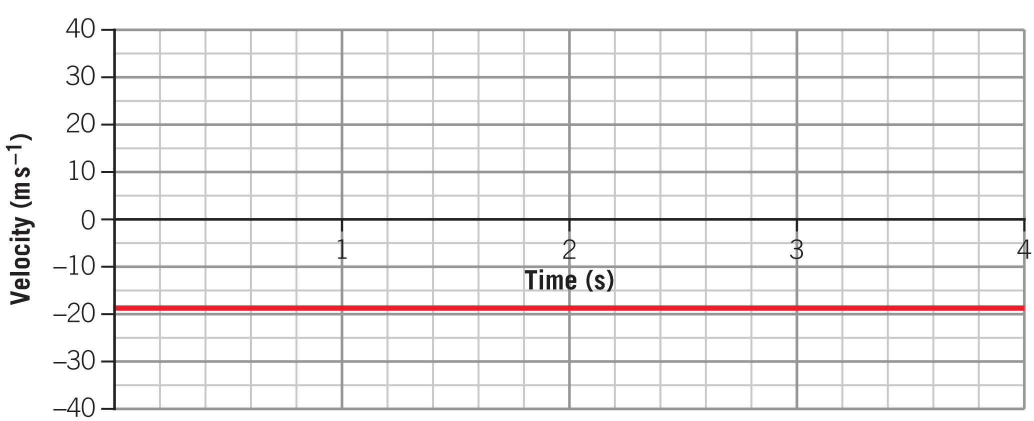
B



C



D



d Draw an acceleration–time graph of the motion of the coin. An appropriate scale, units, and *x*- and *y*-axis labels should be included.

e What was the total distance covered by the coin?

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7C Analysing straight-line motion with uniform acceleration

Study Design:

- Analyse graphically, numerically and algebraically, straight-line motion under constant acceleration $v = u + at$, $v^2 = u^2 + 2as$, $s = \frac{1}{2}(u+v)t$, $s = ut + \frac{1}{2}at^2$, $s = vt - \frac{1}{2}at^2$

Glossary:
Free-falling
Net force
Parabolic path

ENGAGE

The fastest man on Earth

On a still day in the Holloman Air Force Base in New Mexico, United States, Colonel John Paul Stapp climbed inside his Sonic Wind rocket sled, ready to be launched down the empty track. John Stapp was a pioneer of the effect of acceleration on the human body and he would often test on himself, as he was doing this day. The rocket sled accelerated from rest to a speed of 1015 km h^{-1} in 5 s and was then brought to rest again in 1.5 s. The top speed achieved by Stapp in Sonic Wind broke the existing land speed record, making him the fastest man on Earth over land.

Figure 7C–1 Colonel John Paul Stapp set a new land speed record of 1015 km h^{-1} in a rocket-driven sled

Such rapid acceleration and deceleration subjected Stapp's body to g-forces up to 46.2 *g*. This is still the highest known acceleration that has been voluntarily encountered by a human. A medical exam of Stapp after his world record revealed broken blood vessels in his eyes as well as numerous lacerations and bruises across his body. Stapp became a pioneer in seatbelt technology and helped to develop the car seatbelt commonly used today.

VIDEO 7C–1
STRAIGHT–LINE MOTION WITH UNIFORM ACCELERATION

EXPLAIN

Deriving the formulas for constant acceleration

When analysing straight-line motion, graphs are extremely useful. From graphs, you can derive the formulas for constant straight-line acceleration shown below:

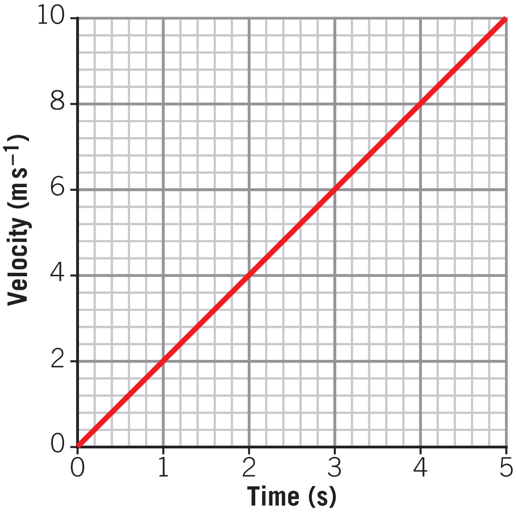

Figure 7C–2 Velocity–time graph for a cyclist accelerating at 2 m s^{-2} for 5 seconds

Formula 7C–1 Equations of constant acceleration

$$v = u + at$$

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

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

Where:

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

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

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

t = Time (s)

s = Displacement (m)

These formulas can then be applied to problems involving constant acceleration to quickly find a solution.

An object moving with constant acceleration is represented by a diagonal line on a velocity–time graph that has a constant, non-zero, gradient. For example, a cyclist accelerates at a constant rate of 2 m s^{-2} for 5 seconds. The velocity–time graph of the cyclist's motion is shown in Figure 7C–2.

Let's say you wanted to find the average velocity of the cyclist. The distance travelled is the area under the graph, so $d = \frac{1}{2}(5)(10) = 25\text{ m}$. Now, to find the average velocity, the distance is divided by the time, so $v = \frac{25}{5} = 5\text{ m s}^{-1}$.

Figure 7C–3 shows that even though the cyclist has an ever-changing velocity over time, they will cover the same distance in 5 seconds as a cyclist moving at a constant velocity of 5 m s^{-1}. Note that this average velocity is only applicable when the cyclist travels for 5 s. The average velocity would be less if the cyclist were to travel for less than 5 s and greater if travelling more than 5 s with the same acceleration.

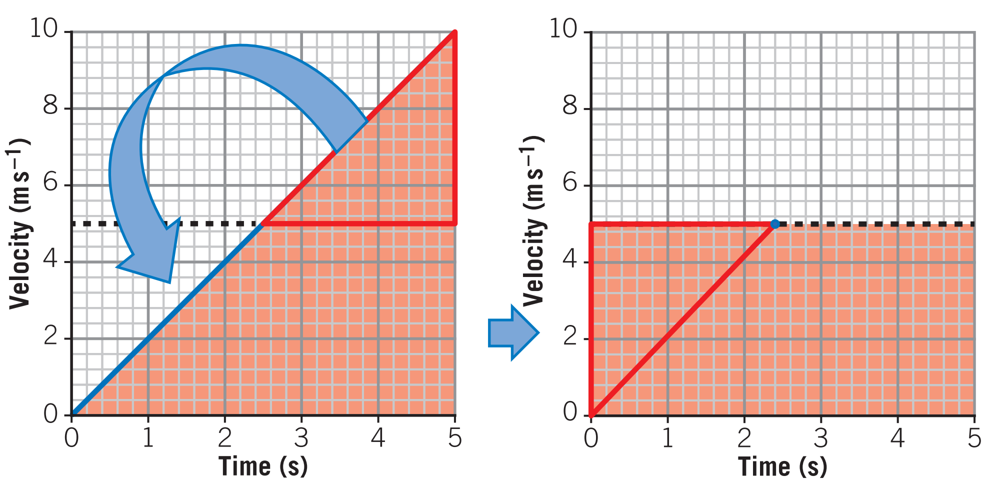

Figure 7C–3 A geometric view of the area under the velocity–time graph for the accelerating cyclist. The black dashed line is the average velocity, and this diagram shows that the area under the plotted line in the velocity–time graph is the same as the area under the average velocity plotted on the same axes.

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As you learned earlier in this chapter, the gradient of a velocity–time graph is the acceleration:

$$\text{gradient} = a = \frac{\text{rise}}{\text{run}} = \frac{\Delta v}{\Delta t} = \frac{v-u}{\Delta t}$$

This can be rearranged to give:

$v = u + at$ **This is one equation.**

Now consider the motion of another cyclist that is initially riding at 6 m s^{-1} and accelerates at a constant rate of 1 m s^{-2} for 5 s, as shown in Figure 7C–4. As you learned earlier in this chapter, the area under a velocity–time graph is the displacement. To find the displacement of the cyclist after their 5 s journey, the graph would have to be divided into a rectangle and a triangle.

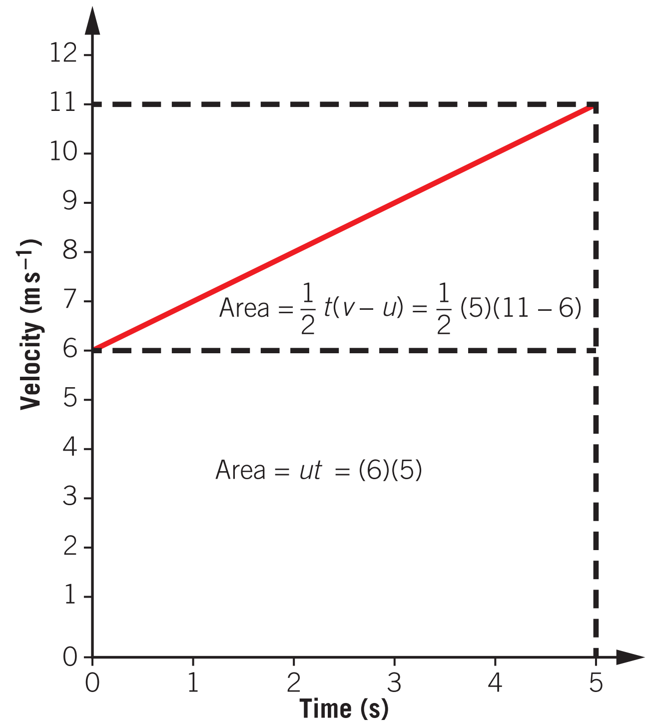

Figure 7C–4 Displacement of a cyclist initially riding at 6 m s^{-1} and accelerating at 1 m s^{-2} for 5 seconds

From Figure 7C–4, the displacement is given by:

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

All the other equations for uniform acceleration can be derived from this formula. The equation can be expanded and simplified to:

$$s = \frac{1}{2}tv - \frac{1}{2}tu + ut$$

$s = \frac{1}{2}(u+v)t$ **This is a second equation.**

You have learned that the acceleration is given by:

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

You can rearrange this to:

$$at = v - u$$

This means that at can be substituted for $v - u$ giving:

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

$$s = \frac{1}{2}t(at) + ut$$

$s = ut + \frac{1}{2}at^2$ **This is a third equation.**

The acceleration formula can then be rearranged to:

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

Then substituted into the equation as follows:

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

$$s = \frac{u+v}{2}\left(\frac{v-u}{a}\right)$$

$$s = \frac{v^2-u^2}{2a}$$

$v^2 = u^2 + 2as$ **This is a fourth equation.**

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The acceleration formula can be rearranged to:

$$u = v - at$$

It can then be substituted into the following equation:

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

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

$$s = vt - \frac{1}{2}at^2$$ **This is a fifth equation.**

All of the equations of constant acceleration are shown in Formula 7C–1. Note: It is not a requirement to know how to derive these formulas.

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Horizontal motion

LINK CHAPTER 8

Newton's first law, which will be discussed in more detail in Chapter 8, states that a body in motion or at rest will remain in its state of motion unless acted upon by an unbalanced force. This means that when a body moves horizontally through space, its velocity will not change unless acted upon by an unbalanced force. Often objects will have a constant unbalanced force applied to them, like a car that is accelerating uniformly or a sprinter who is sprinting out of the blocks. In these situations of uniform motion, the equations of motion can be applied. When solving horizontal motion questions about objects with constant straight-line acceleration:

- draw a diagram of the situation and put all the information that you have on the diagram in SI units
- choose an appropriate equation based on the data that you have and the data that you need. Remember that when vectors act in opposite directions, set one direction as positive; the opposite direction will then have a negative sign (except for t)
- round your final answer to three significant figures. Include units in your answer and, if your answer is a vector, a direction as well.

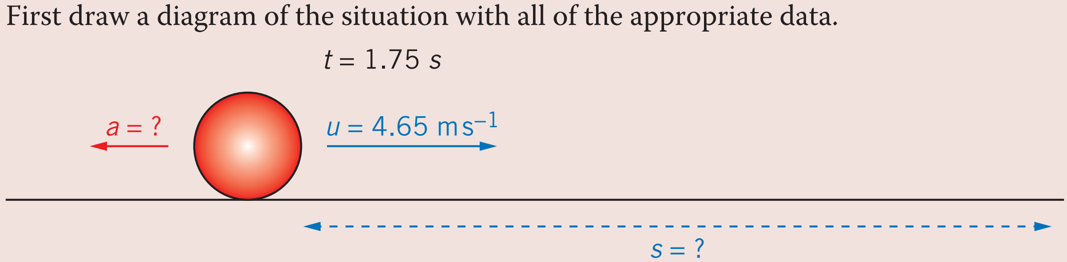
Figure 7C–5 Cheetahs are the fastest land animals on the planet; their acceleration is equal to most Lamborghini and Ferrari cars.

Worked example 7C–1 Using equations of constant acceleration

A ball travels forward with a velocity 4.65 m s^{-1}. As it rolls over the ground, it slows to a stop in 1.75 s. A force acts on the ball, causing a constant deceleration (negative acceleration). Calculate the distance the ball travels before coming to a stop.

Solution

First draw a diagram of the situation with all of the appropriate data.



Select the appropriate formula and solve the problem.

$$s = \frac{1}{2}(u+v)t = \frac{1}{2}(4.65+0)(1.75) = 4.07\,\text{m}$$

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WORKSHEET 7C–1 ANALYSING STRAIGHT LINE MOTION WITH UNIFORM ACCELERATION

Check-in questions – Set 1

1 A ball that has an initial velocity of 5 m s^{-1} is acted upon by a constant frictional force that causes it to decelerate at a constant rate of 1.42 m s^{-2}.
 a Calculate how much time passes before the ball comes to a stop.
 b Calculate the distance that the ball travels before coming to a stop.

2 A car accelerated from 18 km h^{-1} to 108 km h^{-1} in 10.2 s.
 a Calculate the acceleration of the car in m s^{-2}.
 b When the velocity of the car was 108 km h^{-1} the driver uses the brakes for 3 s and the brakes caused the car to decelerate at a constant rate of 6.22 m s^{-2}. Calculate the velocity of the car after the brakes were applied.

Vertical motion

Free-falling when a body is falling and the only force acting on the body is gravity

When a body is launched vertically, and if air resistance is ignored, there is generally only one force acting on the body – the downwards force of gravity. Close to the surface of Earth, the force due to gravity will cause all **free-falling** objects to accelerate at 9.8 m s^{-2} down, to the surface of Earth.

For example, imagine if a 1 kg mass and a 2 kg mass that are initially at rest are dropped and allowed to free-fall. If air resistance is ignored, they will both reach a velocity of 9.8 m s^{-1} down after 1 second, and then reach a velocity of 19.6 m s^{-1} down after 2 seconds. If the 1 kg and 2 kg masses are thrown up with a velocity of 19.6 m s^{-1}, the two masses will accelerate downwards towards the surface of Earth. After 1 second, the velocity of both masses would be reduced to 9.8 m s^{-1} up, and after 2 seconds the velocity of both masses would be reduced to zero.

Figure 7C–6 A Peregrine falcon mid-dive. During such dives the peregrine falcon can reach speeds of 390 km h^{-1}, which is about 30% faster than the top speed of the civilian helicopter.

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Although there is no direct record of it, it is said that in the 1500s, Italian scientist Galileo Galilei dropped two objects off the Leaning Tower of Pisa. Even though one of the objects was much lighter than the other, they both fell at the same rate, indicating that the acceleration on both masses is the same. In 1971, during the Apollo 15 Moon landing, astronaut David Scott dropped a feather and a hammer at the same time. Since there was minimal air resistance on the Moon, both the feather and the hammer hit the ground at the same time.

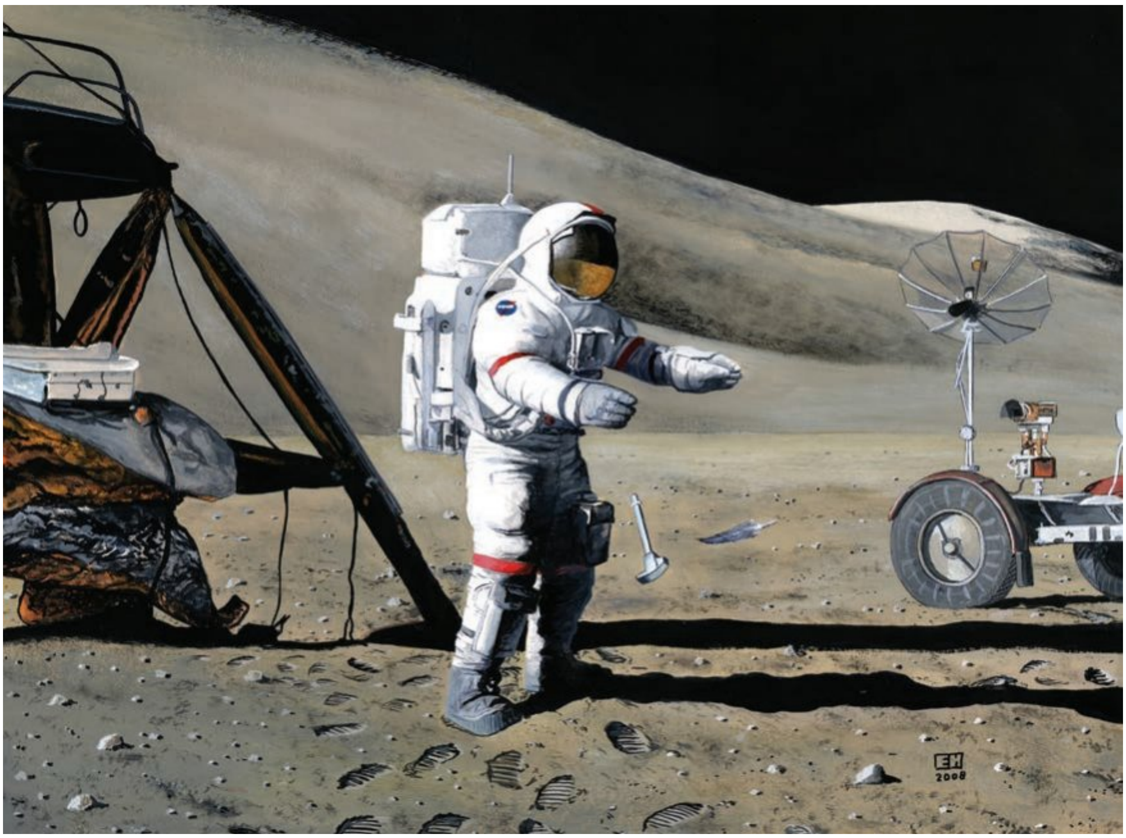

Figure 7C–7 David Scott dropped a feather and a geology hammer during the Apollo 15 mission in 1971

These examples demonstrate that the acceleration close to the surface of Earth is unaffected by an object's mass or velocity. Both masses had the same change in velocity and even the masses that were travelling upwards had a change in their velocity equal to 9.8 $m\,s^{-1}$ downwards every second.

The steps to solving a vertical motion problem are the same as the steps to solving a horizontal motion problem. However, in vertical motion problems there are a number of key things to remember that will assist in solving them (ignoring air resistance).

- The constant acceleration acting on all free-falling bodies is 9.8 $m\,s^{-2}$ down.
- Gravity is usually given a negative sign in an equation of motion and velocities directed upwards are given a positive sign.
- An object that is thrown upwards will slow down until it comes to a stop; gravity will then begin to bring the object back down to Earth.
- The stationary point of an object that is projected up in the air is its maximum height and half of the total flight time if the object lands at the same level that it was launched.

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Worked example 7C–2 Vertical motion from a drop

A cliff diver of mass 76 kg jumps off a cliff that is 15.1 m tall. If the cliff diver has no velocity when he leaves the cliff, calculate the velocity of the diver the moment before he hits the water. Ignore the effects of air resistance.

Solution

The first step is to determine which direction is positive. In this example, it is easier to take down as positive. The second step is to identify all of the information in the question:

$m = 76\ \text{kg}$

$s = 15.1\ \text{m}$

$u = 0\ \text{m s}^{-1}$

$a = 9.8\ \text{m s}^{-2}$

$v = ?$

The mass of the diver is included but is irrelevant to this question as the acceleration of gravity is the same on all objects. Once you have all the relevant information, find an appropriate formula and solve the equation.

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

$$v = \sqrt{u^2 + 2as}$$

$$= \sqrt{(0)^2 + 2(9.8)(15.1)}$$

$$= 17.2\ \text{m s}^{-1}$$

Note that since gravity was acting down and the displacement was in the down direction, both numbers have been given a positive sign.

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Worked example 7C–3 Vertical motion from a throw

A student throws a ball of mass 200 g into the air vertically upwards, with an initial velocity of 20 m s^{-1}. When the ball leaves the student's hand, it is already 1.22 m above the ground.

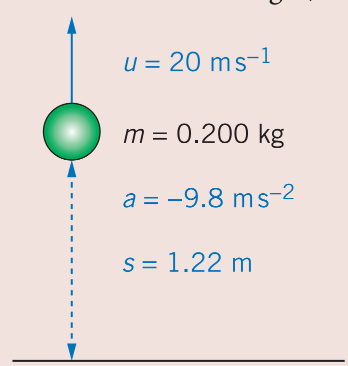
a Calculate the maximum height above the ground reached by the ball.

b Calculate the total flight time of the ball, assuming that the student catches the ball at a height of 1.22 m above the ground.

Solution

a The first step is to draw a diagram with all of the information given.

There is another piece of important information to remember; when the maximum vertical height is reached, the velocity of the ball will be zero. This means if you consider the movement of the ball from when it is released to its maximum height, the final velocity of the ball will be zero.



With this piece of information, you can now apply an appropriate formula:

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

$$s = \frac{v^2 - u^2}{2a}$$

$$= \frac{(0)^2 - (20)^2}{(2)(-9.8)} = 20.4 \text{ m}$$

This is the distance that the ball travelled before it reached its turning point; to get the maximum height the initial height of the ball must be added.

maximum height = 20.4 + 1.22 = 21.6 m

b This problem can be solved with the knowledge that the time to reach the maximum height is half of the total flight time, as the ball lands at the same height that it was launched. Therefore, you must choose an appropriate formula with time:

$$v = u + at$$

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

$$= \frac{(0) - (20)}{(-9.8)} = 2.04 \text{ s}$$

total time = 2.04 × 2 = 4.08 s

There is often more than one way of reaching a solution. When a projectile is in free-fall, there is symmetry in the projectiles upwards and downwards movement. When the ball is travelling upwards, its upwards velocity is reducing by 9.8 m s^{-1} every second; in this case the ball will travel 20.4 m up before the ball no longer has any upwards velocity. After this momentary stationary point, the ball will then fall a distance of 20.4 m, which means that just before the ball is caught, it will be travelling down at 20 m s^{-1}. This can then be used as the final velocity as follows.

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

$$= \frac{(-20) - (20)}{(-9.8)} = 4.08 \text{ s}$$

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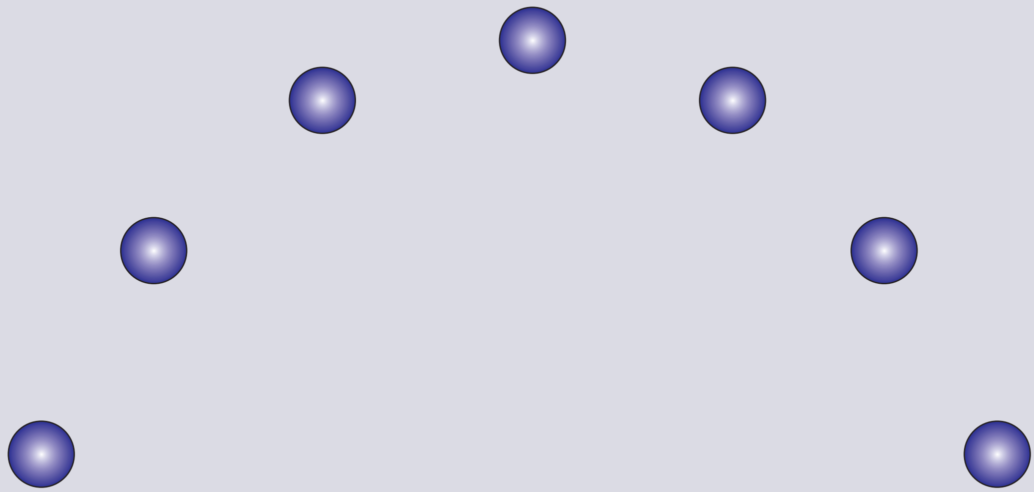
VIDEO 7C–2 SKILLS: UNDERSTANDING GRAVITY

Parabolic path an approximately U-shaped plane curve that is mirror-symmetrical. This is the path taken by a projectile that is only under the influence of gravity and air resistance is considered negligible.

7C SKILLS

Understanding gravity

If you throw a ball as far as you can, it will trace a **parabolic path** as shown below, if the effect of air resistance is ignored.



If you ignore air resistance, what are the forces acting on the ball throughout its flight?

Some students may say that since the ball is going up, the force on the ball must be up. This is not true. The ball may be going up, but the only force acting on the ball is the force due to gravity, which is downwards and constant.

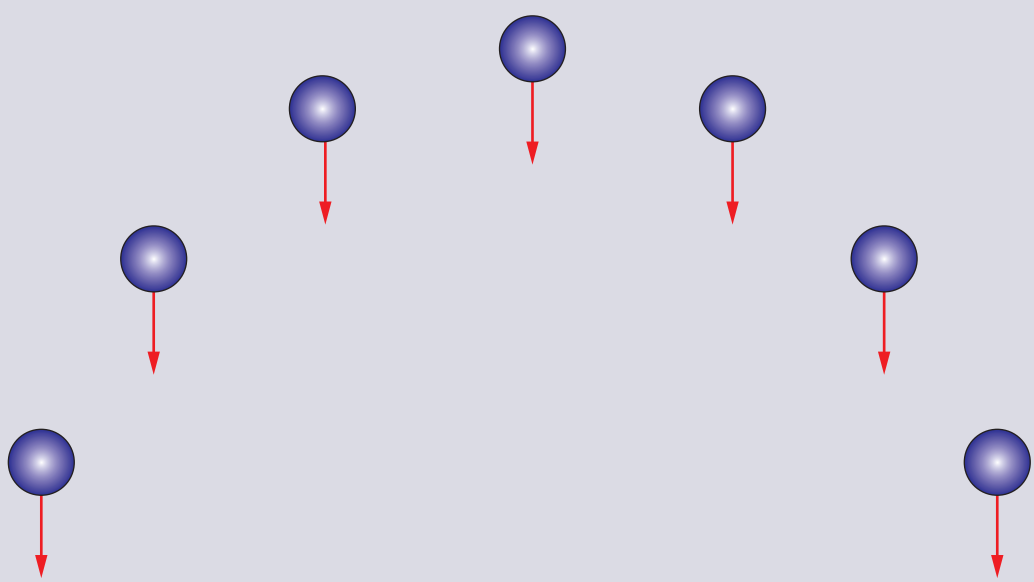


Figure 7C–8 When a body is in flight, the only force acting on it is the force due to gravity, which is downwards and constant.

Net force the sum of all of the forces acting on an object

Bodies will accelerate in the direction of the **net force**, so the constant downward force of gravity will create a constant acceleration on the ball of 9.8 m s^{-2} down. This means that whenever you are solving a question that involves a body in free-fall, you will always know that the magnitude and direction of the acceleration acting on the body is 9.8 m s^{-2} down.

It is important to note that the acceleration and the velocity are not the same. For example, when you throw the ball it is initially moving up; it then has a momentary point of zero velocity before its velocity is then in the downwards direction. Causing these changes to the ball's velocity is the acceleration due to gravity, 9.8 m s^{-2} down.

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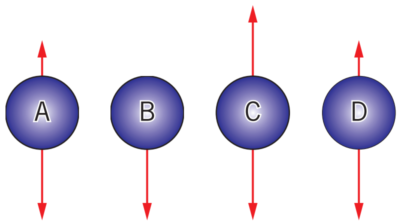
Section 7C questions

Multiple-choice questions

1 A ball is thrown vertically up into the air. As the ball is travelling up, which of the diagrams below represents the magnitude and direction of all the forces acting on the ball?



A A
B B
C C
D D

2 A cricket player hits a ball up vertically from ground level. The ball travels unaffected by air resistance and lands back down in the same spot from which it was hit. Which of the following statements relating to the motion of the ball once it has left the cricket bat is incorrect?
A The velocity with which the ball leaves the bat will be equal in magnitude but opposite in direction to the velocity with which the ball hits the ground.
B When the ball is moving up, it must have a force acting on it that is also up.
C The acceleration that the ball experiences does not depend on its mass.
D The time taken to reach the turning point will be half of the total flight time.

3 In a game of volleyball, a player hits the ball vertically upwards. Which of the following is the best description of the ball's motion when it reaches its maximum height?
A The ball's velocity and acceleration have been reduced to zero.
B The ball's velocity is zero, but the acceleration is down.
C The ball's velocity is in the upward direction, but the acceleration is down.
D Both the velocity and the acceleration are downwards.

4 A car driving through bad weather slows from 99 $km\,h^{-1}$ to 18 $km\,h^{-1}$ in 14 s. The magnitude of the acceleration of the car is
A 20.8 $m\,s^{-2}$
B 10.2 $m\,s^{-2}$
C 5.79 $m\,s^{-2}$
D 1.61 $m\,s^{-2}$

5 A coin, initially at rest, is dropped into a well. The coin travels 3.96 m before it hits the surface of the water in the well. What is the velocity of the coin just before it strikes the surface of the water?
A 77.6 $m\,s^{-1}$
B 19.4 $m\,s^{-1}$
C 8.8 $m\,s^{-1}$
D 3.96 $m\,s^{-1}$

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Short-answer questions

6 A passenger onboard a hot air balloon drops her camera. It takes the camera 7.88 s to fall from rest down to the ground. Assume air resistance is negligible.

a Show that the camera was dropped from a height of 304 m.

b Calculate how much time it took for the camera to cover the first half (the first 152 m) of its journey to Earth.

c Calculate the velocity of the camera just before it strikes the ground.

7 The minimum braking distance of a car is determined by the driver's reaction time and the deceleration provided by the brakes. A car is travelling at a speed of 81 km h^{-1} when the driver sees a kangaroo jump on the road. The driver travels 9.44 m during the reaction time and a further 31 m while the car is braking with a constant acceleration.

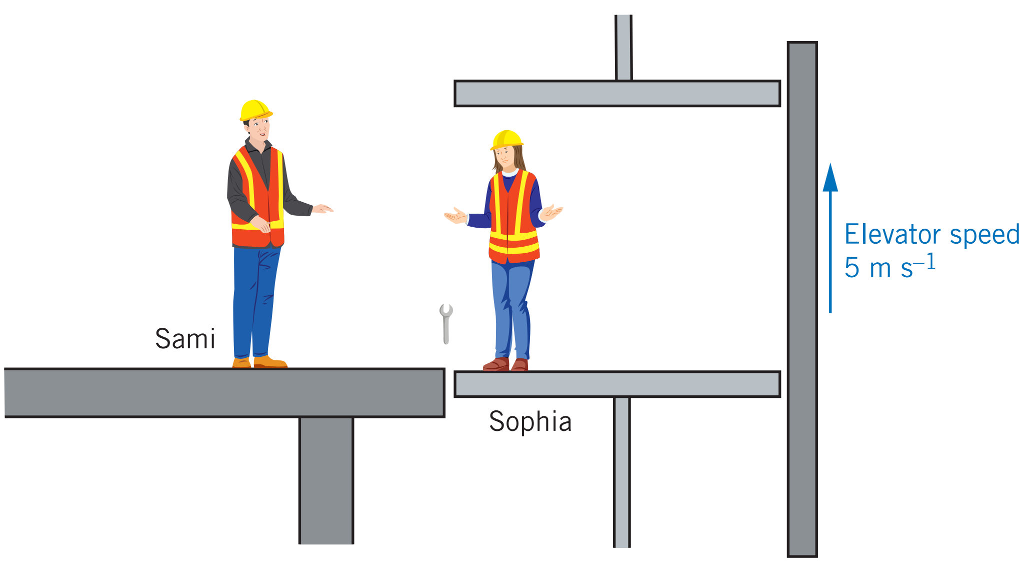
a What is the speed of the car in metres per second?

b Calculate the driver's reaction time.

c What is the magnitude of the acceleration of the car during braking?

d Calculate the total time that it took to stop the car.

8 On a construction site of a new skyscraper, Sophia takes an open elevator up to the top floor. The elevator moves at a constant speed of 5 m s^{-1}. As Sophia passes the third floor, she drops a wrench outside the elevator and onto the third floor. Sami is standing on the third floor and sees Sophia drop the wrench. Sophia states that in her point of view the wrench is falling down as soon as she drops it so Sami must also see the wrench falling down as soon as Sophia drops it.



a Comment on the accuracy of Sophia's statement.

b At the exact moment that Sophia drops the wrench, Sam throws a bolt in the air with a speed of 5 m s^{-1}. Which would land on the floor of the third floor first? Explain your answer.

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9 A truck is travelling at a constant velocity of 126 $\mathrm{km\,h^{-1}}$ when it passes a stationary police car. As soon as the two vehicles are level, the police car accelerates at 5 $\mathrm{m\,s^{-2}}$ to catch up to the speeding truck.

a How much time does it take before the velocity of the police car is equal to the velocity of the truck?

b If the police car continues to accelerate at the same rate and the velocity of the truck stays constant, how much time does it take before the police car is level with the truck?

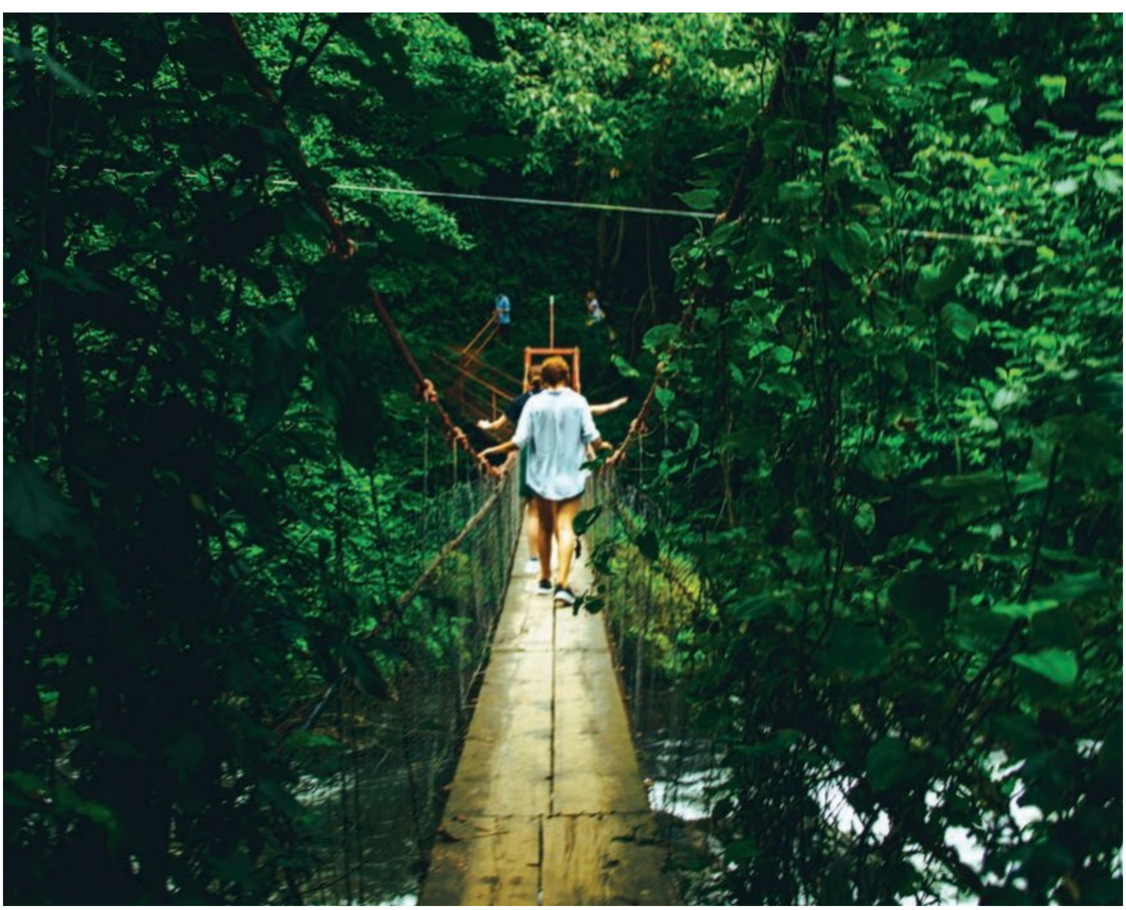
10 Two students, Adam and Meg, are standing on a bridge that is 12.4 m above the water below. Adam has a 1 kg stone and Meg has a 0.5 kg stone. Adam throws his stone up with a velocity of 13.0 $\mathrm{m\,s^{-1}}$ and Meg throws her stone down with a velocity of 13.0 $\mathrm{m\,s^{-1}}$. Assume that air resistance is negligible.

a What is the maximum height above the water achieved by the stone that Adam throws?

b Adam says that both stones will hit the water with the same velocity, but Meg says that the stone that she throws straight down will hit the water below with the greatest velocity. Who is correct? Justify your answer.

c Whose stone hits the water first? Prove your answer by calculating the exact time for each person's stone to hit the ground.

d Adam's stone is twice the mass of Meg's stone. If air resistance is ignored and Meg threw her ball directly up, like Adam, what effect would the mass of the stone have on the stone's motion? Explain your answer.



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Chapter 7 review

Summary

Create your own set of summary notes for this chapter on paper or in a digital document. A model summary is provided in the Teacher Resources, which can be used to compare with yours.

Checklist

In the Interactive Textbook, the success criteria are linked from the review questions and will be automatically ticked when answers are correct. Alternatively, print or photocopy this page and tick the boxes when you have answered the corresponding questions correctly.

Success criteria – I am now able to:		Linked questions
7A.1	Recall that a vector requires a magnitude and direction while a scalar only needs a magnitude	14☐
7A.2	Recall common types of vectors and scalars	2☐
7A.3	Perform basic straight-line addition of vectors	1☐, 7☐, 14☐
7A.4	Determine the components of vectors.	3☐, 16☐
7A.5	Determine an unknown vector when when given the initial vector and the resultant vector	4☐, 15☐
7B.1	Interpret a displacement–time graph	6☐, 13☐
7B.2	Apply the knowledge that the gradient of a displacement–time graph is the velocity	6☐, 13☐
7B.3	Interpret a velocity–time graph	5☐, 19☐, 20☐
7B.4	Apply the knowledge that the gradient of a velocity–time graph is the acceleration	5☐, 8☐, 19b☐, c☐
7B.5	Apply the knowledge that the area under a velocity–time graph is the total displacement and the absolute values of the area under the graph is the total distance travelled	9☐, 19b☐, c☐
7B.6	Interpret an acceleration–time graph	12☐
7B.7	Apply the knowledge that the area under an acceleration–time graph is the change in velocity	12☐
7C.1	Analyse numerically and algebraically, straight-line motion under constant acceleration using the formulas: $v = u + at$, $v^2 = u^2 + 2as$ and $s = \frac{1}{2}(u+v)t = ut + \frac{1}{2}at^2 = vt - \frac{1}{2}at^2$	11☐, 14☐, 15☐, 17☐, 18☐, 19☐, 20☐

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Multiple-choice questions

1 Two men are having a tug of war. One man pulls on one end of the rope with a force of 200 N to the left and the other man pulls on the opposite end of the rope with a force of 150 N right. A diagram of this situation is shown below.

The net force applied to the centre of the rope is

A 350 N left.
B 200 N right.
C 50 N right.
D 50 N left.

2 Which of the following is a not scalar quantity?

A mass
B time
C acceleration
D speed

3 A towing cable is placed between two cars. The tension in the cable is 20 000 N and the cable makes an angle of 15° to the horizontal. The horizontal component of the tension force is

A 20 000 N
B 19320 N
C 1456
D 518 N

4 A basketball player is bouncing a basketball up and down. On one particular bounce the ball hits the ground with a velocity of 7.80 $m\,s^{-1}$ down and rebounds with a velocity of 5.30 $m\,s^{-1}$ up. The change in the velocity is

A 13.1 $m\,s^{-1}$ up.
B 13.1 $m\,s^{-1}$ down.
C 2.50 $m\,s^{-1}$ up.
D 2.50 $m\,s^{-1}$ down.

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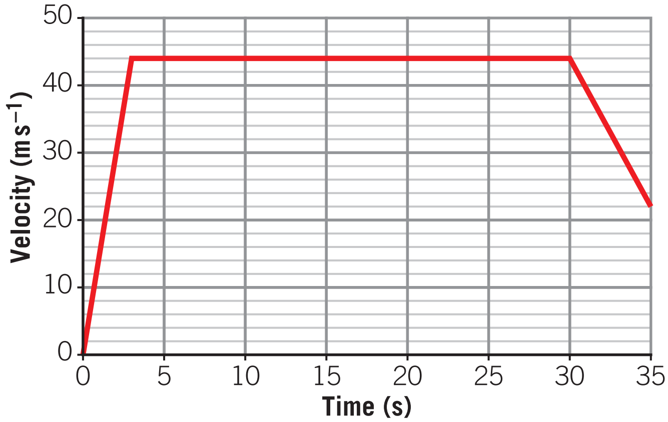
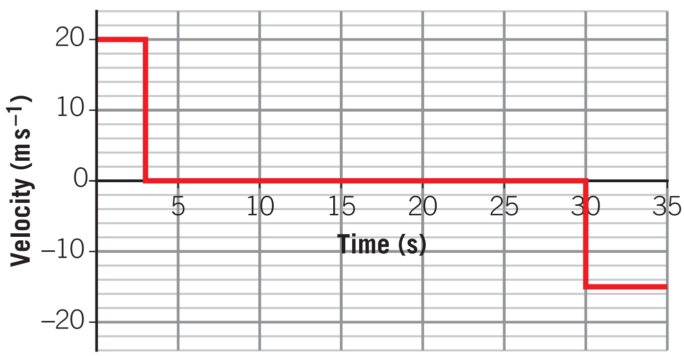
5 A car accelerates from rest at a constant rate for 3 s. The car then stays at a constant velocity for 27 s before slowing down at a constant rate for 5 s. Which of the following is an accurate graph for the motion of the car?

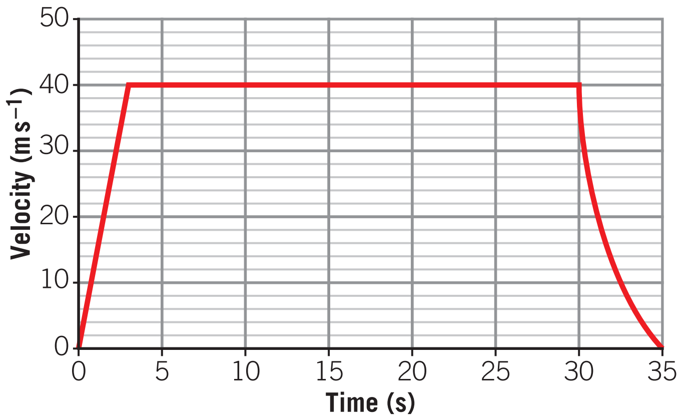
A



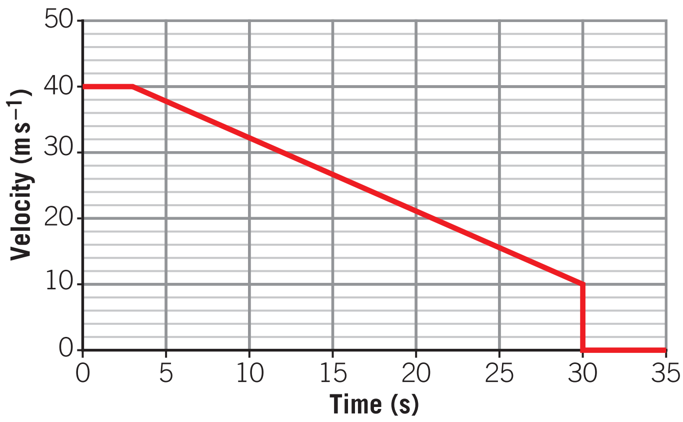
B



C



D



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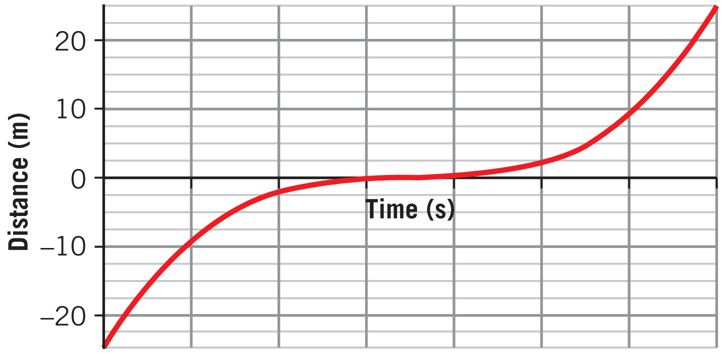
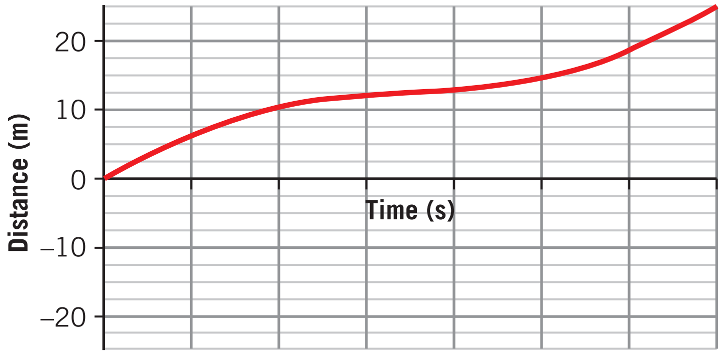
6 A ball is thrown vertically up into the air. Ignoring air resistance, which of the following is the best graph of the total distance travelled by the ball?

A

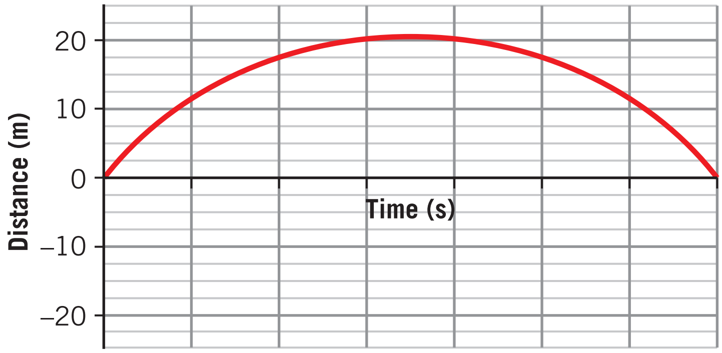


B



C

D



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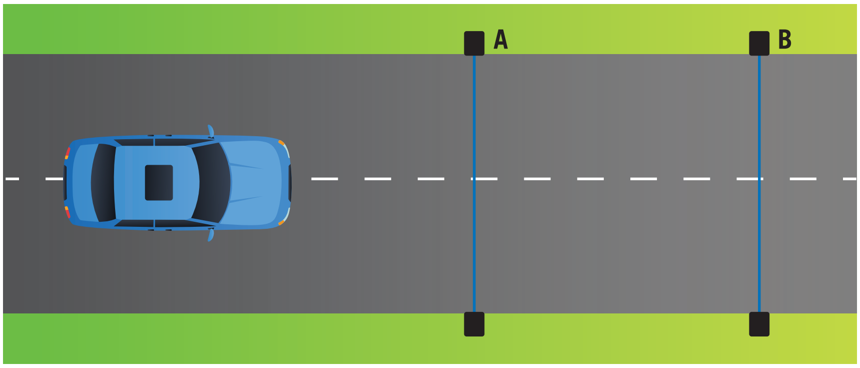
7 A person in a car travels past a bus stop at a constant velocity of 72 $km\,h^{-1}$. While passing the pedestrians at the bus stop, the driver accidentally drops his sunglasses out of the window. Which one of the following statements correctly describes the motion of the sunglasses? Ignore air resistance.

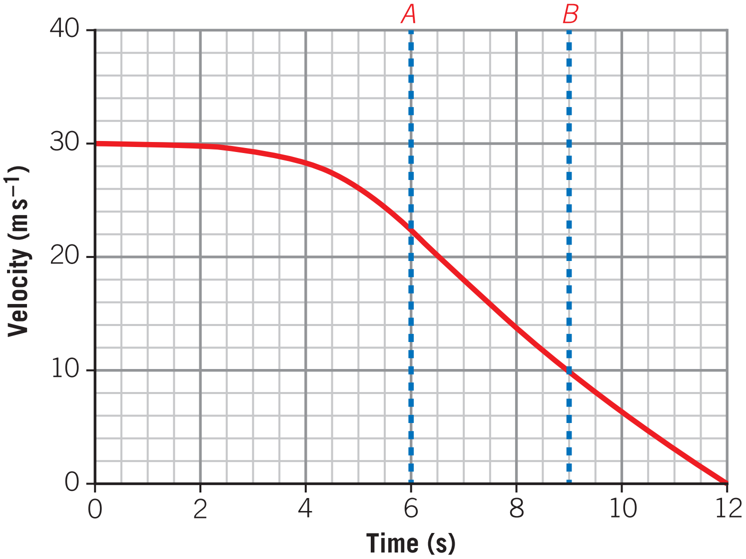
A The sunglasses will move back and down, as seen by the driver.
B The sunglasses will move vertically down and not move horizontally, as seen by the driver.
C The sunglasses will move vertically down and back, as seen by the pedestrians at the bus stop.
D Both A and C are correct.

Use the following information to answer Question 8, 9 and 10.

On a vehicle-testing site, a new car is having its brakes tested. The car moves along a straight road before braking. Set up along the road are two infrared timing gates A and B that are used to measure the motion of the car midway through its brake test. A diagram of this situation is shown below.



The velocity–time graph of the car's motion once the car starts braking is shown below. At times *A* and *B*, the car crosses the timing gates A and B.



8 Calculate the average acceleration of the car between times *A* and *B*.

A 3.66 $m\,s^{-2}$
B 1.11 $m\,s^{-2}$
C −3.6 $m\,s^{-2}$
D −4.00 $m\,s^{-2}$

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9 What is the distance covered by the car between points *A* and *B*?

A 144 m
B 96 m
C 48 m
D 24 m

10 What is the average speed of the car measured by the infrared timing gates A and B?

A 22 $m\,s^{-1}$
B 16 $m\,s^{-1}$
C −16 $m\,s^{-1}$
D −4 $m\,s^{-1}$

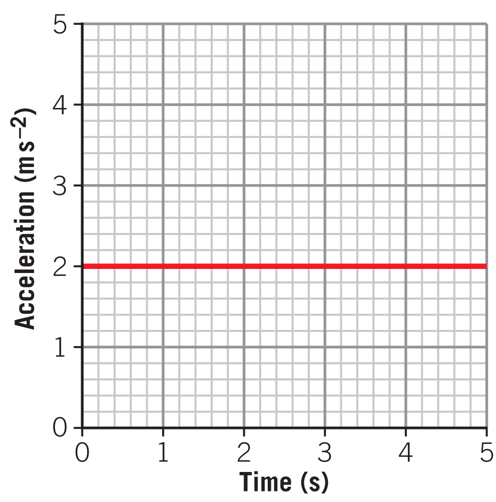
Short-answer questions

11 A skydiver is falling vertically down with a constant velocity of 5 $m\,s^{-1}$ downwards. When the skydiver is 100 m above the ground, a pen falls from their pocket. Assume that the pen falls with no air resistance and that the skydiver continues to fall with a constant velocity of 5 $m\,s^{-1}$ down.

a Calculate the speed with which the pen strikes the ground. (2 marks)
b How much time passes before the pen hits the ground? (2 marks)
c How much time passes once the pen hits the ground before the skydiver lands on the ground? (2 marks)

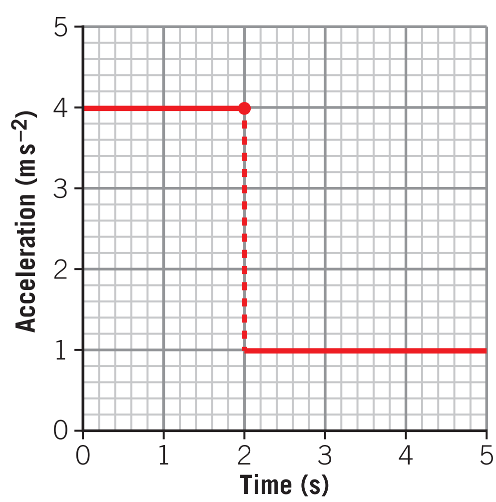
12 A track cyclist starts from rest and the first 5 s of their start is recorded in the acceleration–time graph on the right.

a Sketch a velocity–time graph of the cyclist's motion in the first 5 s. (2 marks)



Another cyclist sets off, and their acceleration–time graph is given on the right.

b Calculate the final velocity of the cyclist after these 5 s have gone by. (2 marks)



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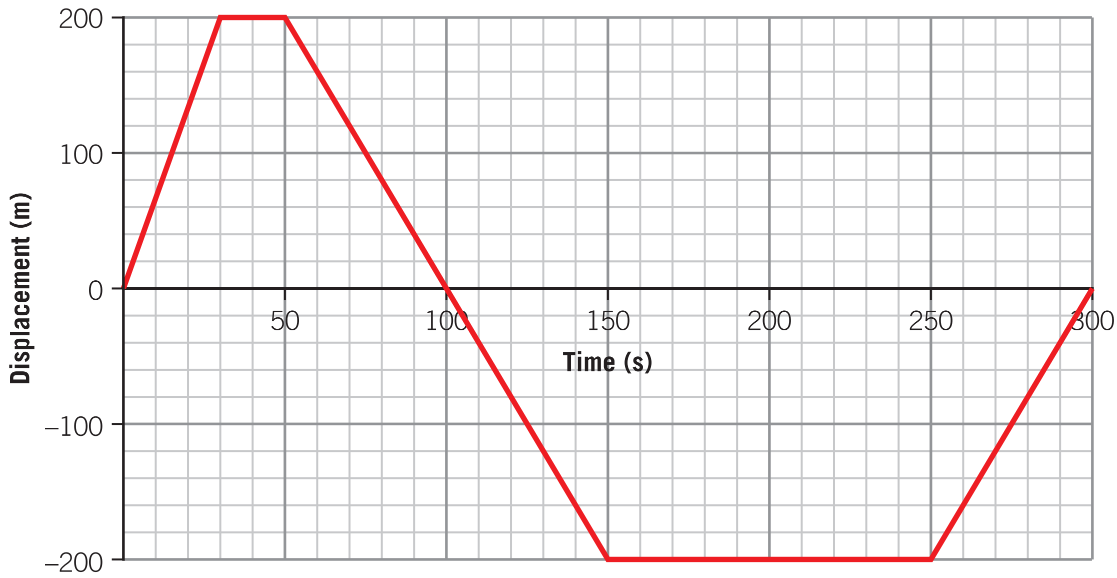
13 A runner places their water bottle on the ground and begins doing sprints to and past the water bottle. A displacement–time graph of the runner's motion is shown below, where the position of the bottle represents the origin.



a What is the total distance covered by the runner? (2 marks)

b What is the longest distance that the runner completes without stopping for a break. (1 mark)

c What is the maximum speed of the runner throughout their 300 s run? (2 marks)

14 A water rocket is launched into the air. It has a thrust force of 1.5 N up and a weight force of 0.5 N down. Assume that air resistance is negligible.

a Is force a vector or a scalar? Justify your answer. (2 marks)

b What is the net force on the rocket? (2 marks)

After 0.433 s, the rocket is travelling with a velocity of 8.55 $m\,s^{-1}$ up and it is 4.33 m above the ground. The rocket has used up all its water and so the only force acting on the rocket is the force due to gravity.

c Calculate the time to reach the maximum height. (2 marks)

15 A car is travelling with a velocity of 20 $m\,s^{-1}$ north but slows down for a school zone to a velocity of 11 $m\,s^{-1}$ north.

a What is the change in velocity of the car? Include a direction in your answer. (3 marks)

b If the car travelled 88.7 m while braking, how much time was the driver braking for? (2 marks)

c What is the acceleration of the car? Include a direction in your answer. (3 marks)

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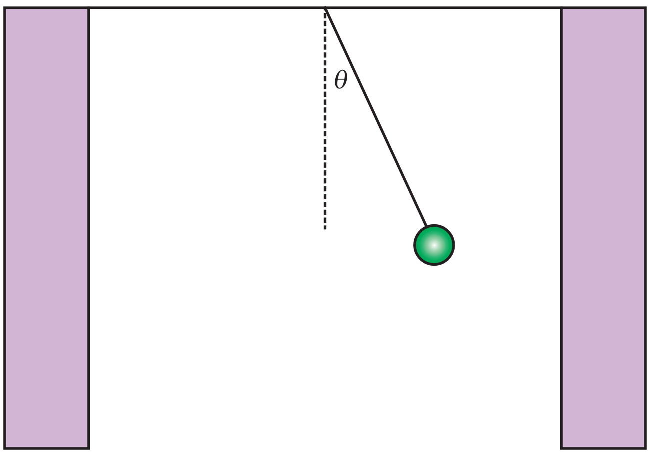
16 A charged metal ball is suspended by a string between two electric plates. When the plates are turned on, they apply an electrostatic attractive force on the ball to the right of 200 N. The force due to gravity on the ball is 550 N.



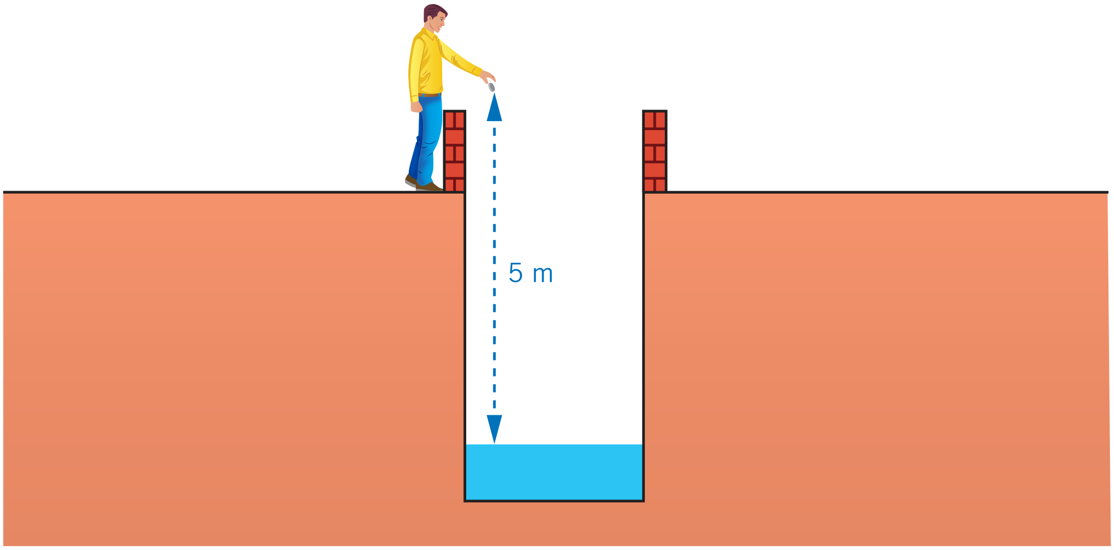
Calculate the angle that the string makes with the vertical. (3 marks)

17 A car is at rest at a set of lights. When the green light turns on, the car accelerates to a velocity of 99 $km\,h^{-1}$ in 7.91 s.

a Calculate the magnitude of the acceleration of the car during this time. (3 marks)

b Calculate the distance travelled by the car while accelerating. (2 marks)

18 A person is standing by a deep wishing well. They hold their coin 5 m above the surface of the water in the well and flick it up with a speed of 3.75 $m\,s^{-1}$. The coin travels up and then falls down into the well. A diagram of this is shown below.



a Calculate the maximum distance above the water of the well that the coin reaches. (3 marks)

b Calculate the speed with which the coin strikes the water. (2 marks)

c Calculate the total flight time. (2 marks)

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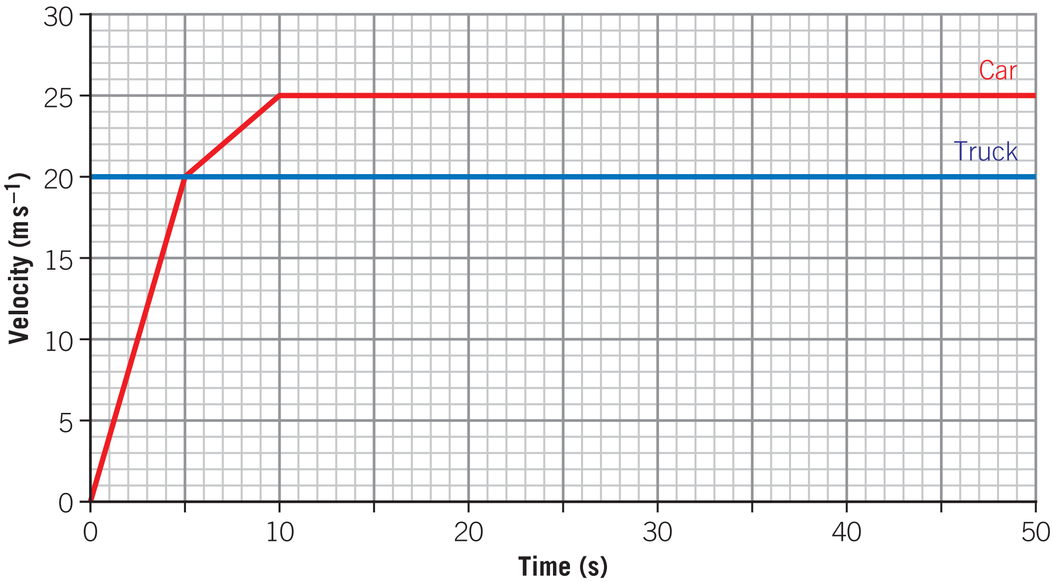
19 A truck is driving down a straight road when it passes a car at $t = 0$, the car then sets off and travels along the same straight road. A velocity–time graph of the two vehicles is shown below.



a Describe the motion of the car. (3 marks)

b What is the average acceleration, in metres per second, of the car during the first 10 s? (2 marks)

c At what time does the car overtake the truck? (3 marks)

20 A man in a hot air balloon is filming a hawk. The man drops some of the hawk's food, which is initially at rest, from the balloon. Seeing the food drop, the hawk flies down and passes the point where the food was initially dropped 0.730 s later with a velocity of 20 m s^{-1}. Once the hawk is level with where the food was initially dropped from, it tucks into a dive position, which means only gravity is accelerating the hawk down.

a How much time passes after the hawk takes off when the food is caught by the hawk? (3 marks)

b How much distance does the food travel before getting caught? (2 marks)

c Use a velocity–time graph to sketch the motion of the hawk and its food. (2 marks)

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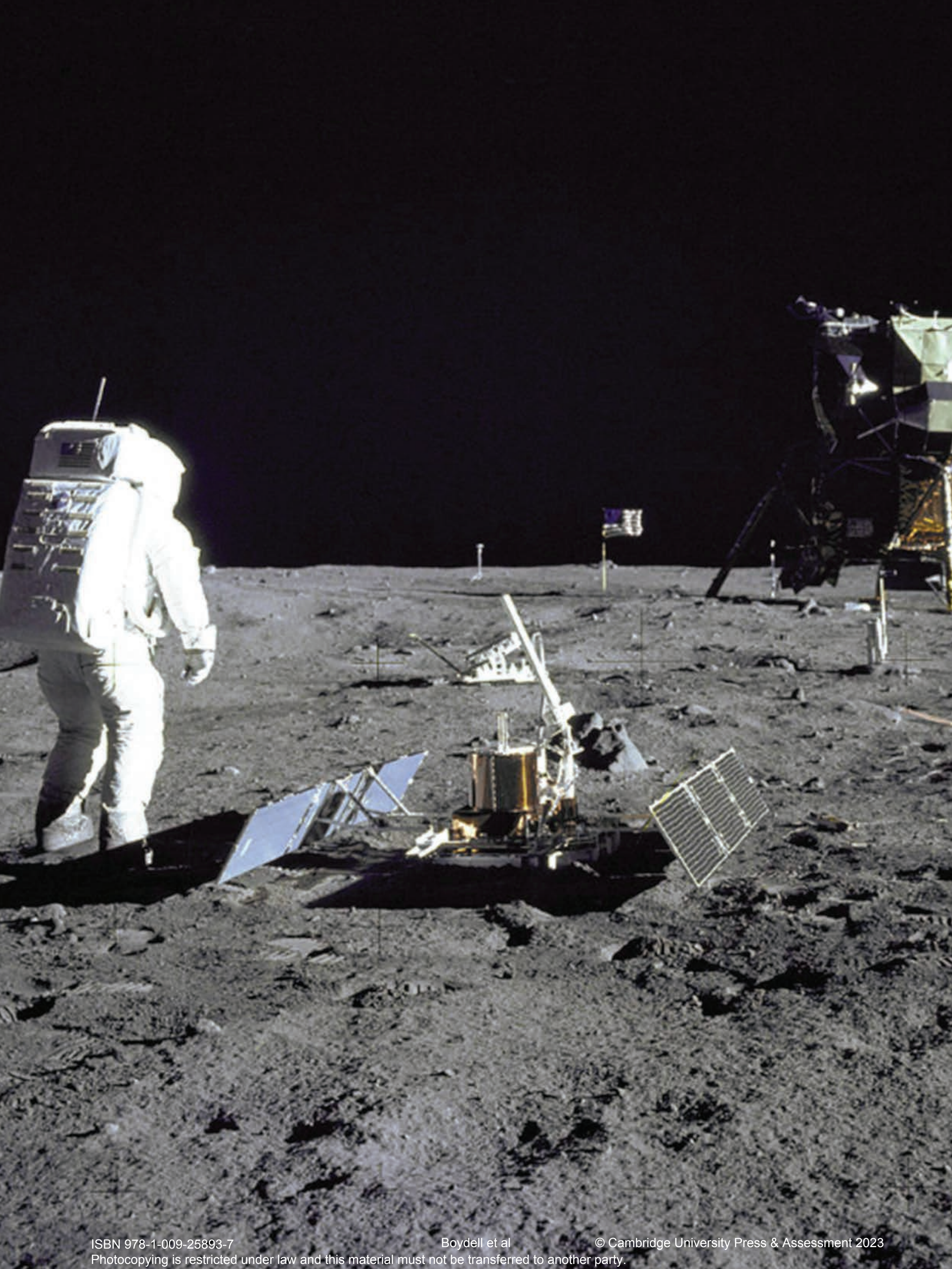

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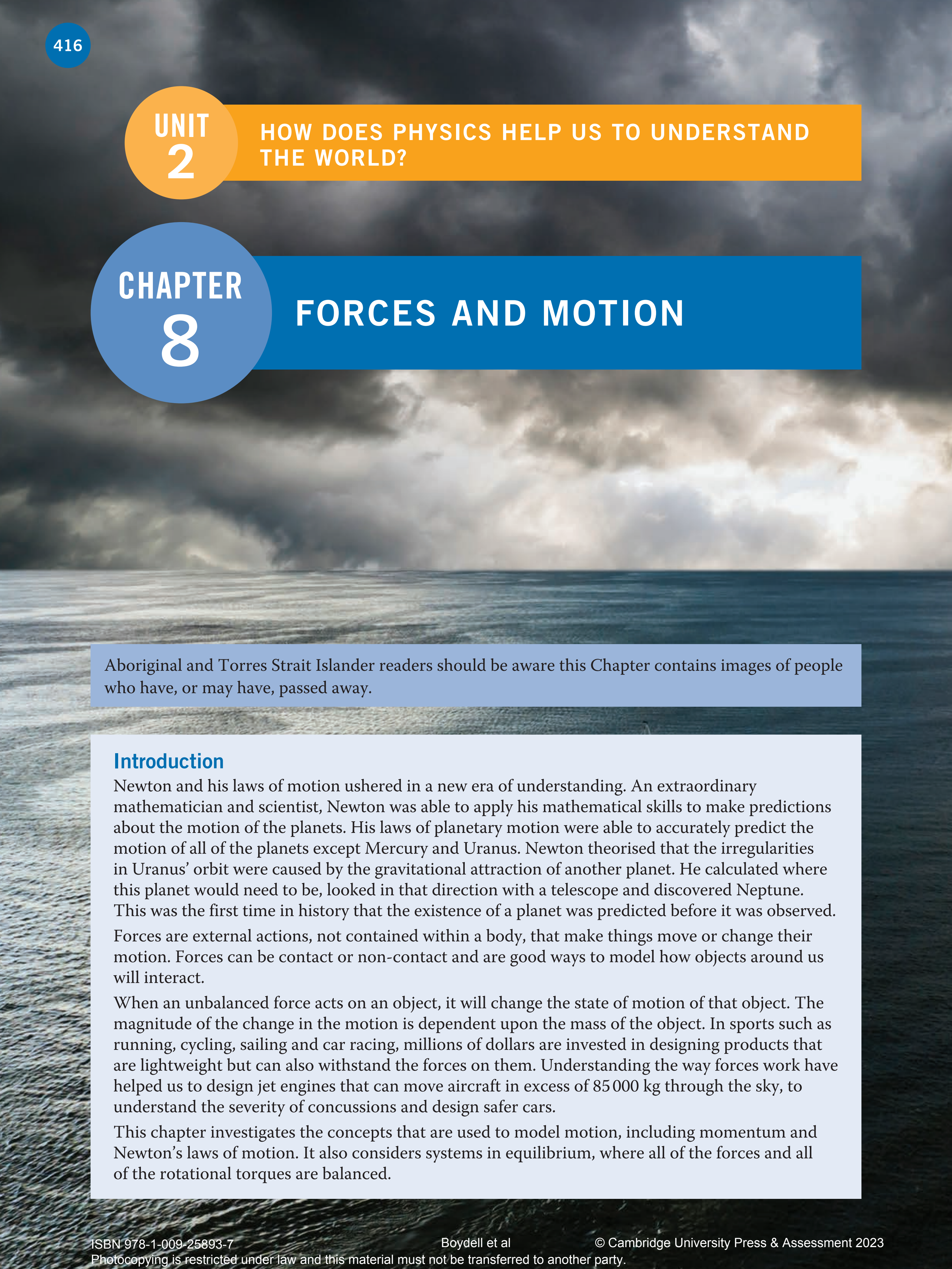

UNIT 2 HOW DOES PHYSICS HELP US TO UNDERSTAND THE WORLD?

CHAPTER 8 FORCES AND MOTION

Aboriginal and Torres Strait Islander readers should be aware this Chapter contains images of people who have, or may have, passed away.

Introduction

Newton and his laws of motion ushered in a new era of understanding. An extraordinary mathematician and scientist, Newton was able to apply his mathematical skills to make predictions about the motion of the planets. His laws of planetary motion were able to accurately predict the motion of all of the planets except Mercury and Uranus. Newton theorised that the irregularities in Uranus' orbit were caused by the gravitational attraction of another planet. He calculated where this planet would need to be, looked in that direction with a telescope and discovered Neptune. This was the first time in history that the existence of a planet was predicted before it was observed.

Forces are external actions, not contained within a body, that make things move or change their motion. Forces can be contact or non-contact and are good ways to model how objects around us will interact.

When an unbalanced force acts on an object, it will change the state of motion of that object. The magnitude of the change in the motion is dependent upon the mass of the object. In sports such as running, cycling, sailing and car racing, millions of dollars are invested in designing products that are lightweight but can also withstand the forces on them. Understanding the way forces work have helped us to design jet engines that can move aircraft in excess of 85 000 kg through the sky, to understand the severity of concussions and design safer cars.

This chapter investigates the concepts that are used to model motion, including momentum and Newton's laws of motion. It also considers systems in equilibrium, where all of the forces and all of the rotational torques are balanced.

Curriculum

Area of Study 1 Outcome 1
How is motion understood?

Study Design	Learning objectives – at the end of this chapter I will be able to:
Concepts used to model motion • Apply concepts of momentum to linear motion: $p = mv$ **Forces and motion** • Explain changes in momentum as being caused by a net force: $\Delta p = F_{net}\Delta t$ **Energy and motion** • Analyse impulse in an isolated system (for collisions between objects moving in a straight line): $F\Delta t = m\Delta v$ • Investigate and analyse theoretically and practically momentum conservation in one dimension	**8A Momentum** **8A.1** Use the formula $p = mv$ to calculate the momentum of bodies **8A.2** Understand that as long as no external forces are acting on an object, its momentum is conserved **8A.3** Apply conservation of momentum to solve problems relating to two objects colliding in a straight line **8A.4** Be able to determine mathematically if a collision is elastic or inelastic **8A.5** Use the formulas $I = \Delta p = m\Delta v = mv - mu = F_{av}\,\Delta t$ to model impulse and change in momentum **8A.6** Understand that the area under a force–time graph is the impulse and apply this knowledge to solve a variety of problems
Forces and motion • Apply the vector model of forces, including vector addition and components of forces, to readily observable forces including the force due to gravity, friction and normal forces • Model the force due to gravity, F_g, as the force of gravity acting at the centre of mass of a body, $F_{\text{on body by Earth}} = mg$, where g is the gravitational field strength (9.8 N kg^{-1} near the surface of Earth) • Model forces as vectors acting at the point of application (with magnitude and direction), labelling these forces using the convention 'force on A by B' or $F_{\text{on A by B}} = -F_{\text{on B by A}}$ • Apply Newton's three laws of motion to a body on which forces act: $a = \frac{F_{net}}{m}$, $F_{\text{on A by B}} = -F_{\text{on B by A}}$ **Application of motion** • Investigate the application of motion concepts through a case study, for example, through motion in sport, vehicle safety, a device or a structure	**8B Newton's laws of motion** **8B.1** Recall Newton's three laws of motion **8B.2** Be able to add forces to find the net force on an object **8B.3** Use the formula $F_{net} = ma$ to model Newton's second law of motion **8B.4** Understand the normal force **8B.5** Apply Newton's laws to a number of different situations, including using the formula $a = \frac{F_{net}}{m}$ to calculate the acceleration of a system and $F = ma$ to calculate the force on different parts of the system **8B.6** Be able to label forces using the convention 'force on A by B' or $F_{\text{on A by B}} = -F_{\text{on B by A}}$ **8B.7** Understand the difference between mass and the force due to gravity **8B.8** Model the force due to gravity, F_g, as the force of gravity acting at the centre of mass of a body **8B.9** Apply motion concepts to discuss vehicle safety

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Study Design	Learning objectives – at the end of this chapter I will be able to:
Equilibrium • Calculate torque, $\tau = r_{\perp}F$ • Analyse translational and rotational forces (torques) in simple structures in translational and rotational equilibrium	**8C** **Equilibrium** **8C.1** Use the formula $\tau = r_{\perp}F$ to calculate torques **8C.2** Be able to apply the idea that when a system is in rotational equilibrium, the sum of the clockwise torques is equal to the sum of the anticlockwise torques: **8C.3** Be able to apply the idea that when a system is in translational equilibrium, the sum of the forces is equal to zero: $\sum F = 0$

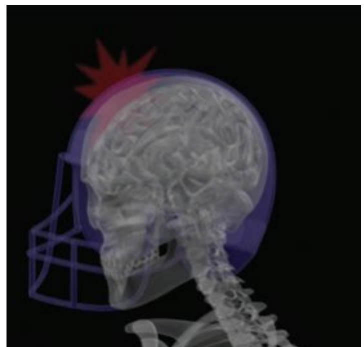
Glossary

Centre of mass
Closed system
Elastic collision
Equilibrium
Force diagram
Gravitational field strength
Impulse
Inelastic collision
Inertia
Kinetic energy
Law of conservation of momentum
Mass
Momentum
Normal force
Pivot point
Rotational equilibrium
Rotational force
System
Torque
Translational equilibrium
Translational force

Concept map

Concepts of motion and the role of force

8A Momentum

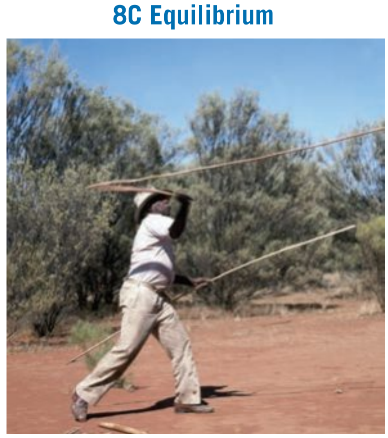


Changes in momentum are caused by a net force

8B Newton's laws of motion

If forces and torques are balanced, a system can be in equilibrium

8C Equilibrium



See the Interactive Textbook for an interactive version of this concept map interlinked with all concept maps for the course.

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8A Momentum

Study Design:
- Apply concepts of momentum to linear motion: $p = mv$
- Explain changes in momentum as being caused by a net force: $\Delta p = F_{net}\Delta t$
- Analyse impulse in an isolated system (for collisions between objects moving in a straight line): $F\Delta t = m\Delta v$
- Investigate and analyse theoretically and practically momentum conservation in one dimension

Glossary:
Closed system
Elastic collision
Impulse
Inelastic collision
Inertia
Kinetic energy
Law of conservation of momentum
Mass
Momentum

ENGAGE

Just how bad is a concussion?

Our brain is a fragile organ that houses 100 billion interconnected nerve cells called neurons. To protect this fragile organ, the brain is encased in a hard skull, and between the brain and the hard skull is a layer of cerebrospinal fluid, which acts as a shock absorber against sudden impacts. During an impact, the brain continues to move within the skull. Usually the cerebrospinal fluid shifts to accommodate this movement and the momentum transferred from the brain into the moving cerebrospinal fluid is sufficient to slow the brain down.

Figure 8A–1 Will Hamill of the Adelaide Crows and teammate Nick Murray lie on the ground after colliding during the 2021 AFL Round 21 match between the Adelaide Crows and Port Adelaide Power at Adelaide Oval on 7 August 2021 in Adelaide.

But sometimes the brain can be moved so violently that its momentum is not fully transferred to the cerebrospinal fluid and the brain hits the wall of the skull. This causes shockwaves through the brain that can shear the neurons apart. The dying neurons release toxins that can cause further damage. The blood vessels within the brain also have their momentum abruptly changed, which places large forces on these delicate structures and can rupture them. An impact of the brain against the skull wall that causes neurological damage is known as a mild traumatic brain injury or a concussion.

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The difficulty with concussion is that it can often go undetected or unreported and not appear on medical imaging. That is why it is important to know the common symptoms of a concussion, which include dizziness, headaches, mood changes and trouble forming clear thoughts. In the United States alone, 1.6–3.8 million people suffer sport-related concussion each year with about 300 000 of these people experiencing long-term effects. Children and teens are most susceptible to the effects of a concussion because their young brains are not fully developed. Studies have shown that young brains are easier to damage and take longer to recover. The Australian Institute of Sport and Australian Medical Association recommend that athletes under the age of 18 should have at least 14 days symptom-free before returning to contact sport.

Even repeated sub-concussive impacts, which are lower impacts that don't result in immediate symptoms, may have long-term effects. A 2013 study looked at soccer players who repeatedly headered the ball and found that, on average, they performed worse on short-term memory test and had structural changes to their brain.

So, what is the solution? A simplistic approach is to give players some form of head protection such as helmets. But such an approach may have unintended consequences as players may gain a false sense of security and they may take more risks and tackle harder. American Football players use helmets and although the helmets do protect the players from a skull fracture and external damage it does not change the brain's movement inside the skull. American Football players experience more than double the force on an average tackle compared to rugby players. These collisions that involve a greater change in momentum and large forces on the brain may actually increase the damage experienced by these players.

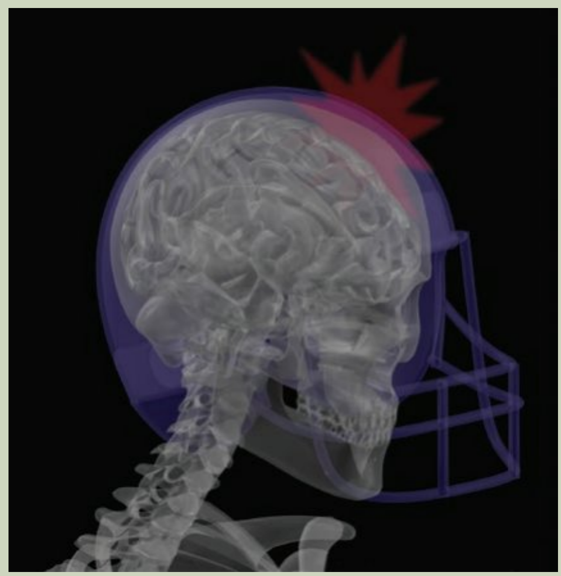

Figure 8A–2 An impact while wearing a sports helmet (in American football) although the helmet and skull's momentum changes rapidly, the brain continues its momentum through a thin layer of fluid. Then when it hits the hard skull, its momentum changes rapidly, which causes large forces on delicate neural structures and blood vessels. This causes concussion.

Concussions are a complex problem that require a holistic solution. In New Zealand and the United States, some football clubs are using accelerometers in mouth guards and patches behind the ears to measure the severity of collisions. Current data suggests that many of the impacts are similar to a moderate car crash. This data should lead to better pre- and post-game screening for concussion, which is desperately needed. One New Zealand study showed that in one match of rugby there were more than 3000 recorded impacts, yet no concussive injuries were detected when using the King-Devick test, an objective assessment of concussion severity. The research into concussions is so far inadequate, and high-level studies need to be done to evaluate the effects of resting period, pharmacological interventions, rehabilitative techniques and exercise for individuals who are slow to recover from a sport-related concussion.

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Momentum, p the product of an object's mass and velocity

Mass a body's resistance to acceleration when a force is applied

EXPLAIN

Modelling motion with momentum

A heavy object is harder to stop than a lighter object at the same speed. This simple fact helps you to develop an understanding of momentum. **Momentum, p**, is an object's **mass** multiplied by its velocity.

Formula 8A–1 Momentum

$$p = mv$$

Where:

p = Momentum ($kg\,m\,s^{-1}$)
m = Mass (kg)
v = Velocity ($m\,s^{-1}$)

Momentum is a vector quantity and it must have both magnitude and direction. The direction of the momentum vector and velocity vector will always be the same. Momentum can only be changed when a net external force is applied.

Worked example 8A–1 Momentum of a car

Calculate the momentum of a 1.45×10^3 kg car driving north at 72.0 km h^{-1}.

Solution

Convert the speed from km h^{-1} to m s^{-1}:

$$u = \frac{72}{3.6}$$
$$= 20.0\ m\ s^{-1}$$

Substitute into the momentum equation:

$$p = mv$$
$$= (1.45 \times 10^3)(20)$$
$$= 2.9 \times 10^4\ kg\,m\ s^{-1}$$

Therefore, the momentum of the car is 2.9×10^4 kg m s^{-1} north.

Inertia a body's tendency to resist a change in its state of motion

Closed system a system that does not allow the transfer of mass or energy to the surrounding environment

Law of conservation of momentum for a collision involving two or more objects in a closed system, the total momentum will remain the same

Momentum and inertia

It is important to note that momentum and **inertia** are two different concepts. An object that is stationary has no momentum, but it has inertia. Inertia is linked to Newton's first law of motion and is defined as a body's tendency to resist a change in its state of motion when acted upon by a net force. The amount of inertia an object has depends only on the amount of mass that it has – the greater the mass, the greater the inertia.

The law of conservation of momentum states that for a collision involving two or more objects in a **closed system**, the total momentum will remain the same. That is, the total momentum of a system will remain constant as long as no external net force acts on the system. The **law of conservation of momentum** can be expressed mathematically as shown in the Formula 8A–2 box.

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Formula 8A–2 Conservation of momentum

$$\Sigma p_{before} = \Sigma p_{after}$$

$$m_1 u_1 + m_2 u_2 + \ldots = m_1 v_1 + m_2 v_2 + \ldots$$

Where:

m_1 = Mass of the first object (kg)
m_2 = Mass of the second object (kg)
u_1 = Initial velocity of the first object (m s^{-1})
u_2 = Initial velocity of the second object (m s^{-1})
v_1 = Final velocity of the first object (m s^{-1})
v_2 = Final velocity of the second object (m s^{-1})

VIDEO 8A–1 MOMENTUM IN A CAR CRASH

For one-dimensional collisions it is important to use a positive or a negative sign to indicate the direction of straight-line motion.

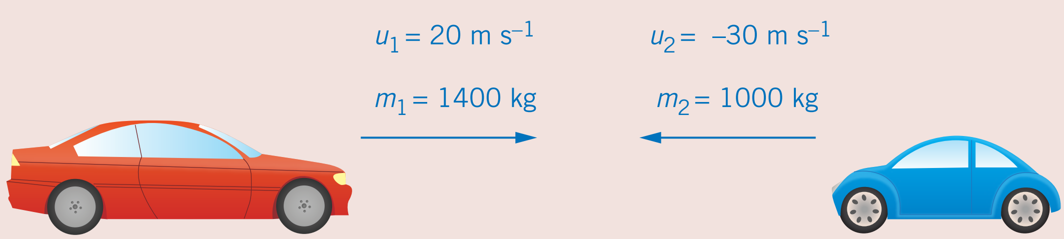
Worked example 8A–2 Momentum in a head on collision

A car of mass 1400 kg is moving to the right at a velocity of 20.0 m s^{-1}. It collides with a car of mass 1000 kg moving at 30.0 m s^{-1} to the left. After the collision, the 1400 kg mass car moves to the left with a velocity of 12.5 m s^{-1}. Calculate the velocity of the 1000 kg car after the collision.

Solution

Let moving to the right be the positive direction.

Before the collision:



After the collision:

$v_1 = -12.5 \text{ m s}^{-1}$

Rearrange the conservation of momentum formula to find v_2:

$$m_1 u_1 + m_2 u_2 = m_1 v_1 + m_2 v_2$$

$$m_2 v_2 = m_1 u_1 + m_2 u_2 - m_1 v_1$$

$$v_2 = \frac{m_1 u_1 + m_2 u_2 - m_1 v_1}{m_2}$$

$$= \frac{(1400)(20) + (1000)(-30) - (1400)(-12.5)}{1000}$$

$$= 15.5 \text{ m s}^{-1}$$

Therefore, the 1000 kg car will be moving to the right at 15.5 m s^{-1} after the collision.

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Two objects colliding and combining

In some cases, two or more objects may collide and then combine and move as one. The resulting object will have the mass of:

$$m_1u_1 + m_2u_2 + \ldots = m_3v_3$$

Worked example 8A–3 Momentum in a rear end collision

A car that has a mass of 1350 kg is moving in traffic at 13.9 m s^{-1} north. The driver of the car is texting and rear ends a 1550 kg car in front of it that was moving at a velocity of 2.00 m s^{-1} north when it was hit. The two cars stick and move as one. Calculate the velocity that the two cars will have after the collision.

Solution

Let moving to the right be the positive direction.

Before the collision:

After the collision:

$$\begin{aligned} m_3 &= m_1 + m_2 \\ &= (1350) + (1550) \\ &= 2900 \text{ kg} \end{aligned}$$

Rearrange the conservation of momentum formula to find v_3:

$$m_1u_1 + m_2u_2 = m_3v_3$$

$$\begin{aligned} v_3 &= \frac{m_1u_1 + m_2u_2}{m_3} \\ &= \frac{(1350)(13.9) + (1550)(2.00)}{(2900)} \\ &= 7.54 \text{ m s}^{-1} \end{aligned}$$

Therefore, the two cars will be moving to the right at 7.54 m s^{-1} after the collision.

A single object breaking apart

In other cases, a single object may break apart into two or more other objects in what is known as an explosive collision. In this case, the law of conservation of momentum still applies:

$$m_1u_1 = m_2v_2 + m_3v_3 + \ldots$$

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Worked example 8A–4 Momentum from throwing a ball

A person of mass 70.0 kg is skating on a frozen lake holding a 200 g ball. The person stops and then throws the ball south with a velocity of 21.3 m s^{-1}. Calculate the velocity of the person once the ball is thrown. Assume that the friction between the skater and the ice is negligible.

Solution

Let south be the positive direction.

Before the collision:

$$m_1 = m_2 + m_3$$
$$= 0.2 + 70.0$$
$$= 70.2 \text{ kg}$$
$$u_1 = 0 \text{ m s}^{-1}$$

After the collision:

$$m_2 = 0.200 \text{ kg}$$
$$v_2 = 21.3 \text{ m s}^{-1}$$
$$m_3 = 70.0 \text{ kg}$$

Rearrange the conservation of momentum formula to find v_3:

$$m_1u_1 = m_2v_2 + m_3v_3$$
$$m_3v_3 = m_1u_1 - m_2v_2$$
$$v_3 = \frac{m_1u_1 - m_2v_2}{m_3}$$
$$= \frac{(70.2)(0)-(0.200)(21.3)}{70.0}$$
$$= -0.0609 \text{ m s}^{-1}$$

Therefore, the person will be moving north at 0.0609 m s^{-1} after the ball is thrown.

Check-in questions – Set 1

1 Two football players are running towards each other. One player of mass 73 kg is travelling east down the field at 9.88 m s^{-1} and the other player, who has a mass of 103 kg, is running towards him at 6.53 m s^{-1} west. If the two players tackle and move as one, calculate the velocity after the collision.

2 A tennis player hits a tennis ball of mass 59 g that is travelling at 26.3 m s^{-1} north down the court with their tennis racquet of mass 300 g that is travelling at 24.9 m s^{-1} south. If the tennis ball travels at 29.8 m s^{-1} south immediately after the collision, calculate the velocity of the racquet immediately after the collision.

3 A roller skater of mass 83 kg, initially at rest, throws a 2 kg medicine ball east with a velocity of 10.5 m s^{-1}. Calculate the velocity of the roller skater after they have thrown the medicine ball.

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CHAPTER 9 LINK

Kinetic energy

Kinetic energy is the energy of motion. The kinetic energy of a body can be calculated by:

Kinetic energy the energy due to movement. It is measured in joules (J) and is a scalar

Elastic collision a collision in which the total kinetic energy is the same both before and after the collision

Inelastic collision a collision in which the total kinetic energy is larger before the collision than after the collision. The 'missing' energy is often converted into other forms, such as thermal energy and sound energy

Formula 8A–3 Kinetic energy

$$E_k = \frac{1}{2}mv^2$$

Where:

E_k = Kinetic energy (J)
m = Mass (kg)
v = Velocity (m s^{-1})

Elastic and inelastic collisions

Collisions may be **elastic** or **inelastic**. If they are elastic, then it is possible to predict the final velocity of the two colliding objects. Completely elastic collisions occur between gas particles and the walls of the container. However, most collisions are not elastic and some of the energy is converted into thermal energy and sound energy. If a collision is 100% inelastic, then all of the energy is converted into thermal energy and sound energy and the two colliding objects will be stationary after the collision. To determine if a collision is elastic or inelastic, the total kinetic energy must be calculated before and after the collision. If the total kinetic energy before and after the collision is equal, then it is an elastic collision. If the total kinetic energy before the collision is greater than the total kinetic energy after the collision, then it is an inelastic collision.

Worked example 8A–5 Inelastic collision

Two billiard or pool balls, each with a mass of 0.160 kg, and moving with a constant speed of 5 m s^{-1} collide head on with each other. After the collision, the balls separate, each moving with a speed of 4 m s^{-1}. A diagram of this situation is shown in Figure 8A–3 and 8A–4.

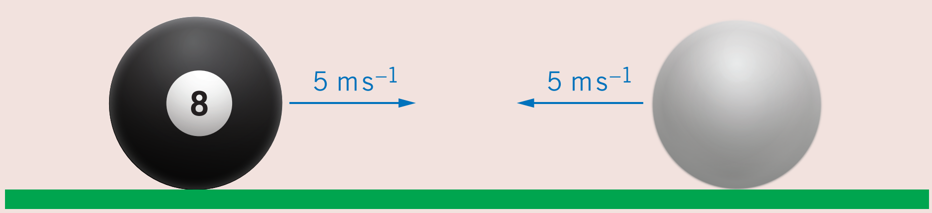

Figure 8A–3 Pool balls moving towards each other before the collision

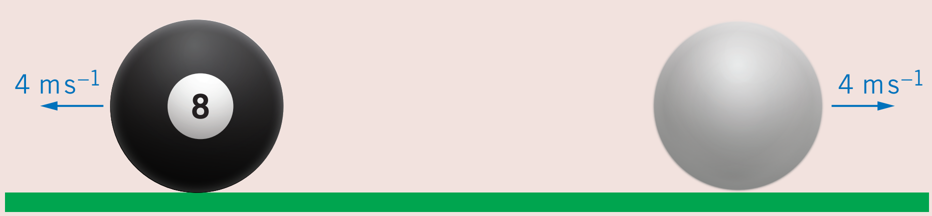

Figure 8A–4 Pool balls moving away from each other just after the collision

a Show that the momentum of the balls is conserved.
b Show that this collision is inelastic.

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Solution

a Calculate the total momentum just before and just after the collision:

$$\sum p_{\text{before}} = m_1u_1 + m_2u_2$$
$$= (0.160)(5) + (0.160)(-5)$$
$$= 0 \text{ kg m s}^{-1}$$
$$\sum p_{\text{after}} = m_1v_1 + m_2v_2$$
$$= (0.160)(4) + (0.160)(-4)$$
$$= 0 \text{ kg m s}^{-1}$$

Note that the velocity of one of the balls must be negative because the balls are travelling in opposite directions.

Since $\sum p_{\text{before}} = \sum p_{\text{after}}$, momentum is conserved.

b Calculate the total kinetic energy before and after the collision:

$$\sum E_{\text{k before}} = \frac{1}{2}m_1(u_1)^2 + \frac{1}{2}m_2(u_2)^2$$
$$= \frac{1}{2}(0.160)(5)^2 + \frac{1}{2}(0.160)(5)^2$$
$$= 4 \text{ J}$$
$$\sum E_{\text{k after}} = \frac{1}{2}m_1(v_1)^2 + \frac{1}{2}m_2(v_2)^2$$
$$= \frac{1}{2}(0.160)(4)^2 + \frac{1}{2}(0.160)(4)^2$$
$$= 2.56 \text{ J}$$

Therefore, since $\sum E_{\text{k before}} > \sum E_{\text{k after}}$, the collision is inelastic.

Change in momentum (impulse)

When all objects are considered in a collision, momentum is conserved provided that no net external force acts on the system. However, if only one object is considered, then momentum may not be conserved (as the momentum is transferred to other objects that are not considered).

When the velocity of an object changes, its momentum also changes. An increase in velocity means an increase in momentum, and a decrease in velocity means a decrease in momentum. This change in momentum is sometimes referred to as **impulse**.

Impulse the change in momentum of an object, caused by a force acting for a certain amount of time

Formula 8A–4 Impulse

$$\Delta p = mv - mu = I = F_{av}\Delta t$$

Where:

Δp = Change in momentum (kg m s^{-1} or N s)

I = Impulse (kg m s^{-1} or N s)

m = Mass (kg)

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

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

F_{av} = Average net force applied (N)

Δt = Time that the force is applied (s)

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Remember that the only way to change an object's velocity (and therefore its momentum) is to apply a net force on the object. The change in momentum (the impulse) is a vector quantity; it requires both a magnitude and a direction. Momentum has a relationship with average net force on the object, as the change in momentum over time is the average net force on the object (this is because it takes a net external force to change momentum). This can be seen in the following way.

Start with Newton's second law for an average net force:

$$F_{av} = ma_{av}$$

Note that an average acceleration is equivalent to a change in velocity over time:

$$F_{av} = \frac{m\Delta v}{\Delta t}$$

Using the definition of momentum, recognise that the numerator is a change in momentum:

$$F_{av} = \frac{\Delta p}{\Delta t}$$

Finally, rearrange this equation, using the definition of impulse:

$$\Delta p = F_{av}\Delta t = I = mv - mu$$

Worked example 8A–6 Applying impulse

A person is travelling south in a car at 72 km h^{-1} when they see an object on the road. They slam on the brakes and come to a complete stop in 4 seconds. The mass of the driver is 70 kg and the mass of the car is 1330 kg.

a Calculate the change in momentum of the car and driver.

b Calculate the average force that the road applies to the car in order to stop it.

Solution

a Let south be the positive direction.

Convert the initial speed from km h^{-1} to m s^{-1}:

$$u = \frac{72}{3.6}$$
$$= 20 \text{ m s}^{-1}$$

Find the change in momentum, noting that the final velocity is zero:

$$\Delta p = mv - mu$$
$$= (70 + 1330)(0) - (70 + 1330)(20)$$
$$= -2.8 \times 10^4 \text{ kg m s}^{-1}$$

Therefore, the change in momentum (impulse) is 2.8×10^4 kg m s^{-1} north.

b Use the definition of impulse:

$$I = \Delta p = F_{av}\,\Delta t$$
$$= \frac{\Delta p}{\Delta t}$$
$$= \frac{-2.8 \times 10^4}{4}$$
$$= 7000 \text{ N}$$

Therefore, the average force applied by the road is 7000 N north.

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Graphing the change in momentum (impulse)

The area under a force–time graph is the impulse.

The impulse for the graph in Figure 8A–5 would be calculated as follows:

$$I = F_{av} \Delta t$$
$$= (6)(8)$$
$$= 48 \text{ N s}$$

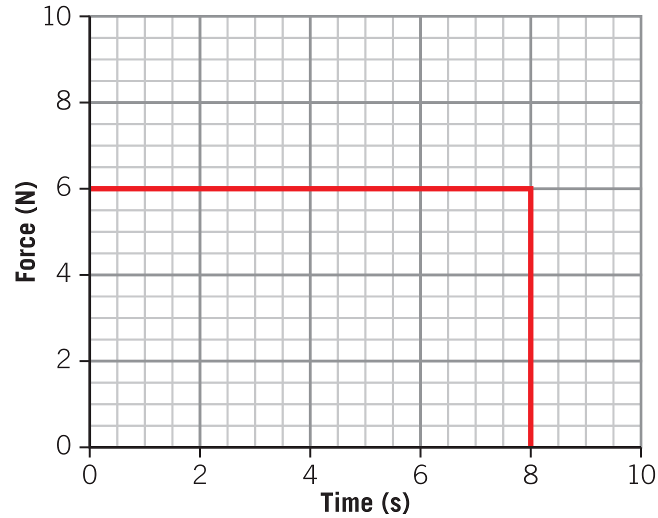

Figure 8A–5 A force–time graph showing a constant force of 6 N being applied to an object for 8 s

If the gradient is constant (and not zero), as in Figure 8A–6, then the impulse can be calculated using the area of a triangle formula.

$$I = \text{area under force–time graph}$$
$$= \text{area of triangle}$$
$$= \frac{1}{2}(8)(8)$$
$$= 32 \text{ N s}$$

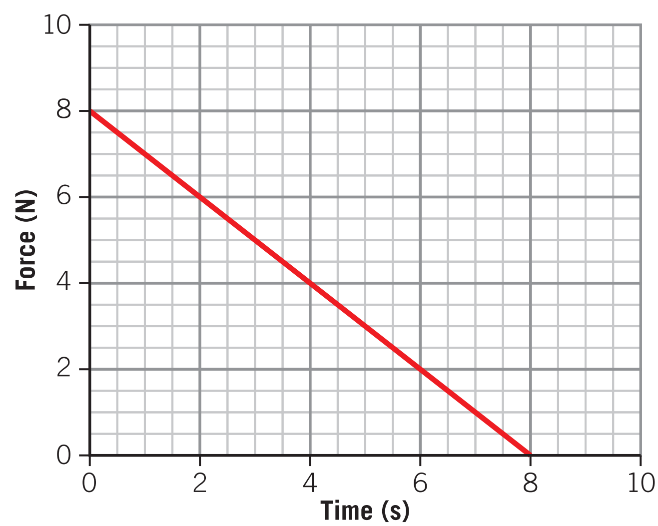

Figure 8A–6 A force–time graph showing decreasing force between 8 and 0 N being applied to an object for 8 s

In some cases, it may be appropriate to use several shapes to calculate the area under the graph. To calculate the area under Figure 8A–7, a square and a triangle are both used:

$$I = \text{area under force–time graph}$$
$$= \text{area of rectangle} + \text{area of triangle}$$
$$= (9)(6) + \frac{1}{2}(9)(2)$$
$$= 63 \text{ N s}$$

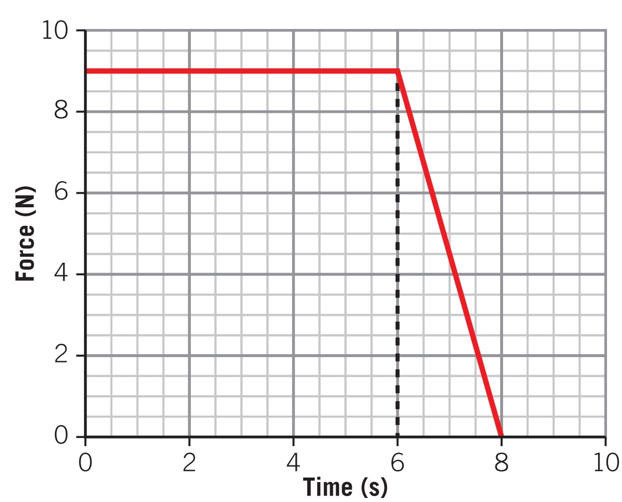

Figure 8A–7 A force–time graph showing a constant force of 9 N being applied to an object for 6, then a decreasing force between 9 and 0 N applied for 2 s

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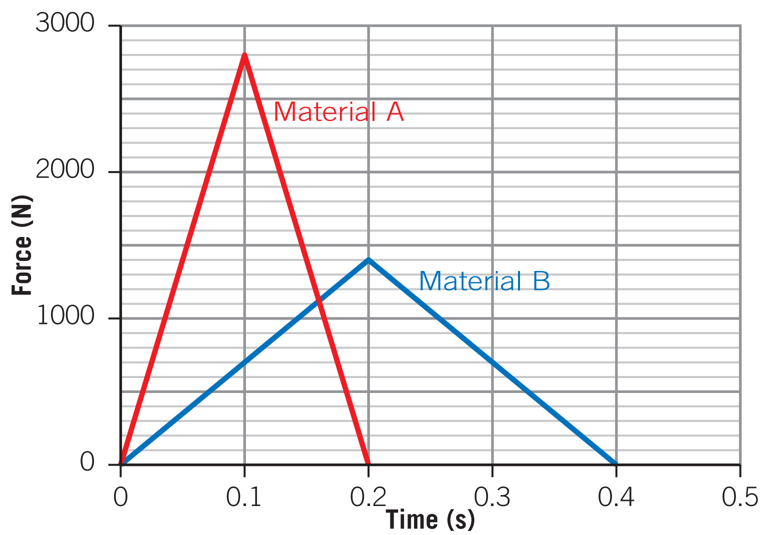
WORKSHEET 8A–1 MOMENTUM

Check-in questions – Set 2

1 A car of mass 1300 kg is travelling at 27 km h^{-1}. The car then accelerates to a velocity of 63 km h^{-1} in 14 s. Calculate the magnitude of the change in momentum of the car.

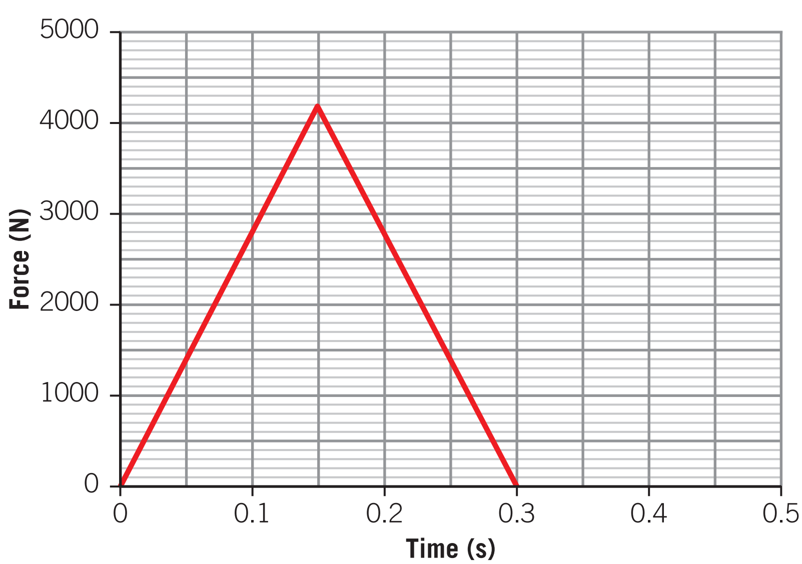
2 A group of engineers are working together to design a new material for a diving board that will launch a diver to the greatest height. They test two the materials by building two prototype diving boards and measure the force applied to the material over time as a 70 kg person dives on the boards. Their results are shown below.



a Calculate the impulse given to the person while in contact with the diving board.

b Which material, A or B, should the engineers choose? Justify your answer.

3 Modern running shoes often have a rigid plate within the shoe that stores energy when the shoes hits the ground. This energy is then returned to the runner when the shoes lifts off the ground. The force–time graph of the shoe of an 83 kg runner as it is in contact with the ground is shown.



Calculate the change in momentum of the person when the shoe is in contact with the ground.

4 A car of mass 1450 kg that is travelling at 108 km h^{-1} west collides into a car of mass 980 kg that is travelling at 99 km h^{-1} east. When the two cars collide, they fuse as one.

a Calculate the velocity of wreckage after the collision.

b Is this collision elastic or inelastic? Justify your answer with calculations.

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8A SKILLS

VIDEO 8A–2
SKILLS: USING DIRECTION IN AN EQUATION

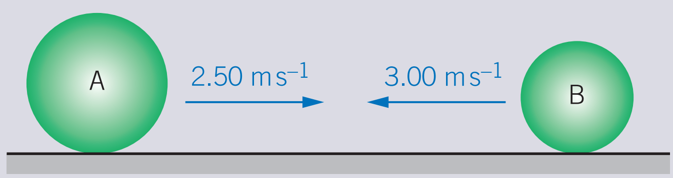
Using direction in an equation

In any question that involves a vector quantity, the direction of the vector must be considered and incorporated into your equation. Direction involving one dimensional motion can be incorporated into an equation with a positive and negative sign representing different directions. This means that whenever you encounter a problem involving vectors in one dimension, one of the first things you must do is determine which direction will be positive and which direction will be negative. Once you have made this decision, write it down on the page as this will allow you to keep track of the meaning of a negative or positive answer.

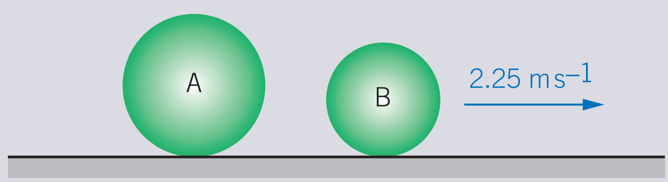
Question

Two balls, A and B, slide towards each other along a frictionless surface at constant speed. Ball A has a mass of 8.42 kg and is travelling 2.50 m s^{-1} east. Ball B has a mass of 6.21 kg and is travelling 3.00 m s^{-1} west. Just after the collision ball B travels 2.25 m s^{-1} east. Calculate the velocity of ball A after the collision. A diagram of this situation is shown below.

Before the collision:



After the collision:



Solution

As this question involves vectors, you must decide which direction is negative, so let the direction west be negative. Then rearrange using the conservation of momentum formula to find v_2:

$$m_1u_1 + m_2u_2 = m_1v_1 + m_2v_2$$

$$m_2v_2 = m_1u_1 + m_2u_2 - m_1v_1$$

$$v_2 = \frac{m_1u_1 + m_2u_2 - m_1v_1}{m_2}$$

$$= \frac{(6.21)(-3)+(8.42)(2.5)-(6.21)(2.25)}{8.42}$$

$$= -1.37 \text{ m s}^{-1}$$

Therefore, ball A will move with a velocity of 1.37 m s^{-1} west.

Note that it does not matter which direction you select as positive and negative. Selecting west to be positive will still give the same result:

$$v_2 = \frac{(6.21)(3)+(8.42)(-2.5)-(6.21)(-2.25)}{8.42}$$

$$= 1.37 \text{ m s}^{-1}$$

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The positive answer indicates the direction, west.

It is important to remember that a negative sign is not needed when calculating the total energy before and after collisions to determine if a collision is elastic. This is because energy is a scalar quantity.

Section 8A questions

Multiple-choice questions

1 Which of the following is a unit for momentum?

A $N\,s^{-1}$

B $N\,s$

C $kg\,m\,s^{-1}$

D Both B and C

2 A cyclist is travelling down a steep hill at 81 $km\,h^{-1}$. The bike and cyclist have a combined mass of 120 kg. The momentum of the bike and cyclist is

A $2.70 \times 10^3\ kg\,m\,s^{-1}$

B $9.72 \times 10^3\ kg\,m\,s^{-1}$

C $14.6 \times 10^3\ kg\,m\,s^{-1}$

D $35.0 \times 10^3\ kg\,m\,s^{-1}$

3 In a crash test, a car is travelling north at 101 $km\,h^{-1}$ and then hits a large sandbag. The car and sandbag continue moving north as one at a velocity of 34 $km\,h^{-1}$. Which of the following statements is correct?

A The direction of the impulse on the car is south.

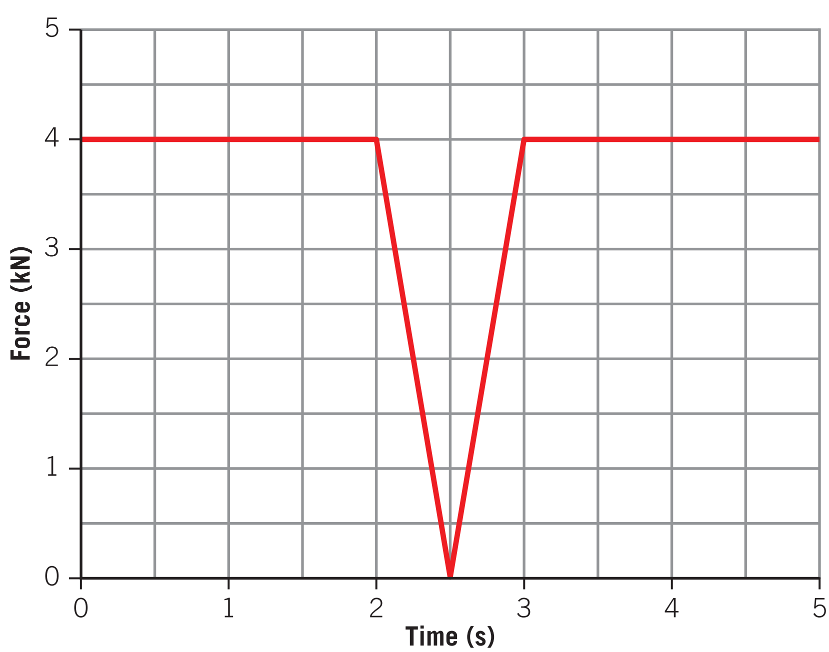
B The change in momentum of the sandbag is south.

C The change in momentum of the car is north.

D Since the car has a good crumple zone, the change in momentum is smaller than if the car had a poor crumple zone.

Use the following information to answer Questions 4 and 5.

A car of mass 1150 kg that is travelling at 72 $km\,h^{-1}$ applies the brakes. A force–time graph for the brakes applying to the car is shown.



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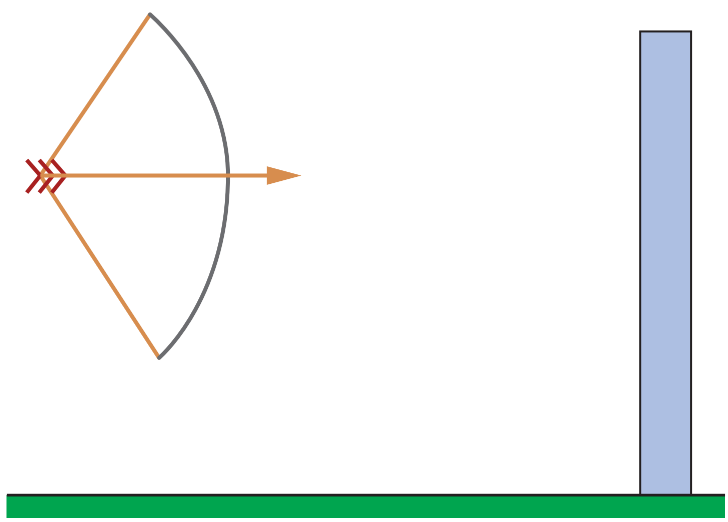
4 What is the magnitude of the change in momentum of the car?
- A 18 N s
- B 20 N s
- C 1.80×10^4 N s
- D 2.00×10^4 N s

5 What is the final velocity of the car?
- A 4.35 km h^{-1}
- B 15.7 km h^{-1}
- C 30.5 km h^{-1}
- D 42.5 km h^{-1}

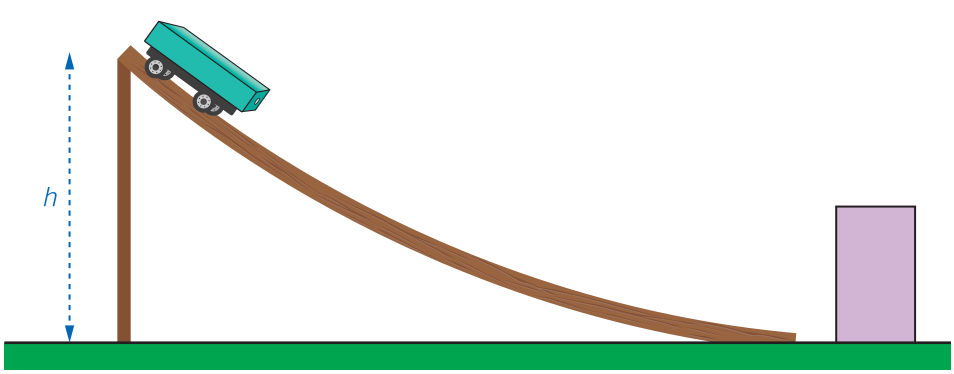
Short-answer questions

6 A 16 g arrow is shot to the right at a target that is resting on the ground. When the bow is released, it applies an average force of 50 N on the arrow, which is initially at rest, for 0.05 s.



- a Calculate the impulse given to the arrow by the bow once it has been fired by the bow.
- b Calculate the final velocity of the arrow when it leaves the bow.

7 A student sets up an experiment to test the effectiveness of crumple zones. The student places a crash cart with a digital force sensor at the top of a ramp. The cart is placed at the same height each time and the mass of the cart is the same each time. A heavy block is placed at the bottom of the ramp for the cart to collide into. A diagram of the student's set-up is shown below.



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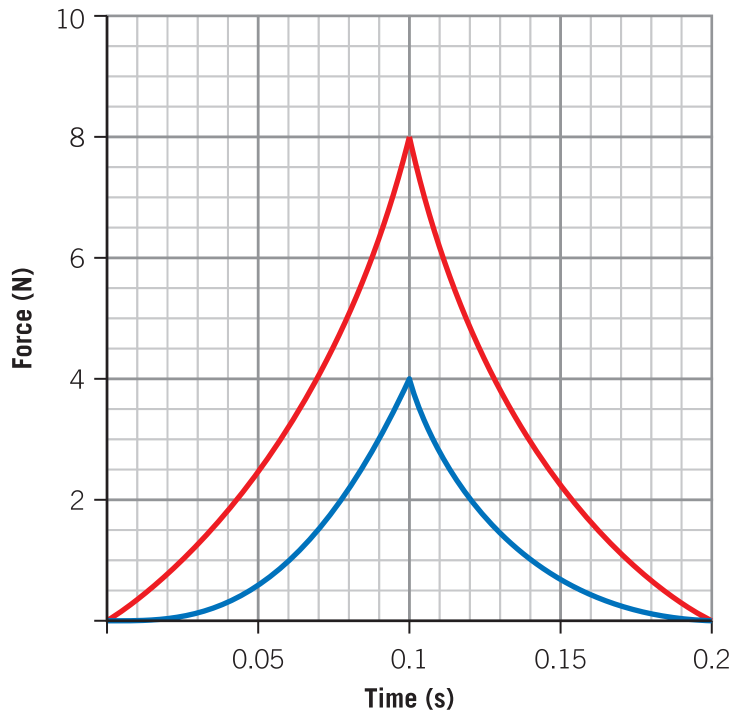
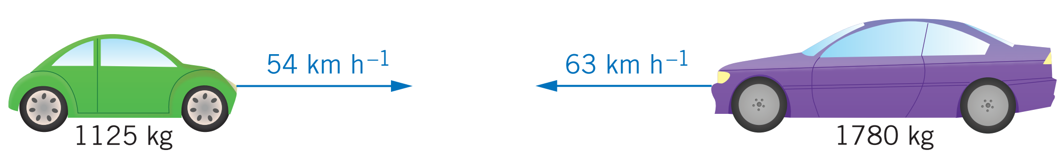
The student takes a control run with no crumple zone and the digital force sensor graphs the force–time graph of the collision in red in the graph below.



The student then makes their own prediction about the likely shape of the graph when a crumple zone is added to the cart. The student's prediction is shown in blue. Discuss the accuracy of the student's prediction. If you think the prediction is wrong, explain why and propose a correct prediction.

8 In a crash test, two cars collide head on. One car has a mass of 1125 kg and is travelling east at 54 km h^{-1}. The other car has a mass of 1780 kg and is travelling west at 63 km h^{-1}. After the collision, the 1780 kg car moves west at 9 km h^{-1}. A diagram of this situation is shown below.



- **a** Calculate the velocity of the car of mass 1125 kg after the collision.
- **b** Is this an elastic collision? Justify your answer.
- **c** Calculate the impulse given to the car of mass 1125 kg. Include a direction in your answer.
- **d** Crumple zones are used in the front of cars. Their purpose is to be a zone that crumples easily, which extends the time of the collision. Use the impulse formula to explain why crumples zones are used in cars instead of a rigid front that would not bend due to force.

9 A cannon and a cannonball have a combined mass of 250 kg. Both are initially at rest until the cannon is fired. Once fired, the cannon ball of mass 60 kg moves north with a velocity of 78 m s^{-1}. Calculate the velocity of the cannon after it is fired; include a direction in your answer.

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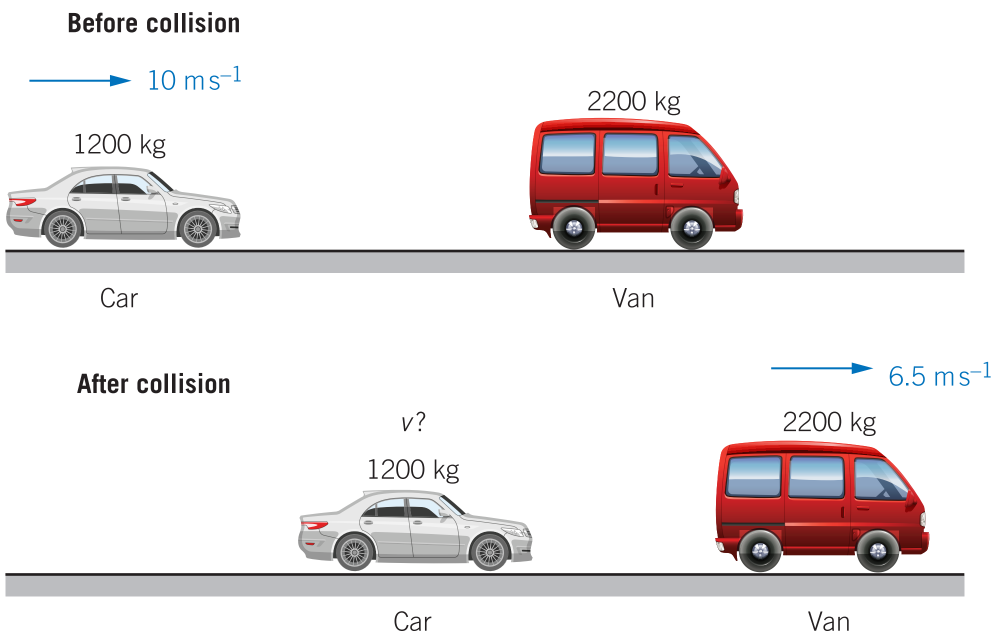
10 Jacinda designs a computer simulation program as part of her practical investigation into the physics of vehicle collisions. She simulates colliding a car of mass 1200 kg, moving at 10 m s^{-1}, into a stationary van of mass 2200 kg. After the collision, the van moves to the right at 6.5 m s^{-1}. This situation is shown below.



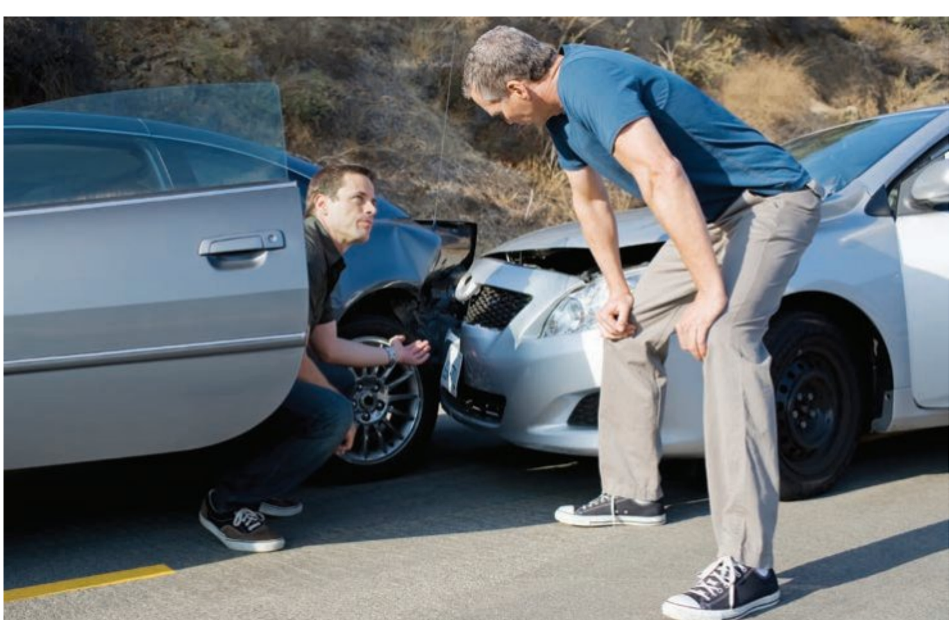
a Calculate the speed of the car after the collision and indicate the direction it would be travelling in. Show your working.

b Explain, using appropriate physics, why this collision represents an example of either an elastic or an inelastic collision.

c The collision between the car and the van takes 40 ms.

  i Calculate the magnitude and indicate the direction of the average force on the van by the car.

  ii Calculate the magnitude and indicate the direction of the average force on the car by the van.



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8B Newton's laws of motion

Study Design:

- Apply the vector model of forces, including vector addition and components of forces, to readily observable forces including the force due to gravity, friction and normal forces
- Model the force due to gravity, F_g, as the force of gravity acting at the centre of mass of a body, $F_{\text{on body by Earth}} = mg$, where g is the gravitational field strength (9.8 N kg^{-1} near the surface of Earth)
- Model forces as vectors acting at the point of application (with magnitude and direction), labelling these forces using the convention 'force on A by B' or $F_{\text{on A by B}} = -F_{\text{on B by A}}$
- Apply Newton's three laws of motion to a body on which forces act: $a = \frac{F_{\text{net}}}{m}$, $F_{\text{on A by B}} = -F_{\text{on B by A}}$
- Investigate the application of motion concepts through a case study, for example, through motion in sport, vehicle safety, a device or a structure

Glossary:
Force diagram
Gravitational field strength
Normal force
System

ENGAGE

How does a jet engine work?

At the most basic level a jet engine is Newton's third law of motion in action. Just like how a balloon 'rocket' filled with air pushes the air out to move, a jet engine also pushes air out at a high velocity. The action force of the jet engine pushing air back causes the air to push on the jet engine, moving the aircraft forwards.

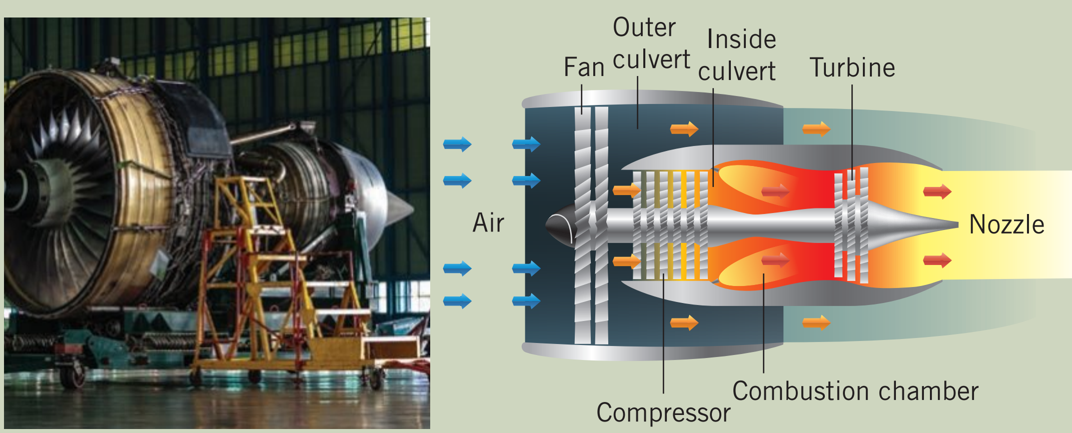

Figure 8B–1 A turbofan jet engine with the cover removed (left) and a diagram of a turbofan jet engine (right)

The key to producing an effective jet engine is to produce a high-speed jet of air that leaves the engine. A high-speed jet of air is created by first heating the incoming air. The hot air then expands and exits the jet at a high velocity. The air is heated by a combustion chamber that is placed in the heart of the jet engine. This combustion chamber releases atomised fuel that is ready to burn. The incoming air needs to be at a moderate temperature and pressure to achieve ideal combustion. To achieve this, a

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series of compressors is used, these compressor blades are driven by a turbine that is located behind the combustion chamber. The rotating blades of the compressor add energy to the incoming air, making it warmer and increasing the air pressure. Rotation in the turbine is caused by the high-velocity air moving over the fan's blades.

As the gas exits the jet engine, the turbine narrows, which results in an even higher exit velocity. The low-pressure turbine and low-pressure compressor are connected together and run at a lower speed; they help to reduce stress on the engine so components last longer. The components discussed so far make up a turbo jet engine. A revolution in jet engines occurred when a large fan was placed in front to make a turbo fan jet engine. Turbo fan jet engines are used for almost all commercial aircraft as they increase the thrust and efficiency of the engine.

EXPLAIN

Defining Newton's laws

Newton's first law

Newton's first law states that an object in a state of rest or travelling at a constant velocity will remain in its state of motion unless acted upon by a net force.

VIDEO 8B–1 NORMAL FORCES

If a car is at rest or travelling at a constant velocity, then the net force on the car is zero. Consider the vertical forces when the car is at rest. The normal force acting on the car provided by the ground balances the gravitational force acting on the car by Earth. For a car that is moving on a straight road at a constant velocity, the horizontal forces of air resistance and rolling friction are balanced by the driving force on the car by the road, and the normal force balances the force gravitational force acting on the car by Earth.

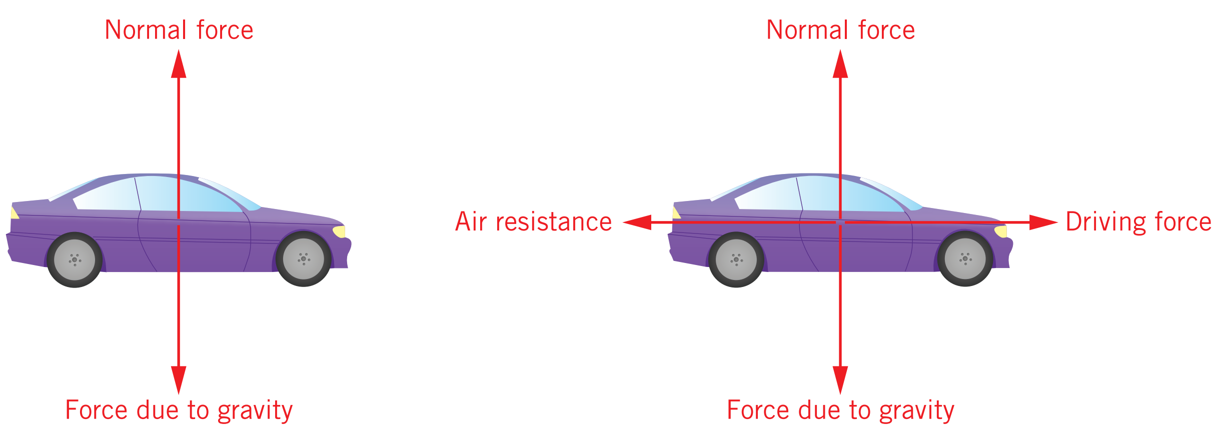

Figure 8B–2 The forces on a car at rest and a car moving at a constant velocity are balanced. This means that the car at rest will remain at rest and the car moving at a constant velocity will continue to move at a constant velocity.

It is contrary to our usual daily experience that an object will continue with a constant velocity indefinitely as long as the sum of the forces acting on the object are zero. This is because in our experience objects will come to rest as a result of friction, because friction causes a net force on objects that directly opposes their state of motion.

Newton's second law

Newton's second law states that the acceleration experienced by a body is directly proportional to the net force on the body and inversely proportional to the mass of the body.

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This law is often expressed in terms of the following formula.

Formula 8B–1 Newton's second law

$$F_{net} = ma$$

Where:

F_{net} = Net force acting on the mass (N)
m = Mass of the mass (kg)
a = Acceleration of the mass ($m\,s^{-2}$)

Force diagram a diagram that shows the relative magnitude and direction of all of the forces acting on a body. The forces are shown acting from the centre of mass of the object.

When determining the net force on a body, it is often helpful to draw a **force diagram**. The force vectors can be added to find the net force vector. For example, calculate the acceleration of a 1150 kg car that has a driving force of 4000 N forwards and a drag force of 2000 N.

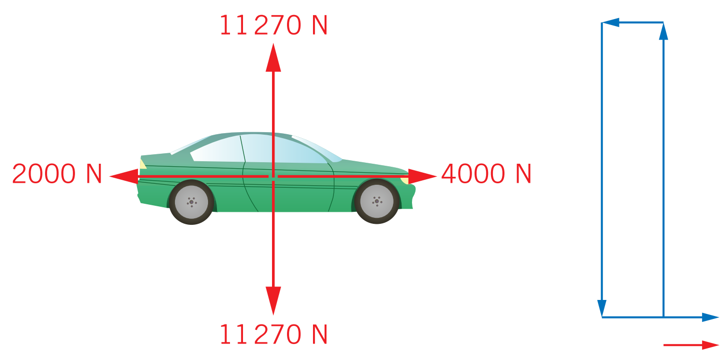

Figure 8B–3 Force diagram of an accelerating car (left) and vector diagram of the same accelerating car (right)

The force diagram to the left and the vector diagram to the right in Figure 8B–3 show that the net force on the car will be 2000 N forwards (also by Newton's second law, the force due to gravity and normal force vectors will cancel as there is no acceleration in the vertical, leaving 4000 N – 2000 N = 2000 N). The acceleration can then be determined:

$$a = \frac{F_{net}}{m} = \frac{2000}{1150} = 1.74\,m\,s^{-2} \text{ forwards}$$

It is important to remember that while two or more bodies are moving with the same acceleration, the force on each of the bodies will not be the same unless the masses are the same. For example, if three balls of mass 1 kg, 2 kg and 3 kg are all dropped from the same height, they will all accelerate towards the surface of Earth at the same rate, 9.8 $m\,s^{-2}$ (if air resistance is ignored). However, to have the same acceleration, the forces on the balls must all be different.

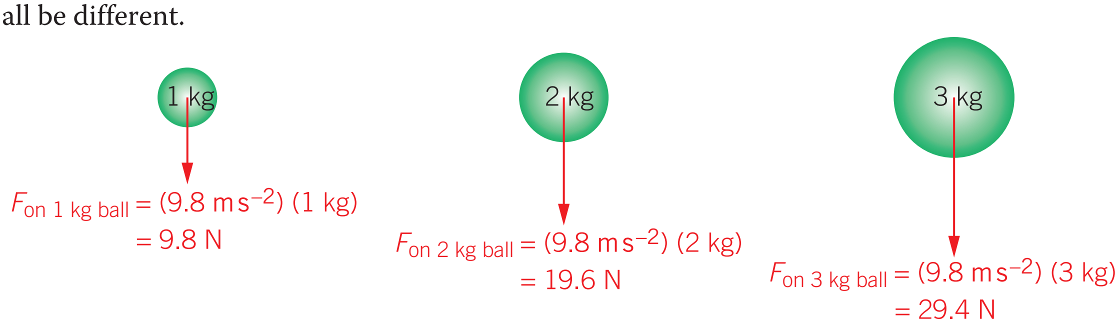

Figure 8B–4 Comparison of the forces on three balls of mass 1 kg, 2 kg and 3 kg, all accelerating due to gravity

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Another fundamental idea is that the only way to cause a body to accelerate is by applying a net force on the body. The body will then accelerate in the same direction as the direction of the net force. This means that the direction of the acceleration and the direction of the velocity are independent. For example, if a car is approaching a red light and the car brakes, the car's velocity will be forwards but the acceleration and therefore the net force on the car will be backwards. Similarly, if a projectile is fired vertically upwards, as soon as the thrust force during the firing is gone, the ball will be accelerating down, since the only force acting on the projectile is the force due to gravity (if air resistance is ignored). The projectile may be moving up, but its upwards velocity is constantly decreasing until the projectile is momentarily stationary at the maximum height, after which point the ball's velocity will be downwards and increasing.

Newton's third law

Newton's third law states that every action force has an equal and opposite reaction force.

Newton's third law describes the force interaction between two separate bodies. For example, if two bodies, A and B, come into contact with each other, then the force on A by B will be equal in magnitude and opposite in direction to the force on B by A.

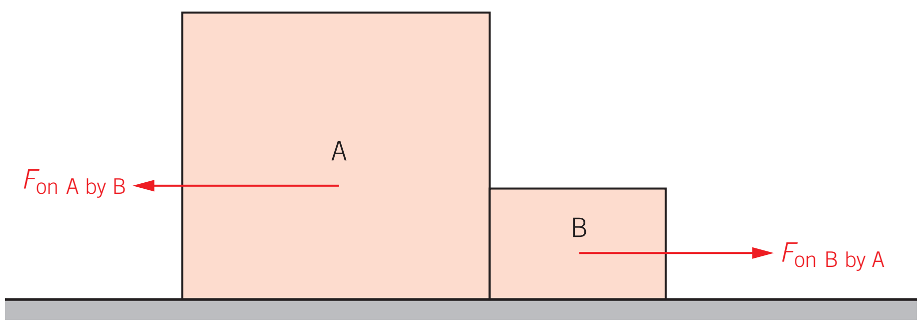

Figure 8B–5 The action and reaction pair when two bodies come into contact. Vector lines show that the forces are equal in magnitude but opposite in direction.

This can be expressed mathematically as:

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

This equation describes the fact that the force pairs are equal in magnitude but opposite in direction. Notice that the size of the object does not matter; as shown in Figure 8B–5, even though object A is very large and object B is very small, the forces on both objects have the same magnitude. Forces are always in pairs, including gravitational, magnetic and electrostatic forces.

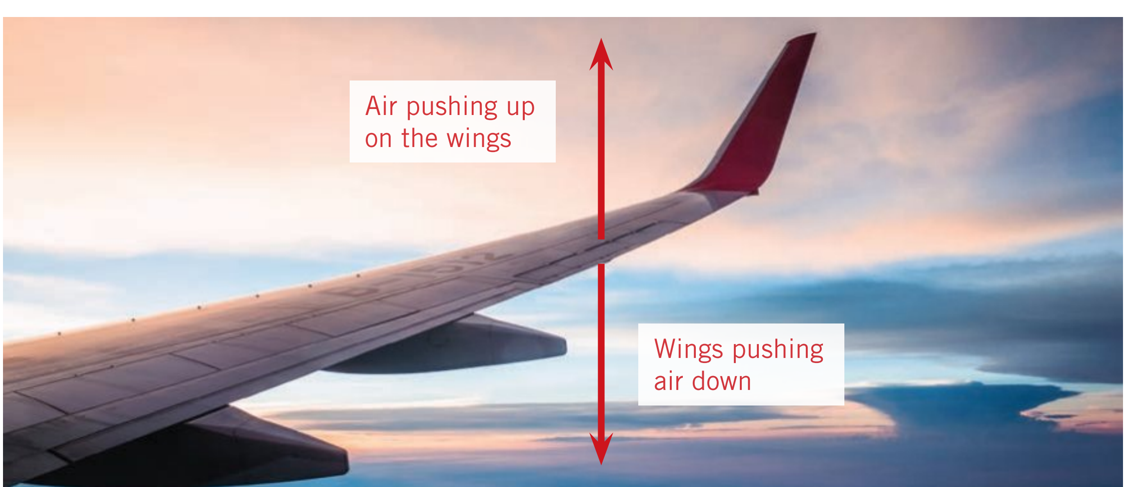

Figure 8B–6 The wing of an aircraft is designed to push air down; the air then pushes back up on the aircraft, providing the lift.

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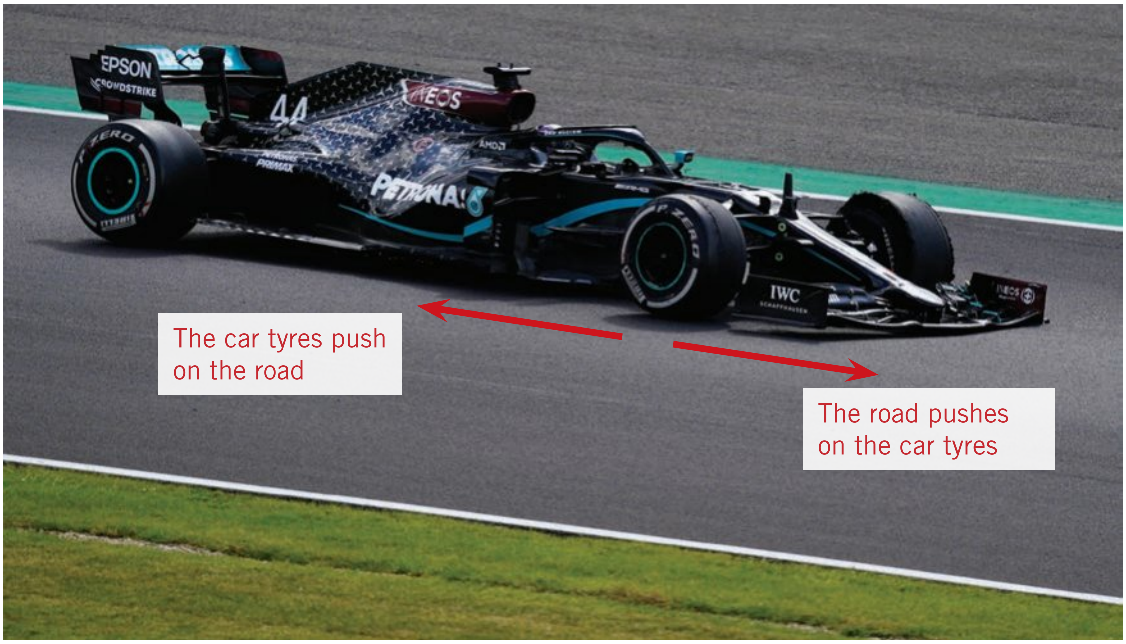

Figure 8B–7 When the wheels of a Formula 1 car turn, they push on the road; the road then pushes back with equal force propelling the car forwards.

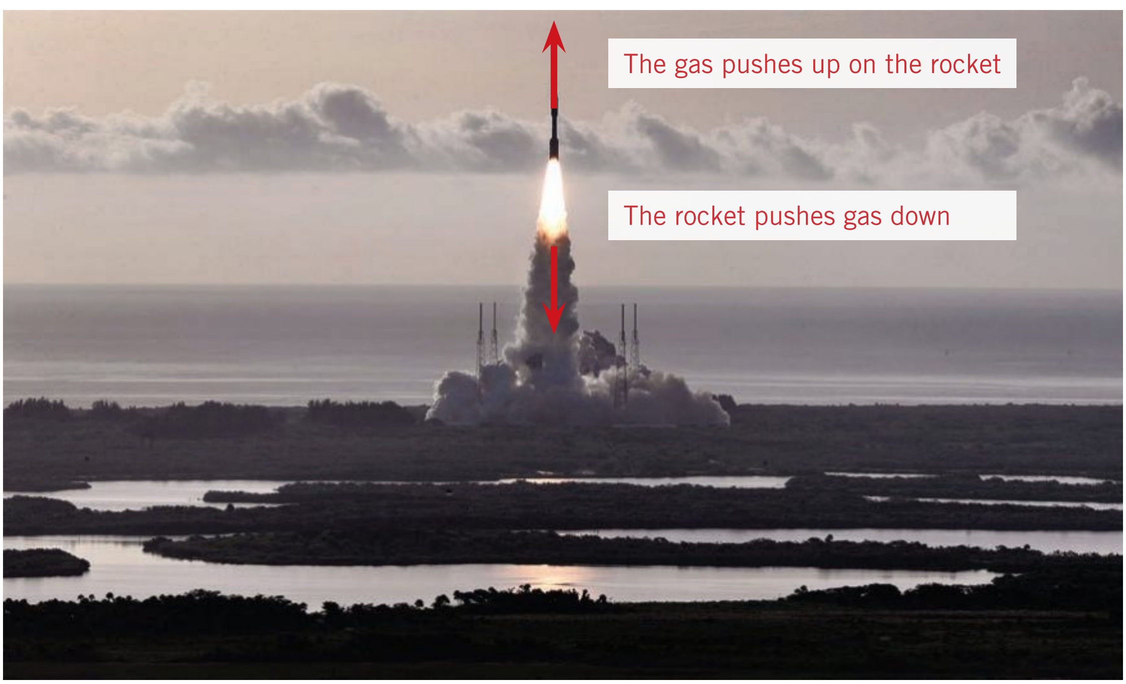

Figure 8B–8 When a rocket is launched, it forces gas from its propulsion system downwards; the gas then pushes back on the rocket with an equal force propelling it upwards.

Check-in questions – Set 1

1 If you were to drive down a freeway at a constant speed and then suddenly brake hard, your body would move forward until it is stopped by the seatbelt. Explain this observation using the relevant laws of motion.

2 One of the most famous golf swings was literally out of this world. In 1971, NASA astronaut Alan Shepard took two shots of golf while on the Moon during the Apollo 14 landing. It was noticed that the golf balls flew consistently higher and further than they would on Earth. Use the relevant laws of motion to describe this observation.

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3 When a set of traffic lights turns green, a car and bike accelerate at the same rate and therefore stay in line for the first 200 m of their journey. Jiang on the bike thinks that the driving force of the bike and the car must be the same, but Alice in the car thinks that the driving force of the bike and the car must be different. Who is correct? Justify your answer.

4 A man pushes a box of mass 250 kg with a force of 500 N along a frictionless surface. Calculate the magnitude of the acceleration of the box.

5 A skydiver who jumps out of a plane and is in free-fall has gravity acting to pull them down towards Earth. If gravity is the action force, what is the reaction force?

Normal force

Imagine a heavy box, labelled A, that is in free-fall close to Earth's surface. When the box is in free-fall, the force of gravity acts to accelerate the box to the ground. The downward gravitational force on box A by Earth is paired with the upwards gravitational force of box A pulling on Earth.

Imagine that box A is now placed on a table B. Box A no longer falls (accelerates down), which means that the net force on the box is zero. Therefore, as the box rests on the table, the force due to gravity acting on the box must be balanced by an upwards force provided by the table's surface. This upwards force is known as the **normal force** and is often expressed as N or F_N.

If you were to push down on box A, it would still not move, which means that the net force on the box is still zero. This means that the normal force has increased to balance the force due to gravity on the box as well as the additional force of you pushing down on the box. Equally, if you apply a force on the box that is opposite to the force due to gravity, the normal force will reduce in size. It is important to note that the force due to gravity on box A and the normal force are not force pairs even though they are quite often equal in magnitude and opposite in direction.

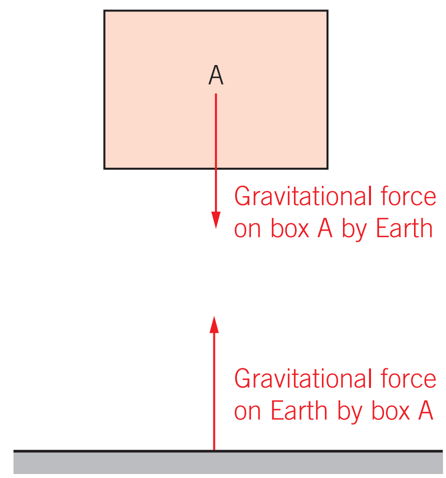

Figure 8B–9 Earth acts to pull A towards it and A acts to pull Earth up towards it.

Normal force the force that a surface applies to a body resting on it. The force is always applied perpendicular to the surface and prevents the body falling through the surface.

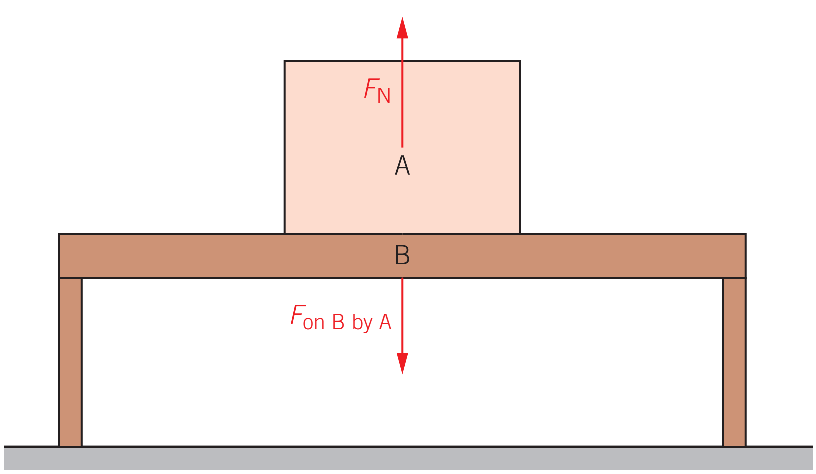

Figure 8B–10 When box A is placed on table B, box A applies a force on table B. As a result, table B pushes back and applies a normal force on box A.

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Force due to gravity

As you read this, you are probably sitting in a chair. The gravitational attraction to Earth is pulling you down. Take a moment to think what the pair for this force is.

Many people will incorrectly say that the force pair is the normal force of the chair acting on themselves. This cannot be correct as Newton's third law describes an interaction between two bodies; when you sit down, the interaction is occurring between your body and Earth. The force of gravity is a non-contact force. That means that if you were in free-fall, gravity would still act to pull you down. Since you have your own mass, things can be gravitationally attracted to you. Therefore, the force pair is Earth being gravitationally attracted to your mass.

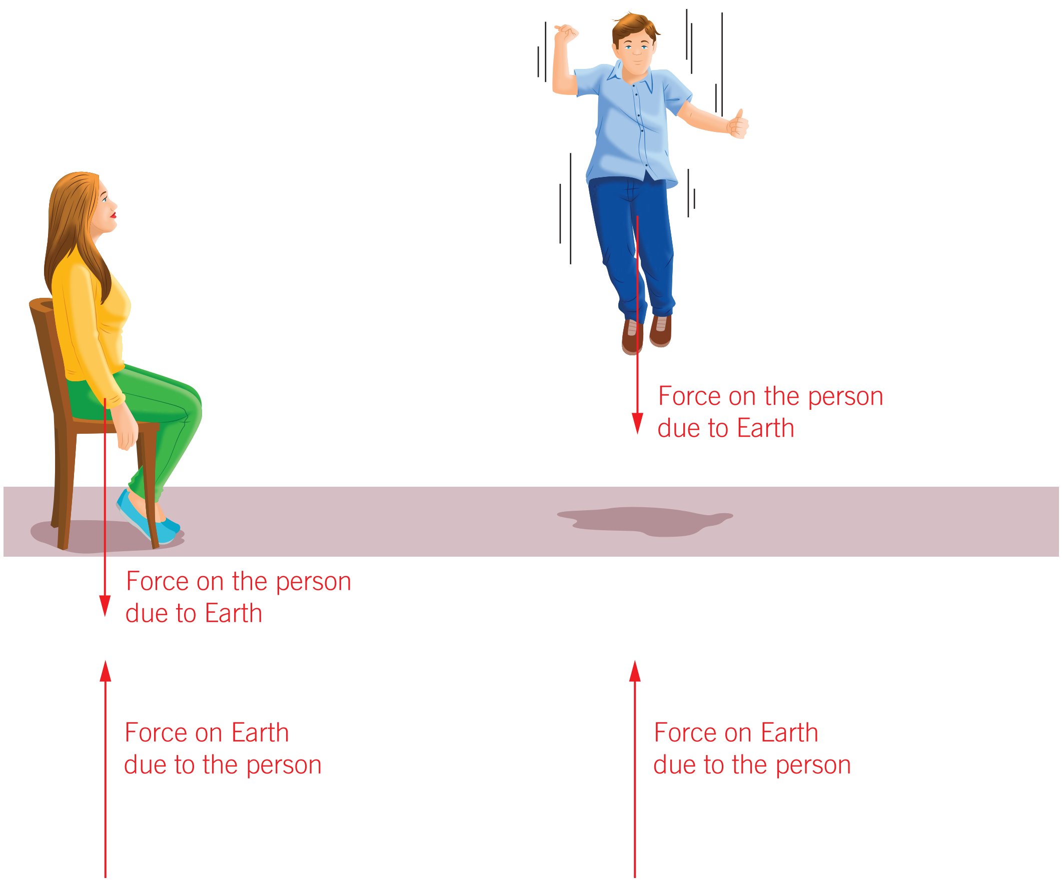

Figure 8B–11 The action–reaction pairs of a person being pulled down, in contact with Earth's surface (left) and falling (right)

The force due to gravity can be expressed mathematically as:

Formula 8B–2 Force due to gravity

$$F_g = mg$$

Where:

F_g = Force due to gravity (N)

m = Mass (kg)

g = Gravitational field strength, 9.8 N kg^{-1} close to the surface of Earth ($m\,s^{-2}$ or N kg^{-1})

Gravitational field strength a theoretical region of space around a mass where the gravitational force can be experienced by other masses. The gravitational field strength is expressed in N kg^{-1}, which is equivalent to the acceleration due to gravity in ms^{-2}.

The gravitational force acts from the centre of mass of all objects. Remember that mass refers to the body's resistance to acceleration when a force is applied and this does not change. However, the gravitational force (sometimes referred to as the weight force) is a force and would change if you were on the Moon, for example, since it has a different **gravitational field strength**.

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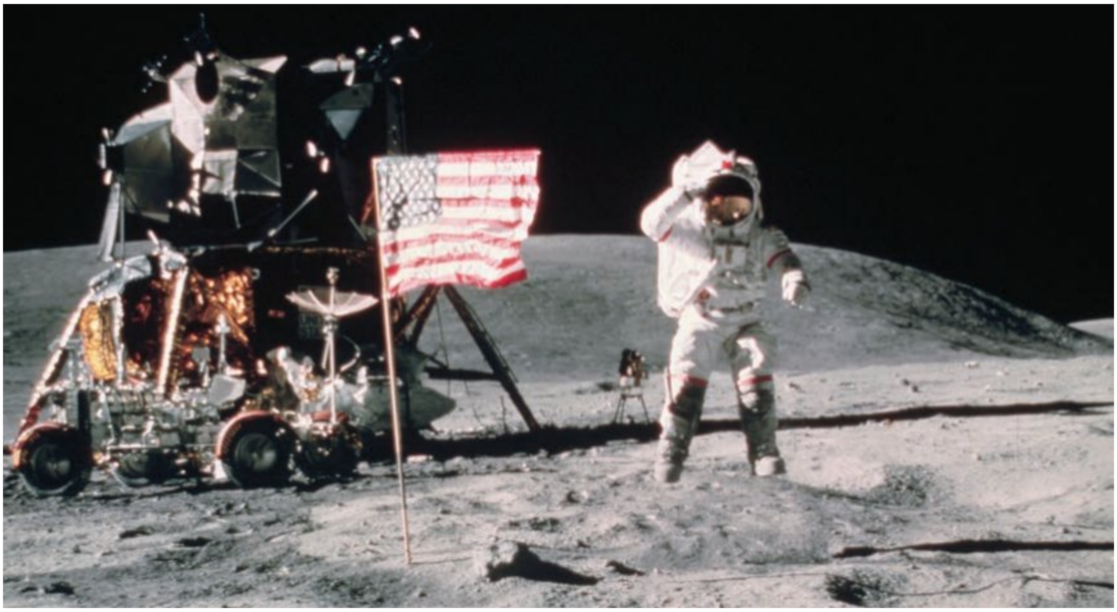


Figure 8B–12 An astronaut with a mass of 75 kg still has that mass on the Moon, but their weight force would only be 16.5% of what it is on Earth due to the Moon's lower gravity.

Applying Newton's laws

Newton's laws can be applied to solve a variety of problems.

Worked example 8B–1 Force on touching blocks

A 45 N force to the right is used to push two blocks, A and B, on a frictionless surface. Block A has a mass of 2 kg and block B has a mass of 1 kg. When they are pushed, both blocks move as one.

a Calculate the acceleration of the two blocks.

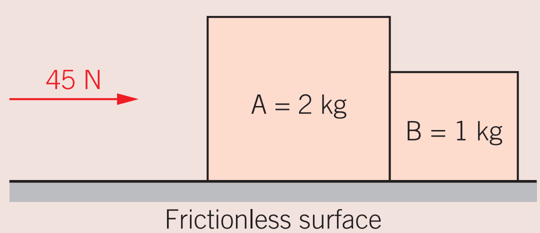
b What is the force on block B by block A?

c What is the force on block A by block B?

Solution

a As the two blocks move as one, you need to add the masses together.

$$a = \frac{F_{net}}{m} = \frac{45}{2+1} = 15\ \text{m s}^{-2}$$



Therefore, the acceleration of the blocks is 15 m s^{-2} to the right.

b As B is accelerating at 15 m s^{-2}, you need to find the force that will accelerate it at this rate.

$$F_{\text{on B by A}} = ma = (1)(15) = 15\ \text{N}$$

Therefore, the force on block B is 15 N to the right.

c Every action has an equal and opposite reaction. The action force is the force that block A applies on block B so the reaction force will be the force that block B applies to block A. Therefore, the force on block A is 15 N to the left.

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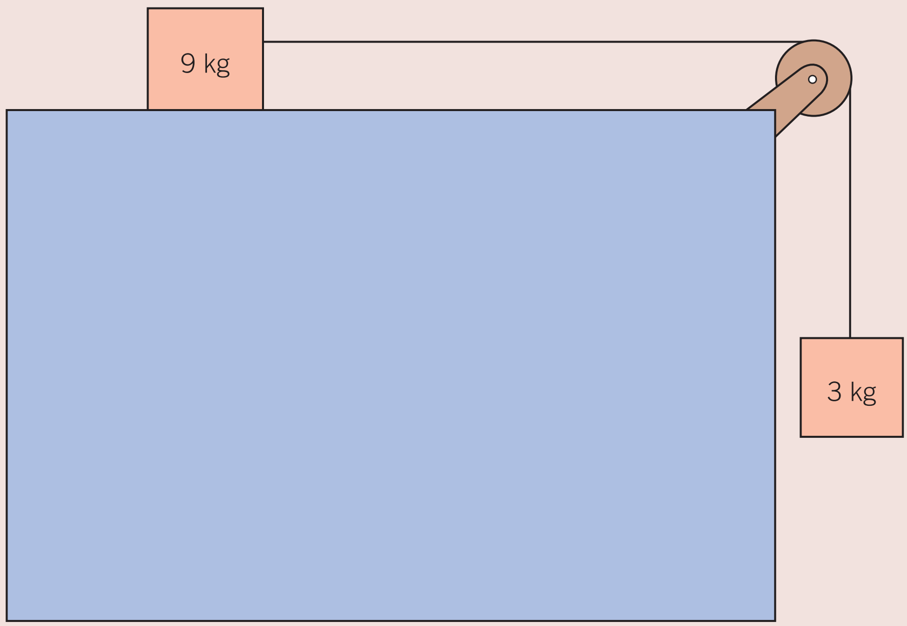
System
a collection of objects that interact with each other

Worked example 8B–2 Force in a pulley system

A mass of 9 kg, initially at rest, lies on a frictionless table. It is attached to a mass of 3 kg, which hangs freely off the table by a string and frictionless pulley **system**. Assume the string's mass is negligible.

a What is the acceleration of the system of the two joined masses?

b Calculate the tension in the string.



a The first step is to determine the net force acting on the system. Since the mass of 3 kg is hanging freely, gravity will provide a net downwards force. As the mass of 3 kg falls, the pulley system will transfer some of the force, via the string, to the block of 9 kg, causing it to slide to the right.

Therefore:

$$F_{net} = mg$$
$$= (3)(9.8)$$
$$= 29.4 \text{ N}$$

Newton's second law can now be applied to calculate the acceleration of the system (note that the two masses are added as the whole system is being accelerated):

$$a = \frac{F_{net}}{m}$$
$$= \frac{29.4}{9+3}$$
$$= 2.45 \text{ m s}^{-2}$$

b The tension in the string is a result of the string pulling on the mass of 9 kg and accelerating it at 2.45 m s^{-2}. Therefore, the tension can be found by applying Newton's second law:

$$F_{net} = ma$$
$$= (9)(2.45)$$
$$= 22.05 \text{ N}$$

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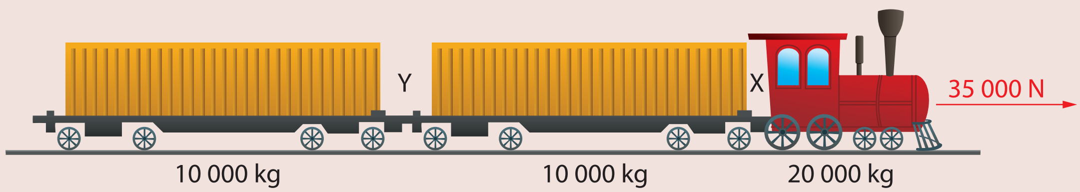
Worked example 8B–3 Tension in a train system

A steam engine with a mass of 20 000 kg is towing two carriages, each with a mass of 10 000 kg. The engine is connected to both of the carriages by cable X and the two carriages are connected by cable Y. As the engine leaves the station, it produces a driving force of 35 000 N. You may assume there is no rolling or air friction in this system. A diagram of this situation is shown below.

a Calculate the acceleration of the engine and carriage system.

b Calculate the tension in cable X.

c Calculate the tension in cable Y.



a Since the engine is towing both of the carriages, they are all part of the same system and will all accelerate at the same rate. This means that the masses can be added together to find the magnitude of the acceleration:

$$a = \frac{F_{net}}{m}$$

$$= \frac{35\,000}{10\,000 + 10\,000 + 20\,000}$$

$$= 0.875 \text{ m s}^{-2}$$

b Cable X is towing two carriages. This means it is subject to the tension required to accelerate both carriages at 0.875 m s^{-2}:

$$F = ma$$

$$= (10\,000 + 10\,000)(0.875)$$

$$= 1.75 \times 10^4 \text{ N}$$

c Cable Y is towing one carriage. This means it is subject to the tension required to accelerate one carriage at 0.875 m s^{-2}:

$$F = ma$$

$$= (10\,000)(0.875)$$

$$= 8.75 \times 10^3 \text{ N}$$

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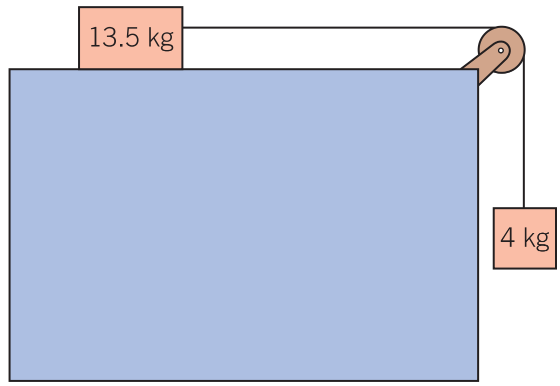
WORKSHEET 8B–1 NEWTON'S LAWS OF MOTION

Check-in questions – Set 2

1 Vijay pushes vertically down on a box of mass 50 kg that is resting on a table with a force of 450 N. Calculate the force applied to the box by the table.

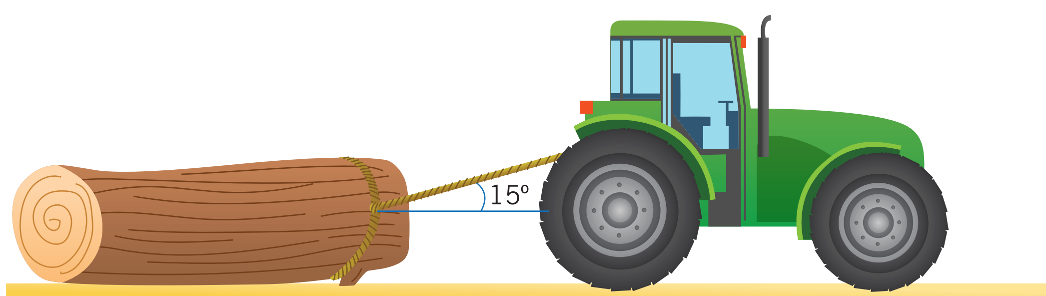
2 A block of mass 13.5 kg is resting on a frictionless table and is tethered to a block of mass 4 kg that is hanging over the edge of the table. A diagram of this situation is shown below. The pulley is frictionless.



a Calculate the acceleration of the system.

b Calculate the tension in the string that tethers the two masses together.

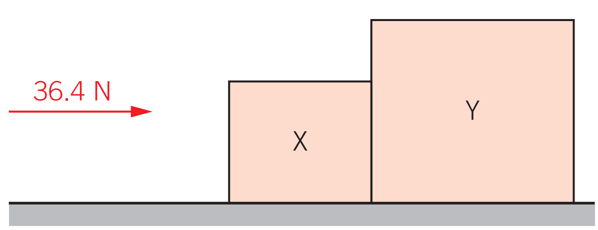
3 A farmer is moving a fallen tree on their property. In order to move the tree, the farmer ties a rope to the tree trunk and a tractor. The tractor has a mass of 2388 kg and the tree trunk has a mass of 4500 kg. The driving force of the tractor is 5500 N. A diagram of this situation is shown below.



a Calculate the acceleration of the tractor.

b Calculate the tension in the rope.

4 Two boxes X and Y move as one when they are pushed across a frictionless floor with a force of 36.4 N north. Box X has a mass equal to M and box Y has a mass equal to $1.5M$. The acceleration of the system is $3.86\ \text{m s}^{-2}$ north. A diagram of this situation is shown below.



a Calculate the mass of Y.

b Calculate the force on X applied by Y. Include a direction in your answer.

Changing normal forces

Imagine that you are standing in an lift that is moving up and down. You have an accurate scale that measures the force that you exert on the surface of the lift and therefore the force that the surface exerts on you (the normal force). You wonder, how would the force change with the motion of the lift?

When you stand on the scale there are only two forces acting on you, the force due to gravity, mg, and the normal force, N.

We can sum the forces in the vertical as shown:

$$\Sigma F_{vertical} = N - mg$$

The force due to gravity, mg, is negative as it acts down. Since a force is just the product of mass and acceleration, the equation can be expressed as:

$$ma_{vertical} = N - mg$$

The acceleration, avertical a_v, is the vertical acceleration of the lift. This can then be rearranged to make the normal force, N, the subject:

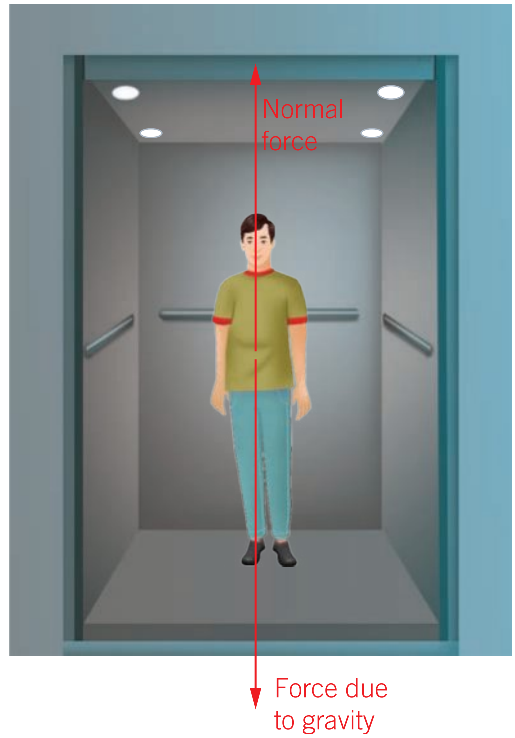


Figure 8B–13 The forces acting on a person in a lift

Formula 8B–3 Normal force

$$N = m(a_{vertical} + g)$$

Where:

N = Normal force of the object by the surface of the lift (N)

m = Mass of the object (kg)

$a_{vertical}$ = Acceleration in the vertical direction ($m\,s^{-2}$)

g = Gravitational field strength close to the surface of Earth, 9.8 $N\,kg^{-1}$ (or $m\,s^{-2}$)

The scale is reading the normal force, not the force due to gravity. The normal force and the force due to gravity will only be equal when the lift is either stationary or moving at a constant velocity. When the lift is accelerating up, the normal force will be greater than the force due to gravity, and when the lift is accelerating down, the normal force will be less than the force due to gravity. You may ask yourself what would the normal force be if the lift cable snapped and the lift accelerated down with an acceleration of 9.8 $m\,s^{-2}$. The answer might surprise you: the normal force would be zero; you would be falling down with an acceleration of 9.8 $m\,s^{-2}$ but not getting any normal reaction force from the floor of the lift.

This is what happens when astronauts and cosmonauts orbit Earth in space stations.

Figure 8B–14 American engineer and astronaut Mae Jemison experiencing a zero normal reaction force in Spacelab. The gravitational field strength acting on Mae Jemison is 8.7 N kg-1 but she appears to be floating.

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Worked example 8B–4 Normal force

A 96 kg man stands on a set of scales which measures the force that he applies to the floor inside an elevator. What is the force that the scales read when the elevator is:

a at rest

b moving at a constant velocity of 1.5 $m\,s^{-1}$ down

c moving with an upward acceleration of 0.2 $m\,s^{-2}$

d moving with a downward acceleration of 0.35 $m\,s^{-2}$.

Solution

a At rest, the vertical acceleration is zero; therefore:

$$N = m(a_{vertical} + g) = (96)(0 + 9.8) = 941\text{ N}$$

b When moving with a constant velocity, the vertical acceleration is zero; therefore:

$$N = m(a_{vertical} + g) = (96)(0 + 9.8) = 941\text{ N}$$

c Since the acceleration is up, it will be positive:

$$N = m(a_{vertical} + g) = (96)(0.2 + 9.8) = 960\text{ N}$$

d Since the acceleration is down, it will be negative:

$$N = m(a_{vertical} + g) = (96)(-0.35 + 9.8) = 907\text{ N}$$

Inclined planes

On a slope, such as the one shown in Figure 8B–15, an object will have three forces acting on it: the force due to gravity, which acts vertically down; the normal force, N, which acts perpendicular to the surface; and the friction force, f, which acts parallel to the slope.

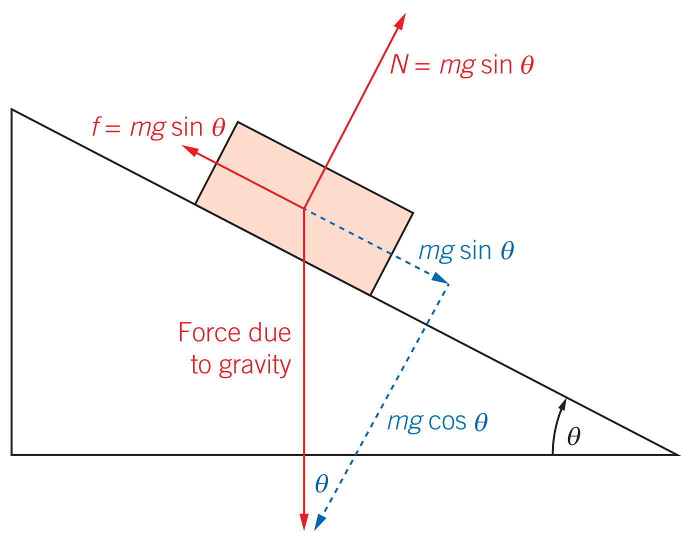

Figure 8B–15 The forces acting on an object that is stationary on an inclined plane

When an object is stationary on an inclined plane, all of the forces will balance. This means that the normal force, which is the force by the surface on the object, will be equal in magnitude but opposite in direction to the component of the force due to gravity that acts perpendicular to the surface. It also means that the friction force, applied by the surface on the object, is equal in magnitude but opposite in direction to the component of the force due to gravity that acts parallel to the slope. This means that when an object is stationary on an inclined slope the equations on Figure 8B–15 are true.

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Where:

$N = mg\cos\theta$

$f = mg\sin\theta$

N = Normal force on the object by the surface (N)

m = Mass of the object (kg)

g = Gravitational field strength close to the surface of Earth, 9.8 N kg^{-1} (or m s^{-2})

f = Friction force (N)

θ = Angle of the slope (°)

If the object is on a frictionless surface, then it will be accelerated down with a force of $mg\sin\theta$. Since $F = ma$, the acceleration of the slope can be determined to be:

$$F = mg\sin\theta$$

$$ma = mg\sin\theta$$

Therefore:

Formula 8B–4 Acceleration on a frictionless slope

$$a = g\sin\theta$$

Where:

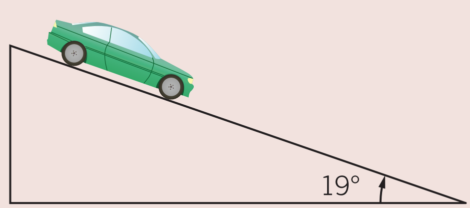
a = Acceleration down a frictionless slope (m s^{-2})

g = Gravitational field strength close to the surface of Earth, 9.8 N kg^{-1} (or m s^{-2})

θ = Angle of the slope (°)

Worked example 8B–5 Acceleration on a frictionless slope

A 1080 kg car is parked at the top of a driveway on Mt Buller. The driveway is inclined at 19°.



a Calculate the magnitude of the normal force on the car by the surface.

b Calculate the magnitude of the frictional force by the surface on the car.

c On a particularly cold morning the driveway becomes covered in ice and all friction between the surface and the tyres is lost. Calculate the magnitude of the car's acceleration down the slope.

Solution

a $N = mg\cos\theta = (1080)(9.8)(\cos 19°) = 1.00 \times 10^4$ N

b $F = mg\sin\theta = (1080)(9.8)(\sin 9°) = 3.45 \times 10^3$ N

c $a = g\sin\theta = (9.8)(\sin 19°) = 3.19\ \text{m s}^{-2}$

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Application of motion: the physics of car safety

In 2019, 1195 people were killed on Australian roads compared to 3798 in 1970, even though there are now many more cars on the roads. Over the past 40 years, an understanding of the physics of car crashes has led to three major innovations in car safety. These three major innovations are seatbelts, air bags and crumple zones. In any collision involving a car, there is a rapid change in momentum that occurs. This rapid change in momentum can create large forces on the occupants, which can cause injury or death.

Before 1972, seatbelts were not required to be worn in Australia. If a passenger is not wearing a seatbelt during a collision, then according to Newton's first law of motion, the passenger will continue in their state of motion. This means if someone crashes at 90 $km\,h^{-1}$, the car will begin to slow but the occupant will continue to move at 90 $km\,h^{-1}$ until they hit something like the windscreen, steering wheel or dashboard. This will apply an unbalanced force on them, causing them to slow down. The introduction of the seatbelt meant that in a car crash, an unbalanced force would be applied across the person's shoulders and hips, the strongest parts of their body, so the person would slow down with the car. However, a person's head would often continue to move forwards and hit the steering wheel, resulting in injury or death.

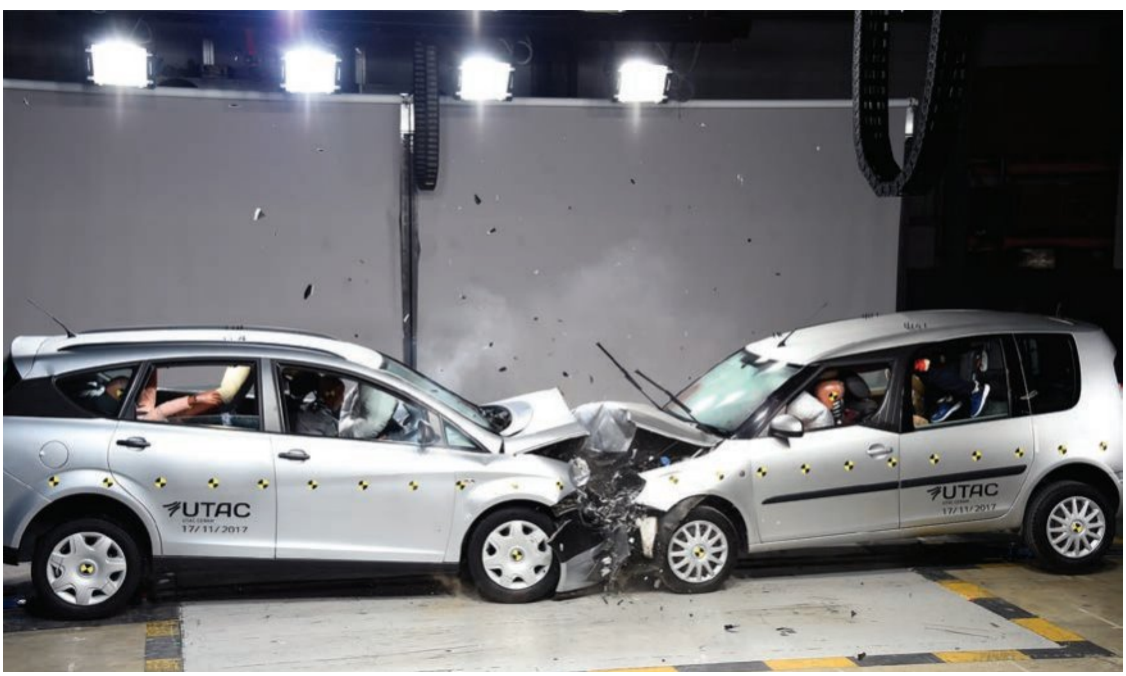

Figure 8B–16 Vehicles collide during a frontal crash test without a safety belt buckled in the back seat. If you look carefully, you can see that the dummy child in the right car is airborne in the car.

It wasn't until 1980 that the air bag helped to solve this problem. During a crash, the air bag will inflate very rapidly. When the occupant's head hits the air bag, the force spreads out more evenly and the collision lasts longer. The impulse will be the same for the crash and as $I = F_{av}\Delta t$, by extending the time of the collision the average force on the occupant is reduced.

Early cars were made to be strong and rigid, as it was believed that this would protect the occupants. But modern cars have crumple zones. These zones in the front, rear and sometimes even sides of the car are designed to crumple in a collision. Similar to an air bag, the crumple zones increase the time of the collision, thereby reducing the average force on the occupants. Modern cars still have a rigid compartment that holds the occupants as you wouldn't want that part to crumple, otherwise it would crush the occupants.

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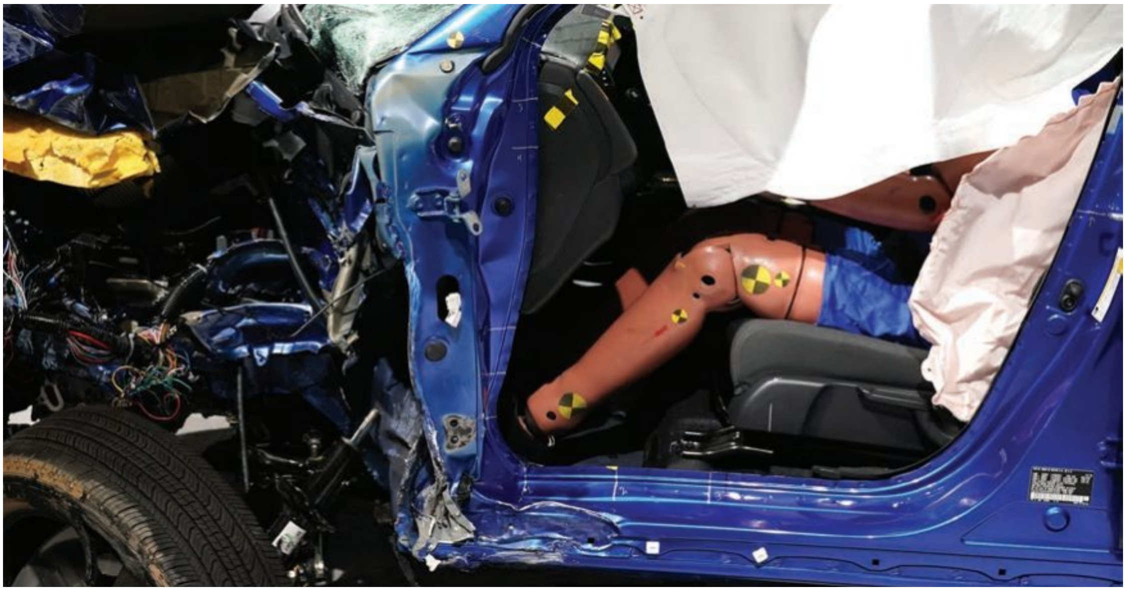

Figure 8B–17 This image shows the front crumple zone and the rigid passenger compartment.

With the impending threat of global warming, it is inevitable that in the next few decades combustion engines will be phased out to make way for electric vehicles. Electric vehicles have many features that make them safer than most non-electric vehicles. As electric vehicles have no combustion engine, the whole front of the car can act as a crumple zone, which further reduces the force on the occupants by extending the time of the collision. The heavy batteries are placed at the base of the car; this lowers the car's centre of mass and reduces the chance that the car will roll. Electric vehicles are also leading the way in active safety measures, which can now be found in many non-electric vehicles. Blind spot monitoring, forward collision warning with emergency braking, lane-departure warning, lane-keeping assist and many more are becoming increasingly common features. It is likely that eventually cars will become self-driving, which will hopefully mean that, thanks to physics, someday no person needs to die on the roads.

Figure 8B–18 A Tesla Model S electric car, equipped with Autopilot hardware and software, drives hands-free on a highway in Amsterdam, Netherlands.

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VIDEO 8B–2
SKILLS: SHOWING YOUR WORKING CLEARLY

8B SKILLS

Showing your working clearly

When completing a question that involves mathematical calculations and is worth two or more marks, it is important to always show your working. Usually the best way to show working out is to identify the formula that is required to answer the question and then rearrange the symbols to solve for the unknown quantity (this minimises errors). Double check that you have the correct indices on the formula. Insert the relevant values in place of their symbols and then solve for the unknown. Your final answer should be rounded to three significant figures. It is important to note that if you cross out your working, the part that has been crossed out will not be considered for marking. For example:

Question

If a ball of mass 40 kg is pushed with a force of 500 N calculate the magnitude of the acceleration of the ball.

Solution

$$a = \frac{F}{m}$$

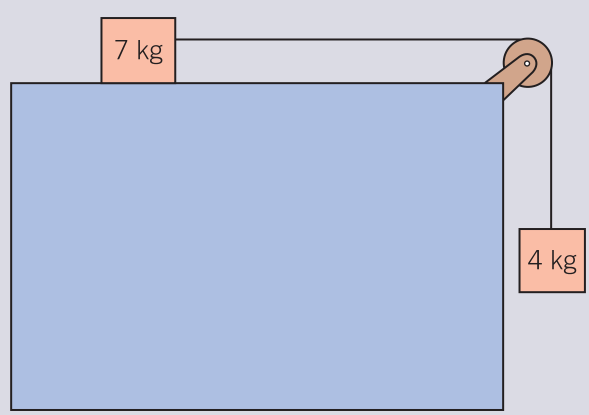
$$= \frac{500}{40}$$

$$= 12.5\ \text{m}^{-2}$$

If there are multiple steps to the calculation, then the unrounded figure should be used for the subsequent steps. Be sure to include the units of the quantity that you are calculating each step of the way to avoid confusion. If you have corrected a question and have two sets of working out, make sure that you cross out the incorrect set of working. For example:

Question

A mass of 7 kg, initially at rest, lies on a frictionless table. It is attached to a mass of 4 kg that hangs freely off the table via a string and frictionless pulley system. Calculate the tension in the string. A diagram of this situation is shown on the right.



Solution

$$a = \frac{F}{m}$$

$$= \frac{(4)(9.8)}{7+4}$$

$$= 3.56\ \text{m s}^{-2}$$

$$F = ma$$

$$= (7)(3.56)$$

$$= 24.9\ \text{N}$$

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Section 8B questions

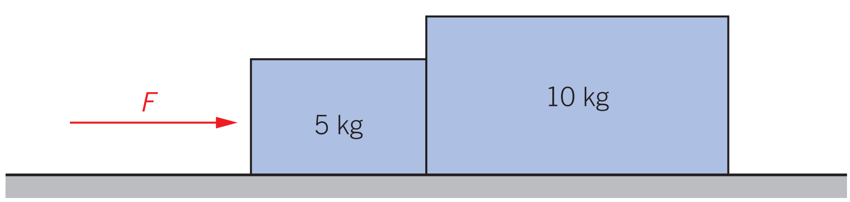
Multiple-choice questions

1 Which of the following statements is true?
- A The direction of the velocity and the direction of the net force will always be the same.
- B The object will always travel in the same direction as the direction of the acceleration.
- C If you throw a ball up, while the ball is travelling up it must have an upward force on it.
- D An object will always accelerate in the direction of the net force.

2 Two objects are pushed with an equal force, F. Object A has a mass of m and object B a mass of $2m$. Which of the following statements is true?
- A Both objects will have the same acceleration.
- B Object A will have double the acceleration of object B.
- C Object B will have double the acceleration of object A.
- D Object A will have four times the acceleration of object B.

3 A car is parked on a hill that has an angle of incline of 30°. If the action force is the force down due to gravity, then the reaction force is
- A Earth being pulled up by the attraction to the car.
- B the force of the brakes on the wheels.
- C the normal force on the car.
- D the force of friction between the tyres and the road

4 Two blocks of mass 5 kg and 10 kg are placed in contact on a frictionless horizontal surface, as shown in the diagram below. A constant horizontal force, F, is applied to the 5 kg block.



Which one of the following statements is correct?
- A The net force on each block is the same.
- B The acceleration experienced by the 5 kg block is twice the acceleration experienced by the 10 kg block.
- C The magnitude of the net force on the 5 kg block is half the magnitude of the net force on the 10 kg block.
- D The magnitude of the net force on the 5 kg block is twice the magnitude of the net force on the 10 kg block.

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5 Close to the surface of Earth, the acceleration due to gravity is $9.8\ \mathrm{m\,s^{-2}}$. If you drop a mass of 1 kg and drop a mass of 100 kg from the same height, which of the following is not true?
- A Both objects will reach the ground at the same time if friction is ignored.
- B Both objects will have the same force on them since the acceleration is the same.
- C Since the object with the mass of 100 kg is 100 times heavier, it must have a force on it 100 times greater than the force on the object with the mass of 1 kg.
- D The acceleration due to gravity is not dependent upon the mass of the object.

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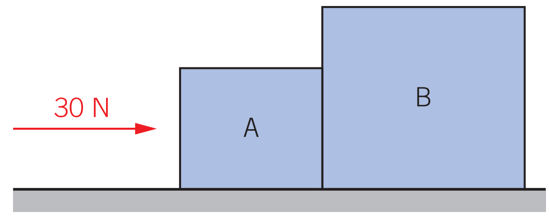
Short-answer questions

6 A learner driver notices that they have to put their foot on the accelerator pedal in order to maintain a constant velocity. This confuses the driver, who is also a physics student, as they know that acceleration means a change in velocity. How would you explain the observation made by this student? Your answer needs to refer to a specific law of motion.

7 A car of mass 100 kg accelerates at 125 m s^{-1}. Calculate the driving force on the car; assume friction is negligible.

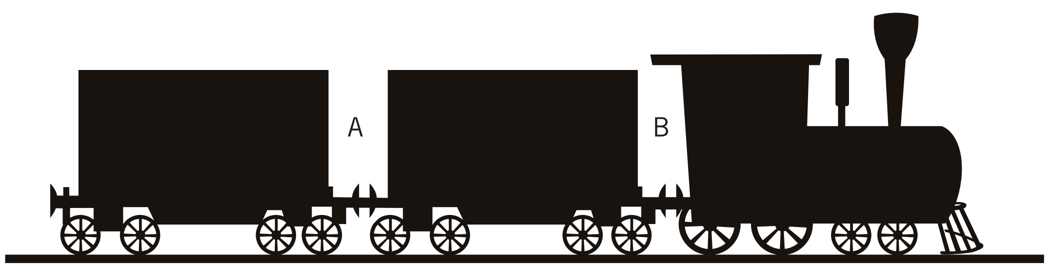
8 Two blocks, A and B, are pushed along a smooth frictionless surface with a force of 30 N. This causes them to accelerate at a rate of 4.60 m s^{-2}. Block B is 3.5 times heavier that block A.



a Calculate the mass of block B.

b What is the magnitude of the force on block B due to block A?

9 A train that has a mass of 5000 kg and a driving force of 450 kN is tethered to two carriages, each with a mass of 2000 kg, via a metal cable B. The two carriages are tethered together by a metal cable A. Friction can be ignored for this question.

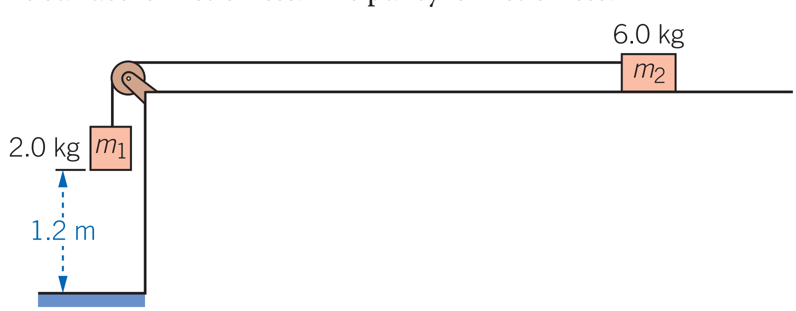


a Calculate the magnitude of the acceleration of the system.

b Calculate the tension in metal cable A.

c Calculate the tension in metal cable B

10 Students set up an experiment that consists of two masses, m_1 of 2.0 kg and m_2 of 6.0 kg, connected by a string, as shown in the diagram below. The mass of the string can be ignored. The surface is frictionless. The pulley is frictionless.



At the start of the experiment, the bottom of mass m_1 is 1.2 m above the floor and both masses are stationary

a Calculate the gravitational force on m_1. Include the correct unit in your answer.

b Calculate the tension in the string as m_1 is falling.

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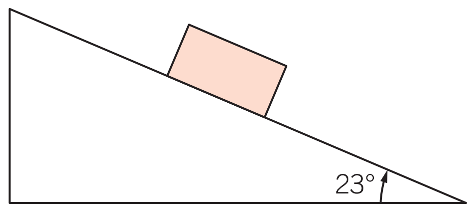
11 A 56 kg woman stands on a set of scales that measures the force that she applies to the floor inside an elevator. What is the force that the scales read when the elevator is:

- **a** at rest?
- **b** moving at a constant velocity of 0.75 $m\,s^{-1}$ up?
- **c** moving with an upward acceleration of 0.4 m $m\,s^{-2}$?
- **d** moving with a downward acceleration of 0.24 $m\,s^{-2}$?

12 An 8.50 kg marble block is placed on a slope that has a constant incline of 23°. The block remains stationary on the slope.



- **a** Draw and label all of the forces acting on the block.
- **b** Calculate the magnitude of the normal force on the block by the surface.
- **c** Calculate the magnitude of the frictional force by the surface on the block.
- **d** The block is then taken off the slope and the block and slope are polished so finely that there is considered to be no friction between them. Calculate the magnitude of the block's acceleration down the slope.

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Equilibrium

Study Design:
- Calculate torque, $\tau = r_{\perp}F$
- Analyse translational and rotational forces (torques) in simple structures in translational and rotational equilibrium

Glossary:
Centre of mass
Equilibrium
Pivot point
Rotational equilibrium
Rotational force
Torque
Translational equilibrium
Translational force

ENGAGE

Levers in life

Give me a lever long enough and a fulcrum on which to place it, and I shall move the world
Archimedes

Have you ever wondered why a door handle is placed so far away from the hinge?

What would happen if the door handle was placed in the centre of the door?

By placing the door handle far away from the pivot point, the person opening the door is placed with a mechanical advantage. As the distance from the pivot point increases, the torque also increases for a given force. The ability to greatly increase the torque by using a long lever has been used by humans for thousands of years, including by Aboriginal and Torres Strait Islander peoples, as covered later in this section.

Levers are used on wheel braces and wrenches to help tighten and loosen bolts, on wheelbarrows to make it easier to lift a heavy load, on pliers, tongs and tweezers to help get a tight grip of things.

Figure 8C–1 Using the long lever on a socket wrench to loosen the wheel nuts on a car

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EXPLAIN

Introducing equilibrium

Looking around the room that you are in, you will see many objects but very few will currently be moving. This does not mean the objects have no forces on them; it just means they are in **equilibrium**. If, for example, you rest a ruler on a desk so that half of the ruler is hanging over the edge, the ruler will have a force due to gravity and normal force acting on it. These **translational forces** will balance each other. Now if you place an eraser at both ends of the ruler, it will be in rotational equilibrium as the eraser to the left is creating an equal **rotational force** as the eraser places on the right end. The addition of these erasers increases the gravitational force on the ruler–eraser system, so the normal force on the ruler by the table will also increase.

If another eraser is then placed to the right of the ruler, the system will no longer be in equilibrium and it will rotate in a clockwise direction.

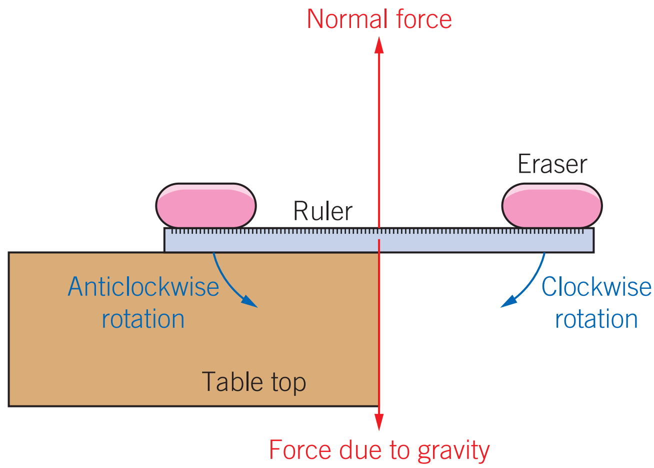

Figure 8C–2 A ruler that has one end over the table does not fall off because it is in translational and rotational equilibrium.

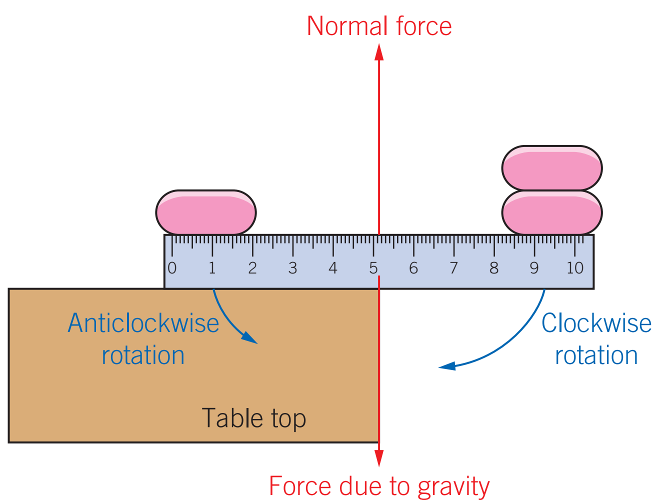

Figure 8C–3 The ruler in Figure 8C–2 now has another eraser added to the end that extends beyond the edge of the table and will rotate clockwise because the sum of the clockwise torques are greater than the sum of the anticlockwise torques.

Equilibrium the state where the sum of the translational and rotational forces on an object are equal to zero

Translational force a force that can cause an object to change its position

Rotational force force that can cause an object to rotate about an axis of rotation

Torque a measure of how much of a force acting on an object is causing it to rotate

Torque

Torque (rotational force) is a measure of the ability to cause rotation. The amount of torque, τ, is given below.

Formula 8C–1 Torque

$$\tau = r_{\perp}F$$

Where:

τ = Torque (N m)

$r_{\perp}$ = Perpendicular distance from the line of action of the force to the pivot point (m)

F = Force (N)

Note: this formula can also be expressed in the form $\tau = F_{\perp}r$, where $F_{\perp}$ is the perpendicular component of the force and r is the distance from the pivot point.

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Torque is a vector quantity; it requires a magnitude and a direction. The direction of torque is either clockwise or anticlockwise. In order to have either clockwise or anticlockwise torques, an object must have a **pivot point**. The pivot point is the point that an object rotates around. It is important to note that no force that passes directly through the pivot point will cause a torque. For example, if you push on a door so that all of the force goes through the hinges, then the door will not swing open.

Pivot point the point that an object rotates around; also known as the axis of rotation

When solving torque problems, it is important to understand the significant of the **centre of mass**. The location of the centre of mass is determined by finding the mean position of all the parts of a system, weighed according to their masses. If a force is applied through the centre of mass, it will cause linear acceleration without a torque on the object. The force due to gravity acts at the centre of mass of the object.

Centre of mass the mean position of all the parts of a system, weighed according to their masses

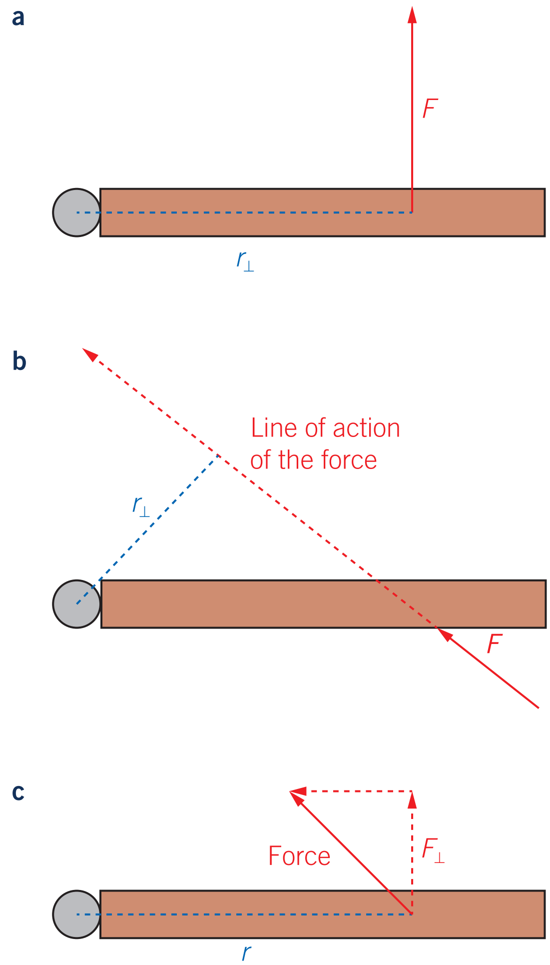


Figure 8C–4 The various ways of calculating torque. **a** The perpendicular distance from the line of action of the force is through the object. **b** The perpendicular distance to the line of action of the force is outside of the object that the torque is being applied to. **c** *r* is taken as the distance from the pivot point to where the force is being applied. The component of the force that is perpendicular to *r* is then found.

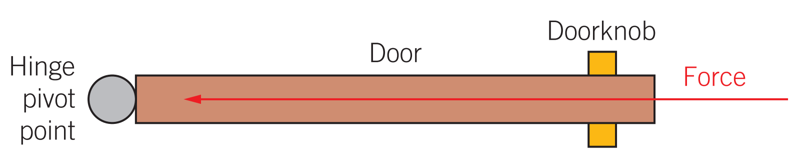
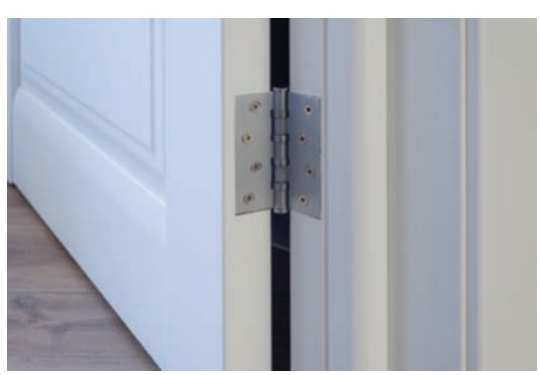


Figure 8C–5 A door, viewed from directly above. When a force goes through the pivot point, no torque is generated.



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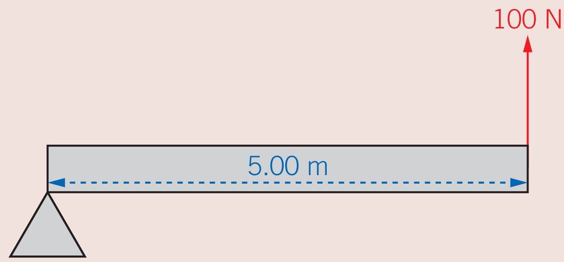
Worked example 8C–1 Torque on a lever

A force of 100 N is applied 5.00 m from the pivot point as shown below.



Calculate the torque and state the direction (clockwise or anticlockwise) in which this bar will rotate.

Solution

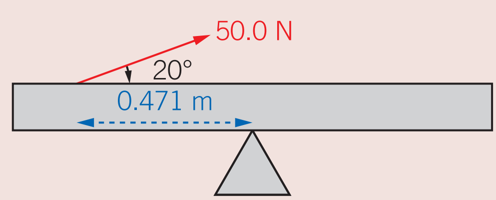
$\tau = r_{\perp}F$

$= (5.00)(100)$

$= 500$ N m, it will rotate anticlockwise.

Worked example 8C–2 Torque when force is not perpendicular

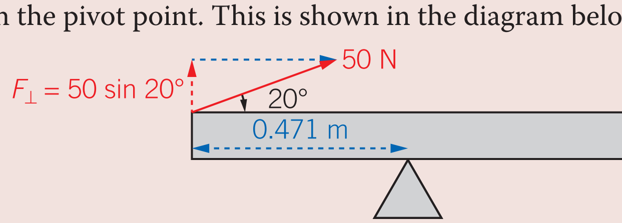
A see-saw is pushed with a force of 50.0 N, 0.471 m to the left of the pivot point. The force makes an angle of 20° to the horizontal. A diagram of this is shown below.



Calculate the torque generated by the force. Include a direction for the torque. Note that, for this question, the force due to gravity of the see-saw acts through the pivot point. Therefore, the perpendicular distance, $r_{\perp}$, is zero and the torque due to gravity on the see-saw is zero.

Solution

In this example, the best approach is to find how far the perpendicular component of the force, $F_{\perp}$, acts from the pivot point. This is shown in the diagram below.



vertical component = $50 \sin 20° = 17.1$ N

$\tau = (17.1)(0.471) = 8.05$ N m, clockwise

Note that since torque is a vector quantity, it must have a direction. In this case, the direction is clockwise as the see-saw will rotate in the same direction that a clock hand would move.

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The Woomera

Aboriginal peoples use leverage to throw spears. A woomera is a device that the spear sits in. It increases the length of the lever arm; therefore, a greater force can be applied to the spear, increasing the distance thrown.

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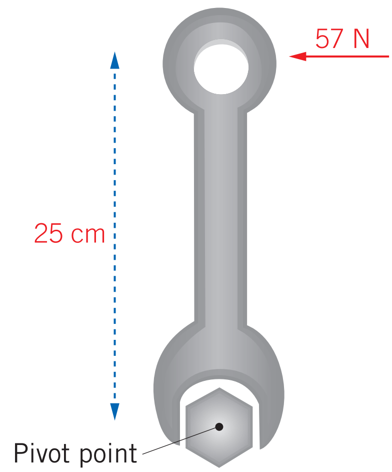
Check-in questions – Set 1

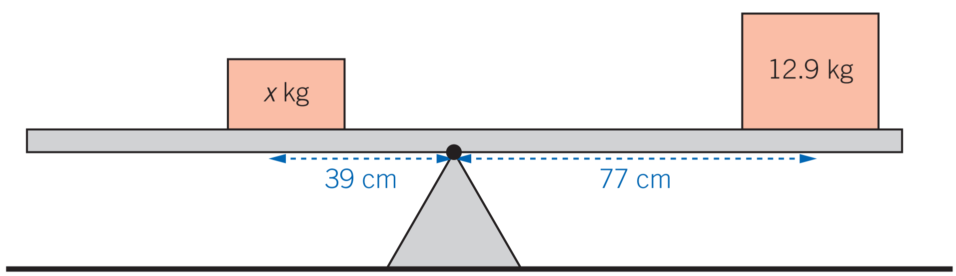
1 A builder uses a spanner to turn a bolt. The builder applies a force of 57 N at a distance of 25 cm from the pivot point.



a Calculate the torque applied to the bolt.

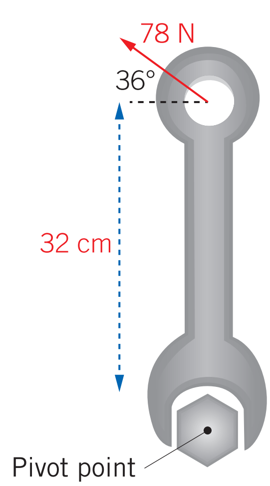
b Other than applying more force, how could the builder increase the torque?

2 Two blocks are placed on a see-saw. The first block has a mass of x kg and is placed so that its centre of mass acts 39 cm to the left of the pivot point; the second block has a mass of 12.9 kg and is placed so that its centre of mass acts 77 cm to the right of the pivot point.



Calculate the mass of x, given that the system is in equilibrium.

3 A builder uses a spanner to turn a bolt. The builder applies a force of 78 N at an angle of 36° from the horizontal and a distance of 32 cm from the pivot point. A diagram of this situation is shown below.



Calculate the torque generated by the builder.

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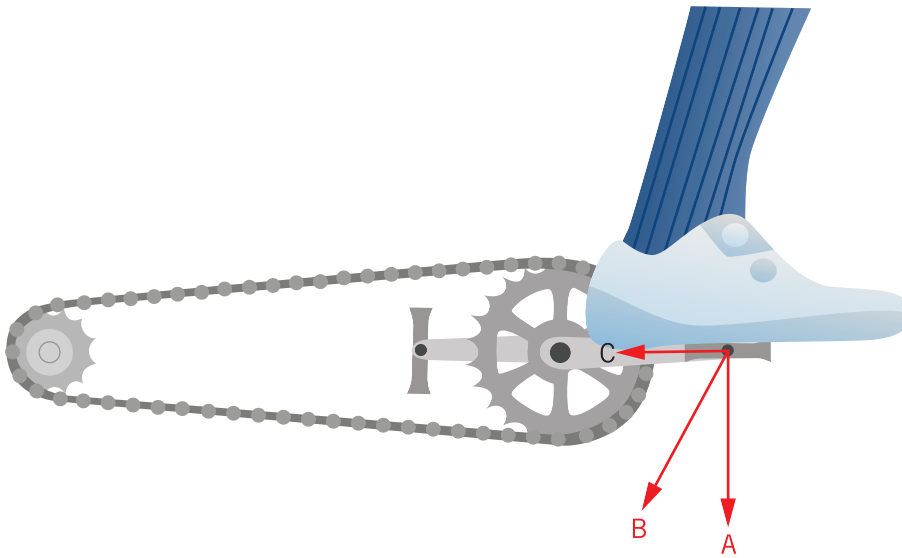
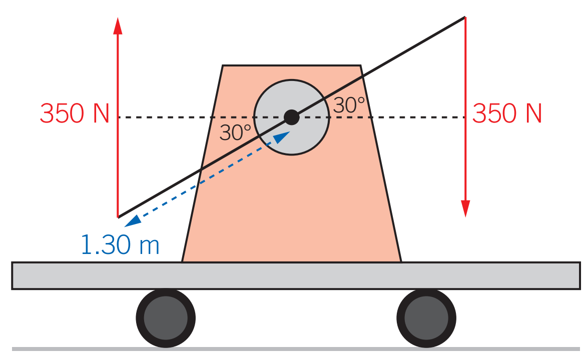
4 When cycling, a cyclist attaches their shoe to the bike pedal that turns the gears that ultimately turns the wheel. The diagram below shows a cyclist pushing on the pedal. In which direction, A, B or C, should the cyclist push? Justify your answer.



5 A hand car is a manually-powered railway vehicle used by workers to inspect and maintain tracks. Workers stand at either end of the black armature holding the brown handles, pumping the armature up and down to turn a circular gear that turns the wheels. In Australia, hand cars were affectionately known as kalamazoos after the Kalamazoo Manufacturing Company that produced them. The length of the armature is 2.60 m, so each end is 1.30 m from the pivot point, as shown in the diagram. Each rider applies a constant force of 350 N while pumping the car.



© Mason Clark

a Calculate the total torque when the armatures make an angle of 30° to the horizontal as shown in the diagram above.

b Sketch a graph showing how the torque varies with time; no values are required. Take the point of time zero to be when the pump lever is in the horizontal position. Note: the maximum angle to the horizontal that the pump lever makes is 40°.

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Types of equilibrium

Rotational equilibrium

Problems that you encounter will often refer to a system being in equilibrium. This means that, not only are all of the forces balanced, but all of the torques are also balanced (as the object is not rotating). When a system is in **rotational equilibrium**, it is not rotating; this means that the clockwise and anticlockwise torques are equal in magnitude. Therefore, for a system in rotational equilibrium:

Rotational equilibrium when a system is not rotating, the sum of the torques is equal to zero

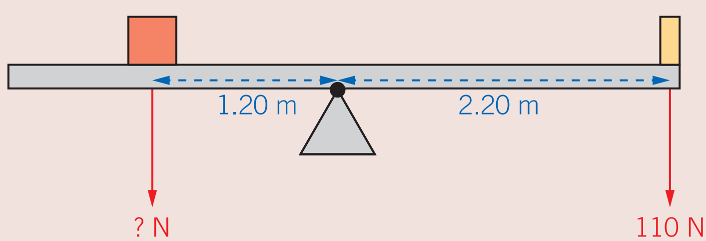
Formula 8C–2 Rotational equilibrium

$$\sum \tau = 0$$

$$\sum \text{anticlockwise moments} = \sum \text{clockwise moments}$$

Worked example 8C–3 Finding rotational equilibrium

If the see-saw shown in the diagram below is in equilibrium, calculate the mass of the block on the left.



Solution

$$\sum \tau = 0$$

$$F(1.20) = (110)(2.2)$$

$$F = 202 \text{ N}$$

$$m = \frac{202}{9.8} = 20.6 \text{ kg}$$

Translational equilibrium

Any object that is stationary or moving at a constant velocity is in **translational equilibrium**. When an object is either stationary or moving at a constant velocity, the sum of the forces on the object are equal to zero. This can be expressed mathematically as:

Translational equilibrium occurs when the velocity of an object is constant. This means that the net force acting on the object is equal to zero.

Formula 8C–3 Translational equilibrium

$$\sum F = 0$$

$$\sum F_{left} = \sum F_{right}$$

$$\sum F_{up} = \sum F_{down}$$

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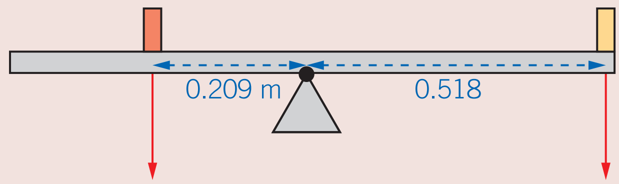
Worked example 8C–4 Force exerted by the pivot

Two masses are placed on a see-saw shown in the diagram below.



If the see-saw is in equilibrium, calculate the force exerted by the pivot.

Solution

$\sum F = 0$

$\sum F_{left} = \sum F_{right}$ (there are no left or right forces on the pivot, so this is zero on both sides)

$\sum F_{up} = \sum F_{down}$

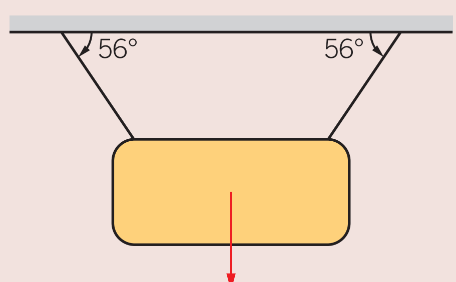
$= 223 + 90$

$= 313$ N

The upwards force exerted by the pivot point is 313 N.

Worked example 8C–5 Finding tension in a sign

A sign is hung by two cables to the ceiling of the shop. The sign has a mass of 35.0 kg and the cables make an angle of 56° to the horizontal. If the mass of the cables is negligible, calculate the tension in each cable.

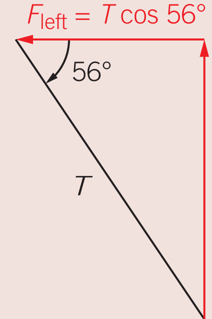


Solution

Since the sign is stationary and not rotating, it is in translational equilibrium; therefore:

$\sum F = 0$ and $\sum \tau = 0$

The downwards force due to gravity must be balanced by the upwards components of the tension force. To determine this, the tension force must be broken up into its component forces as shown below.



$\sum F_{up} = \sum F_{down}$

$2 \times T \sin 56° = (35.0)(9.8)$

$T = 207$ N

Note that the $\sum F_{left} = \sum F_{right}$ will be equal as they will both be equal to $T \cos 56°$ N.

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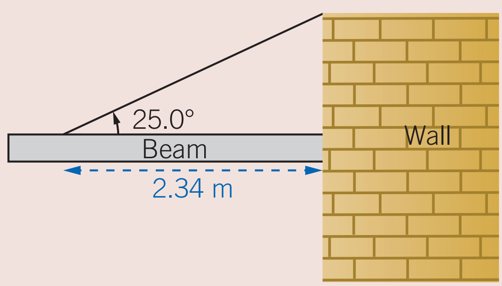
Translational and rotational equilibrium

For a system to be in equilibrium, both the rotational and translational forces must be in equilibrium. Therefore, to solve these types of problems, you must consider how the torques and forces on the system can remain balanced. Generally, it is advisable to do the following.

1. Draw in all of the forces acting on the relevant object.
2. Solve the rotational equilibrium first. To do this, choose a pivot point that will eliminate one of the forces, since any force that passes through the pivot point causes no rotation. Note, you can choose any point to be the pivot point, but some make the calculation easier than others.
3. Solve any unknowns by equating the clockwise and anticlockwise torques.
4. Break all of the forces into their up, down, left and right components.
5. Solve any unknown forces by equating the up and down forces as well as the left and right forces.

Worked example 8C–6 Application to cantilever with support

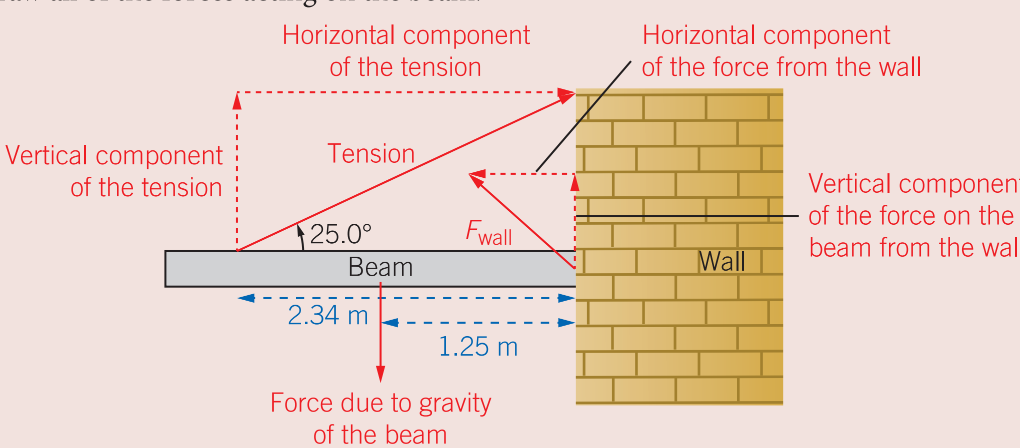
A uniform beam, with a length of 2.50 m and a mass of 13.0 kg, is held to a wall by a metal cable. The metal cable is attached to the beam 2.34 m away from the wall and makes an angle of 25.0° to the horizontal as shown in the diagram below.



Calculate the tension in the metal cable.

Solution

Use the join between the wall and the beam as the pivot point.
Draw all of the forces acting on the beam:



The force due to gravity of the beam acts 1.25 m away from the wall (the pivot point):

$$\sum\tau = 0$$

$$(1.25)(13.0)(9.8) = (T \sin 25°)(2.34)$$

$$T = \frac{(1.25)(13.0)(9.8)}{(\sin 25°)(2.34)} = 161 \text{ N}$$

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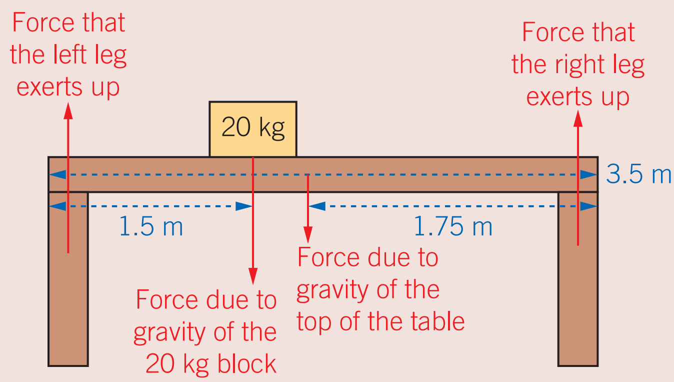
Worked example 8C–7 Equilibrium in a table

A 20 kg box is placed 1.5 m away from the left leg of a table. The table is supported by two legs and the top of the table is a uniform mass of 5.8 kg. The table is 3.5 m long. Calculate the force that the left leg is exerting.

Solution

The first step in these complex problems is to draw all of the forces acting on the relevant object.



You can eliminate one force by choosing the location of your pivot point. Make the location of the pivot point the right leg and then solve for the force on the left leg.

$$\sum \tau = 0$$

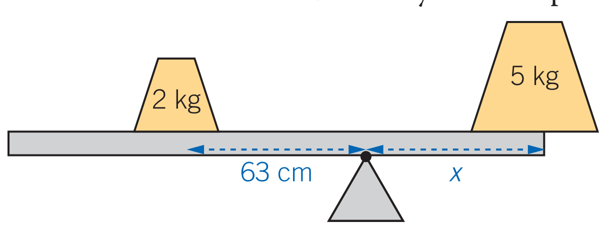
$$(20)(9.8)(3.5 - 1.5) + (5.8)(9.8)(1.75) = F_{\text{left leg}}(3.5)$$

$$F_{\text{left leg}} = 140 \text{ N up}$$

WORKSHEET 8C–1 EQUILIBRIUM

Check-in questions – Set 2

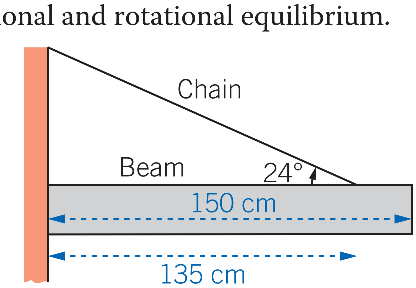
1 A see-saw has two different masses placed on it in such a way that it is in equilibrium. A mass of 2 kg is placed so that its centre of mass is 63 cm from the pivot point and a mass of 5 kg is placed so that its centre of mass is x m away from the pivot point.



a Calculate the distance x.

b Calculate the force applied by the pivot point to the beam.

2 A 150 cm long uniform beam that has a mass of 13.4 kg is held in place by the wall and a chain that is attached 135 cm along the beam. A diagram of this situation is shown. The system is in translational and rotational equilibrium.



Calculate the tension in the chain.

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8C SKILLS

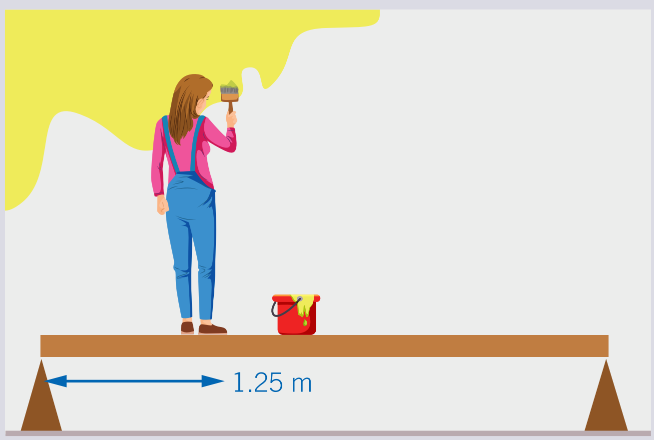
VIDEO 8C–1
SKILLS: USING DIAGRAMS TO ANSWER QUESTIONS

Using diagrams to answer questions

Physics questions will often have a lot of quantities that must be considered. When large amounts of information are given, it can sometimes be overwhelming to know where to start. This is why you should use the diagram provided or draw your own diagram because as it helps you to visualise the information that you have so that the relationship between the quantities can be more easily shown. As you read through the question, you should immediately circle or highlight any quantities and convert these quantities into SI units so that they can be used in a formula. If a diagram is provided, you should also write down the quantities on the diagram as you read them. If a diagram is not provided, then you should sketch a diagram of the situation as you read the information, inserting all relevant values.

Question

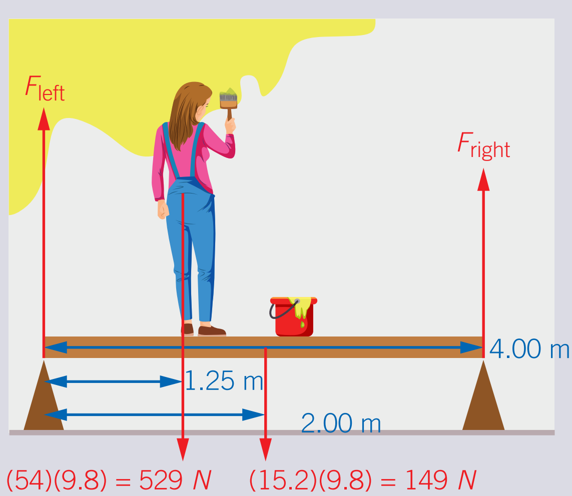
A 54.0 kg woman is paining a wall. She is standing on a 4.00 m long plank that has supports at both ends. The plank has a mass of 15.2 kg and its centre of mass acts from its midpoint. The woman is standing so that her centre of mass is 1.25 m from the left support. Calculate the force that the right support applies to the plank. A diagram of the situation is shown below.



Solution

If you add all of the relevant information to the diagram, it should look similar to the diagram below.

F_{left} F_{right} 1.25 m 2.00 m 4.00 m (54)(9.8) = 529 N (15.2)(9.8) = 149 N



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Since the system is in equilibrium, we know that the sum of the torques and forces will be equal to zero. We also have two unknown forces, so we will need to eliminate one. This can be done by making the left support the pivot point. Therefore:

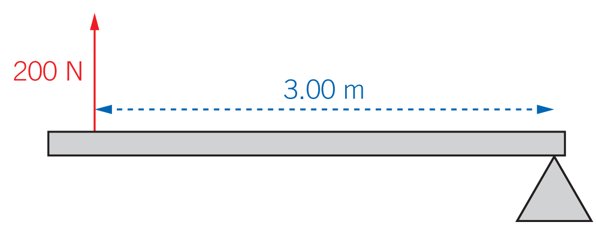
$$(529.2)(1.25) + (148.96)(2) = (4)(F_{right})$$

$$(F_{right}) = \frac{(529.2)(1.25) + (148.96)(2)}{2} = 240 \text{ N}$$

Section 8C questions

Multiple-choice questions

1 A force of 200 N is applied 3.00 m away from the pivot point of a bar as shown below.



Calculate the torque and the direction in which this bar will rotate.

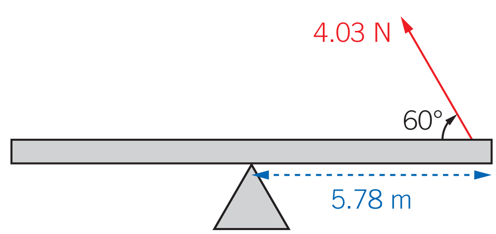
A 600 N m clockwise

B 600 N m anticlockwise

C 300 N m clockwise

D 300 N m anticlockwise

2 A see-saw is pushed with a force of 4.03 N, 5.78 m to the right of the pivot point. The force makes an angle of 60.0° to the horizontal. A diagram of this is shown below.



Calculate the torque generated by the force. Include a direction for the torque. Note that, for this question, the force due to gravity of the see-saw itself acts through the pivot point and can therefore be ignored.

A 20.2 N m clockwise

B 20.2 N m anticlockwise

C 23.3 N m clockwise

D 23.3 N m anticlockwise

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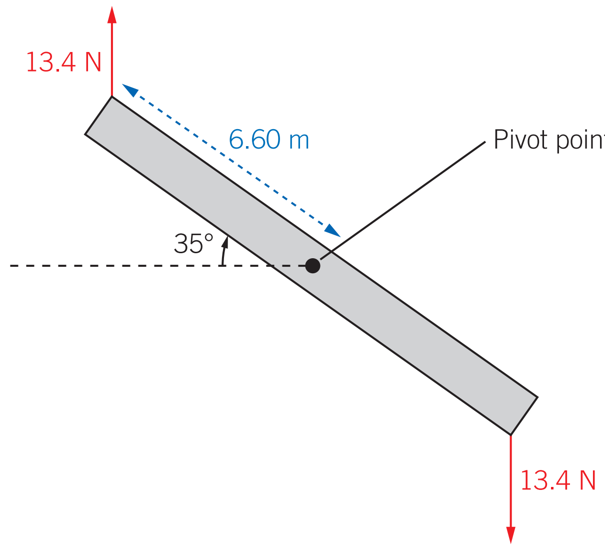
3 An electric motor rotates around a central pivot point. A vertical force of 13.4 N is applied at both ends of this motor. The length of the arm of the motor is 6.60 m. The moment arm makes an angle of 35.0° to the horizontal. Calculate the torque generated.



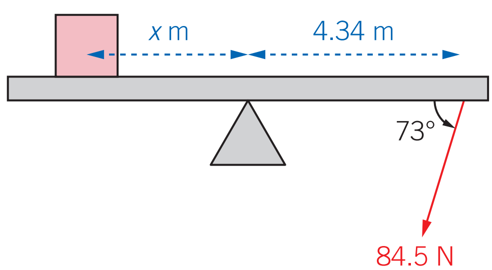
A 72.5 N m clockwise

B 72.5 N m anticlockwise

C 145 N m clockwise

D 145 N m anticlockwise

4 A see-saw is pushed with a force of 8.45 N, 4.34 m to the right of the pivot point. The force makes an angle of 73.0° to the horizontal. A marble block, which has a mass of 14.4 kg, is placed to the left of the pivot point. A diagram of this is shown below.



Calculate the distance from the pivot point that the marble block would need to be placed in order to balance the system. Note that, for this question, the force due to gravity of the see-saw itself acts through the pivot point and can therefore be ignored.

A 2.35 m

B 2.49 m

C 2.56 m

D 25.5 m

5 Which of the following systems is not in translational equilibrium?

A a bridge with cars moving over it

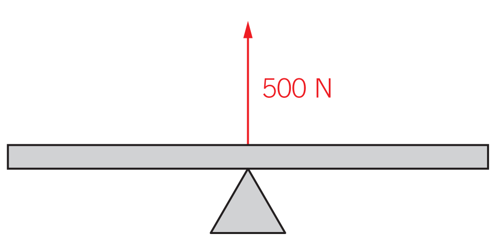
B a ball falling to the ground under the influence of gravity

C an object floating at a constant velocity through deep space

D a car that is moving at a constant velocity into a strong head wind

Short-answer questions

6 A force of 500 N is applied through the pivot point as shown below.



Calculate the torque generated. Justify your answer.

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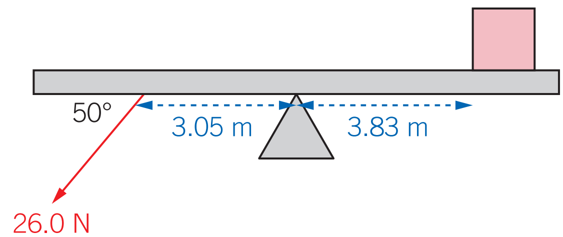
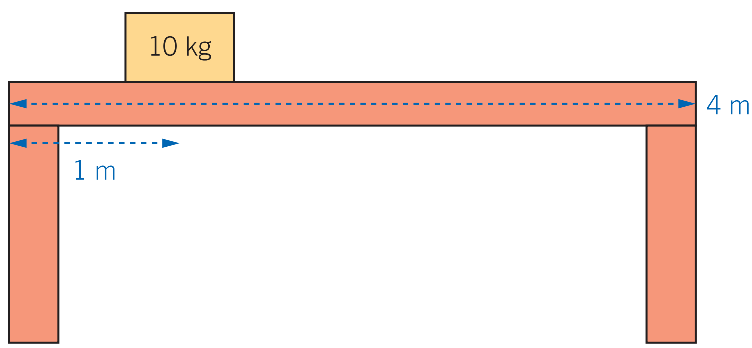
7 A see-saw is pushed with a force of 26.0 N, 3.05 m to the left of the pivot point. The force makes an angle of 50.0° to the horizontal. A marble block, which has a mass of 10.0 kg, is placed so that its centre of mass is 3.83 m. 3.83 m to the right of the pivot point. A diagram of this is shown below.

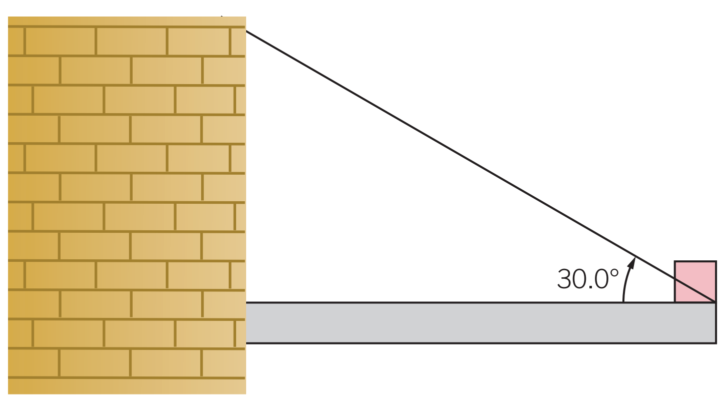


Determine the direction in which this see-saw will rotate. Justify your answer with a calculation. Note that, for this question, the force due to gravity of the see-saw itself acts through the pivot point and can therefore be ignored.

8 A box of mass 10 kg is placed so that its centre of mass is 1m away from the left leg of a table. The table is supported by two legs and the top of the table is a uniform mass of 2 kg. The table is 4 m long. Calculate the force that the right leg is exerting.



9 A 1 metre long, uniform beam of mass 2 kg is suspended to a wall by a cable. The cable, which is attached to the end of the beam, makes an angle of 30° to the beam and a box of mass 3 kg is placed at the end of the beam.



Calculate the tension in the cable.

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Chapter 8 review

Summary

Create your own set of summary notes for this chapter on paper or in a digital document. A model summary is provided in the Teacher Resources, which can be used to compare with yours.

Checklist

In the Interactive Textbook, the success criteria are linked from the review questions and will be automatically ticked when answers are correct. Alternatively, print or photocopy this page and tick the boxes when you have answered the corresponding questions correctly.

	Success criteria – I am now able to:	Linked questions
8A.1	Use the formula $p = mv$ to calculate the momentum of bodies	2☐, 12☐
8A.2	Understand that as long as no external forces are acting on an object, its momentum is conserved	4☐, 7☐, 12☐, 15☐, 19☐
8A.3	Apply conservation of momentum to solve problems relating to two objects colliding in a straight line	4☐, 7☐, 12☐, 19☐
8A.4	Be able to determine mathematically if a collision is elastic or inelastic	4☐, 12☐, 19☐
8A.5	Use the formulas $I = \Delta p = m\Delta v = mv - mu = F_{av}\,\Delta t$ to model impulse and change in momentum	6☐, 12☐, 14☐, 17☐, 19☐
8A.6	Understand that the area under a force–time graph is the impulse and apply this knowledge to solve a variety of problems	17☐
8B.1	Recall Newton's three laws of motion	1☐, 3☐, 8☐, 9☐, 10☐, 15☐, 16☐, 18☐
8B.2	Be able to add forces to find the net force on an object	16☐, 18☐
8B.3	Use the formula $F_{net} = ma$ to model Newton's second law of motion	1☐, 3☐, 8☐, 9☐, 10☐, 15☐, 16☐, 18☐
8B.4	Understand the normal force	13☐
8B.5	Apply Newton's laws to a number of different situations; including using the formula $a = \frac{F_{net}}{m}$ to calculate the acceleration of a system and $F = ma$ to calculate the force on different parts of the system	8☐, 9☐, 10☐, 16☐, 18☐
8B.6	Be able to label forces using the convention 'force on A by B' or $F_{\text{on A by B}} = -F_{\text{on B by A}}$	18☐
8B.7	Understand the difference between mass and the force due to gravity	20☐
8B.8	Model the force due to gravity, F_g, as the force of gravity acting at the centre of mass of a body	20☐
8B.9	Apply motion concepts to discuss vehicle safety	19☐

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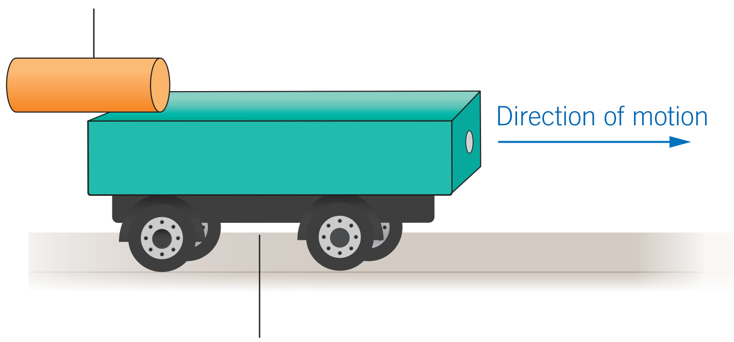
Success criteria – I am now able to:		Linked questions
8C.1	Use the formula $\tau = r_{\perp}F$ to calculate the torques	11☐, 20☐, 21☐
8C.2	Be able to apply the idea that when a system is in rotational equilibrium, the sum of the clockwise torques is equal to the sum of the anticlockwise torques	11☐, 20☐, 21☐
8C.3	Be able to apply the idea that when a system is in translational equilibrium, the sum of the forces is equal to zero: $\sum F = 0$	20☐

Multiple-choice questions

1 A model cart of mass 2.0 kg is propelled from rest by a rocket motor that applies a constant horizontal force of 4.0 N, as shown below. Assume that friction is negligible.



Which one of the following best gives the magnitude of the acceleration of the model cart?

A 0.50 $\mathrm{m\,s^{-2}}$
B 1.0 $\mathrm{m\,s^{-2}}$
C 2.0 $\mathrm{m\,s^{-2}}$
D 4.0 $\mathrm{m\,s^{-2}}$

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2 What is the momentum of a runner of mass 65 kg who is running at a speed of 5 $\mathrm{m\,s^{-1}}$?

A 70 $\mathrm{kg\,m\,s^{-1}}$
B 325 $\mathrm{kg\,m\,s^{-1}}$
C 1170 $\mathrm{kg\,m\,s^{-1}}$
D 1560 $\mathrm{kg\,m\,s^{-1}}$

3 A truck that has a mass of 3000 kg accelerates at the same rate as a car that has a mass of 1000 kg. Which of the following statements is true?

A As the acceleration is the same, the force on the two objects must also be the same.
B The truck will have three times more driving force on it than the car.
C The car will have three times more driving force on it than the truck.
D The car will have double the truck's driving force.

4 A group of students is playing with some inflatable exercise balls. In one instance, two students throw the exercise balls directly at each other at 4 $\mathrm{m\,s^{-1}}$. The exercise balls collide and travel in opposite directions at 3.5 $\mathrm{m\,s^{-1}}$. Which of the following statements about the collision is true?

A Momentum and kinetic energy were conserved.
B Neither momentum nor kinetic energy were conserved.
C Momentum was conserved but kinetic energy was not conserved.
D Momentum was not conserved but kinetic energy was conserved.

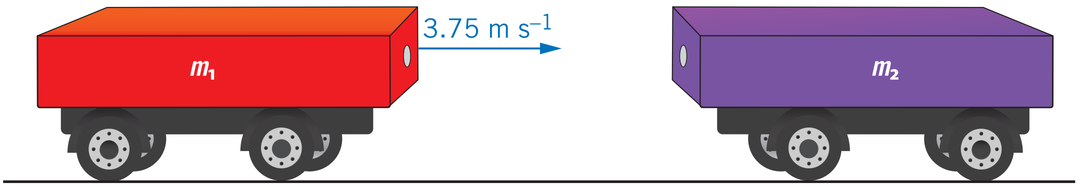
5 A model rocket is fired exactly horizontally and hits a tree. The rocket lodges in the tree and is stationary after the collision. Which of the following statements is correct regarding the momentum of the rocket?

A The momentum has been dissipated as heat and sound during the collision.
B The momentum was destroyed as the tree applied a force on the rocket.
C The momentum was transferred to the tree and then to Earth.
D The momentum of the rocket is the same before and after the collision.

6 What is the change in momentum if a car of mass 995 kg brakes when coming up to a set of lights and its velocity changes from 81 $km\,h^{-1}$ east to 18 $km\,h^{-1}$ east?

A 1.74×10^4 $kg\,m\,s^{-1}$ east
B 1.74×10^4 $kg\,m\,s^{-1}$ west
C 6.27×10^4 $kg\,m\,s^{-1}$ east
D 6.27×10^4 $kg\,m\,s^{-1}$ west

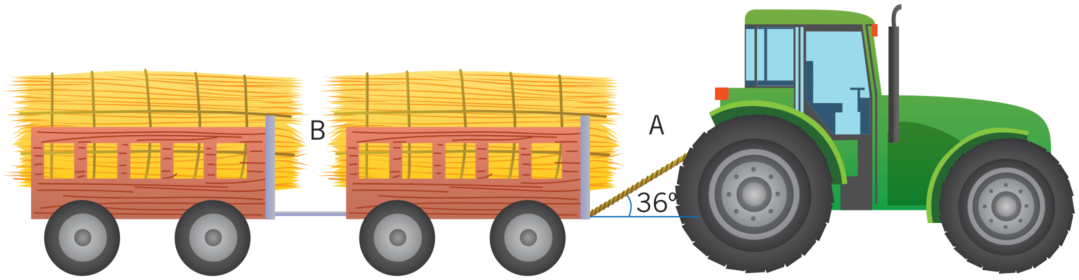
7 A cart with a mass of m_1 is travelling at 3.75 $m\,s^{-1}$ south when it hits a stationary cart that has a mass of m_2. m_2 has double the mass of m_1. Once they collide, they join and move as one and travel as one. The magnitude of the final velocity of the two carts is:



A 0.500 $m\,s^{-1}$
B 0.750 $m\,s^{-1}$
C 1.25 $m\,s^{-1}$
D 2.54 $m\,s^{-1}$

Use the following information to answer Questions 8–10.

A tractor engine has a mass of 3000 kg and a driving force of 7.8 kN. The tractor is tethered to two carts, each with a mass of 1000 kg, via cable A, which acts at 36° to the horizontal. The two carts are tethered to each other via cable B.



8 Calculate the acceleration of the tractor and cart system.

A 1.56 $m\,s^{-2}$
B 2.60 $m\,s^{-2}$
C 1.56×10^{-3} $m\,s^{-2}$
D 2.60×10^{-3} $m\,s^{-2}$

9 Calculate the tension is cable A.

A 2.52×10^3 N
B 3.12×10^3 N
C 3.86×10^3 N
D 9.64×10^3 N

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10 Calculate the tension in cable B.

A 1.56×10^3 N

B 2.60×10^3 N

C 3.12×10^3 N

D 7.80×10^3 N

11 A boy and his cat sit on a see-saw. The cat has a mass of 4 kg and sits 2 m from the centre of rotation. If the boy has a mass of 50 kg, where should he sit so that the see-saw will balance?

A 0.160 m

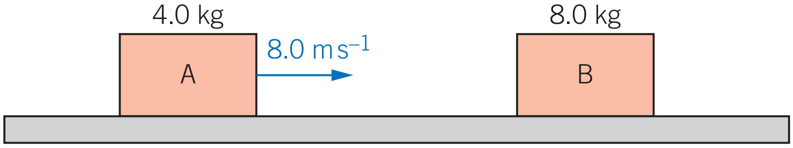
B 0.450 m

C 1.45 m

D 400 m

Short-answer questions

12 Block A, of mass 4.0 kg, is moving to the right at a speed of 8.0 $m\,s^{-1}$, as shown in the diagram below. It collides with a stationary block B, of mass 8.0 kg, and rebounds to the left. Its speed after the collision is 2.0 $m\,s^{-1}$.



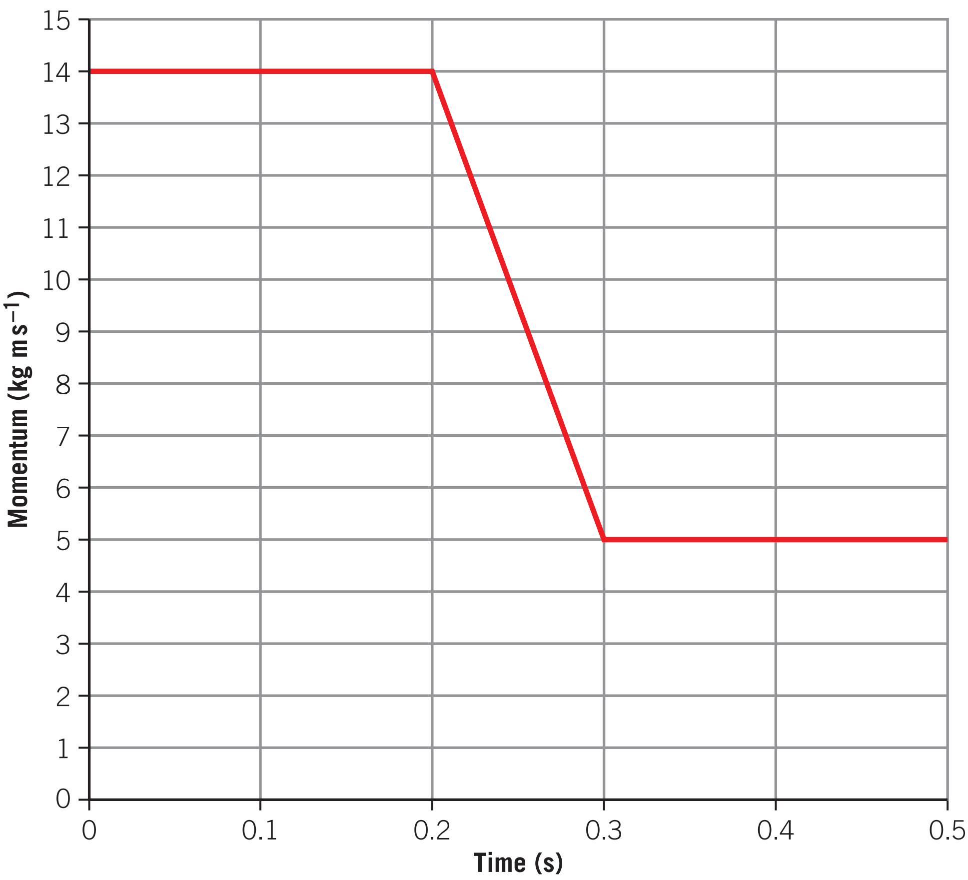
a Calculate the speed of block B after the collision. (2 marks)

b Explain whether the collision is elastic or inelastic. Include some calculations in your answer. (2 marks)

c What are the magnitude, unit and direction of the impulse by block B on block A? (3 marks)

13 If the action force of an elephant standing on solid ground is the force due to gravity, which is 39 000 N down, identify and explain the reaction force. Your answer should refer to a specific law of motion. (2 marks)

14 A small bullet is shot towards a wooden block. The bullet has a mass of 0.02 kg and travels at a velocity of 700 m s^{-1}. The momentum–time graph below shows the momentum of the bullet over time.



- **a** Between which times did the collision occur? (1 mark)
- **b** What is the velocity of the bullet after the collision? (2 marks)
- **c** What does the gradient of the line represent? Justify your answer. (2 marks)
- **d** What is the magnitude of the average force on the bullet during the collision? (2 marks)

15 A skateboarder is travelling at 4.5 m s^{-1} on a concrete path. While travelling down the path, the skateboarder slows and eventually comes to a stop.

- **a** Use one of Newton's laws of motion to explain why the skateboarder comes to a stop. (3 marks)
- **b** Momentum is always conserved, but as the skateboarder's velocity reduced to zero their momentum also reduced to zero. Explain where the skateboarder's momentum has gone. (1 mark)

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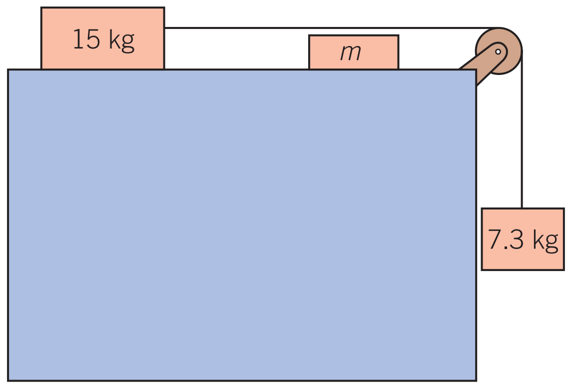
16 A block of mass 15 kg sits on a smooth frictionless table. The block is tethered to a mass of 7.3 kg via a pulley, the mass of 7.3 kg is hanging off the table. There is a block of unknown mass, *m*, that lies on the table.



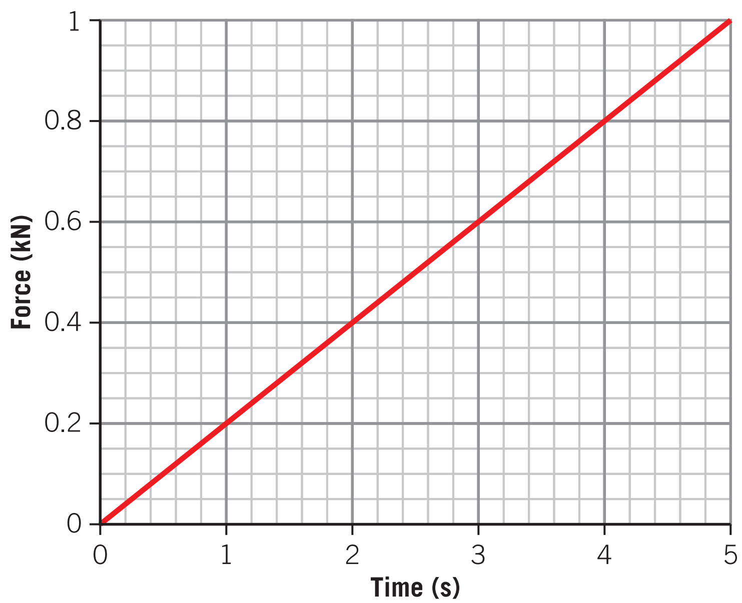
a Calculate the initial acceleration of the system. (2 marks)

b Calculate the initial tension in the pulley. (2 marks)

c Once the mass of 15 kg hits mass *m* on the table, the acceleration of the system becomes 2.53 m s^{-2} to the right. Calculate the mass of *m*. (2 marks)

d What is the force on the mass of 15 kg given by *m*? Include a direction in your answer. (2 marks)

17 A boat of mass 350 kg moves from rest in a straight line due to a thrust force that increases with time as shown in the graph below.



a What is the acceleration of the boat at 4 seconds? (2 marks)

b What is the change in momentum of the boat in 5 seconds? (2 marks)

c What is the final velocity of the boat? (2 marks)

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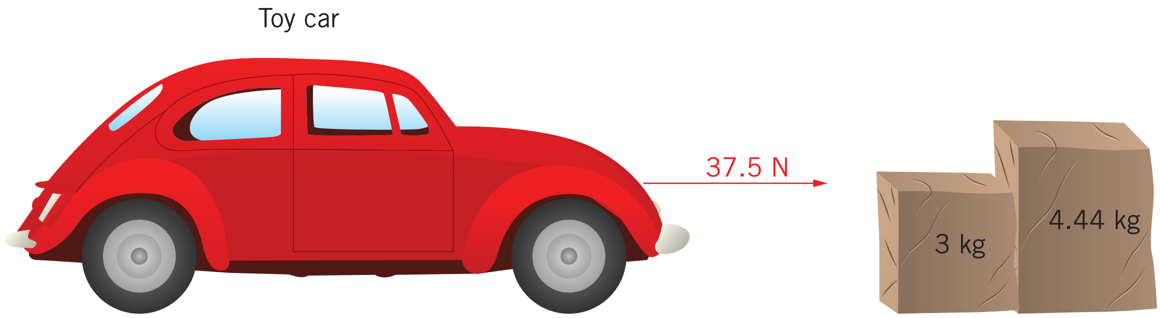
18 A toy car with a mass of 5.65 kg and a driving force of 37.5 N west hits two blocks that are combined and have a mass of 3 kg and 4.44 kg. Once the car hits the two blocks, it moves with them as one and the driving force remains constant. Friction can be ignored in this question.



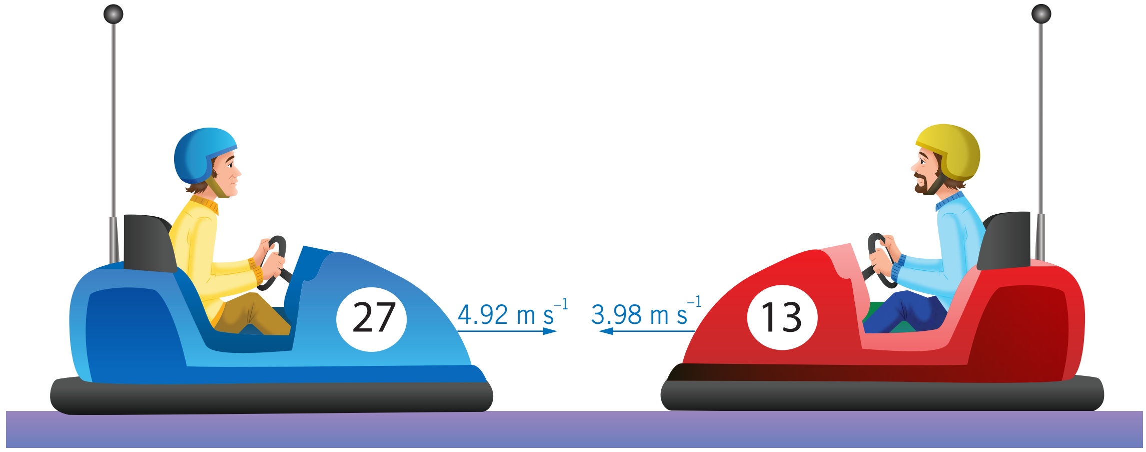
a A student attempts to perform a momentum calculation to predict the velocity of the three objects after the collision but finds that their predicted velocity is constantly lower than the actual velocity. Explain this observation. (2 marks)

b When all three objects are moving as one, what is the acceleration of the system? (2 marks)

c When all three objects are moving as one, what is the force on the 3 kg block given by the toy car? Include a direction in your answer. (1 mark)

d When all three objects are moving as one, what is the force on the toy car given by the 3 kg block? Include a direction in your answer. (1 mark)

19 Two bumper cars collide head on. Bumper car 27 has a total mass of 310 kg and is travelling at 4.92 $m\,s^{-1}$ east. Car 27 collides with car 13 that has a total mass of 275 kg and is travelling at a velocity of 3.98 $m\,s^{-1}$ west. After the collision car 27 has a velocity of 0.10 $m\,s^{-1}$ east.



a Calculate the velocity of car 13 after the collision. Include a direction in your answer. (2 marks)

b What is the change in momentum of car 13? Include a direction for your answer. (3 marks)

c What is the average force on car 13 during the collision given that the collision lasted for 1.25 seconds? (3 marks)

d The occupant of the bumper car complains and says that the force during the collision was too high. Explain one way in which the force on the occupant could be reduced without changing the speed or mass of the car. (2 marks)

e Is this an elastic collision? You must use at least two calculations to justify your answer. (3 marks)

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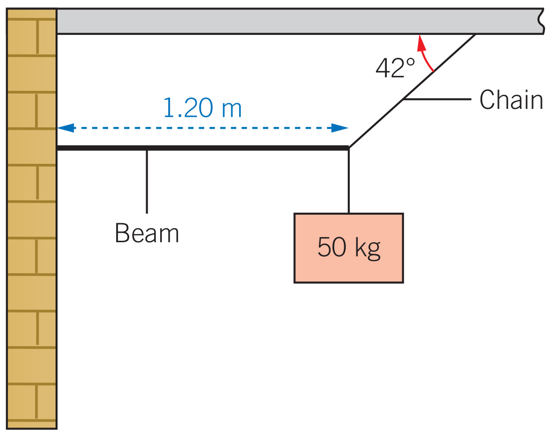
20 A truck of mass 5000 kg is crossing a uniform horizontal bridge of mass 1000 kg and length 100 m. The bridge is supported at its two end-points. What are the reactions at these supports when the truck is one-third of the way across the bridge? (3 marks)

21 A uniform beam of mass 4.50 kg that has a length of 1.20 m is attached to a wall by a hinge and is supported from the ceiling by a cable that makes an angle of 42° to the horizontal. A sign of mass 50.0 kg hangs from the end of the beam. A diagram of this is shown below.



Calculate the tension in the cable. (2 marks)

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UNIT 2 HOW DOES PHYSICS HELP US TO UNDERSTAND THE WORLD?

CHAPTER 9 ENERGY AND MOTION

Introduction

In Greek mythology, Prometheus steals fire from the gods and gifts it to humanity. The gods, thinking humanity cannot be responsible with such power, punish Prometheus by chaining him to a mountain and sending an eagle each day to eat his regenerating liver. This myth has endured thousands of years and at every stage of humanity it is seen as a cautionary tale; to harness the power of the gods takes god-like virtues.

Throughout human history, energy has been both a blessing and a curse. Harnessing fire allowed humans to cook food, smelt ore into metal, move with steam-driven engines and generate electricity with turbines. At some point in history, fire has destroyed nearly every major city.

Currently we as a society are burning through our finite supply of fossil fuels and in the process altering our climate to such an extent that it may cause irreversible changes to the ecosystem and our way of life. Nuclear fission and nuclear fusion could potentially be used in the future to harness large amounts of energy. Our ability to harness energy has allowed us to light up the night, travel to the depths of the ocean and land on the Moon and beyond. We must recognise the negative impacts that utilising energy can have as the choices that we make now will propagate through the centuries.

This chapter explores the topic of energy and the various ways it can be transformed, transferred and stored. You will develop an understanding of how work is done on an object and the effect of the work in increasing the kinetic or potential energy of a body, such as in a gravitational field. The chapter concludes by investigating how springs behave when they are stretched or compressed.

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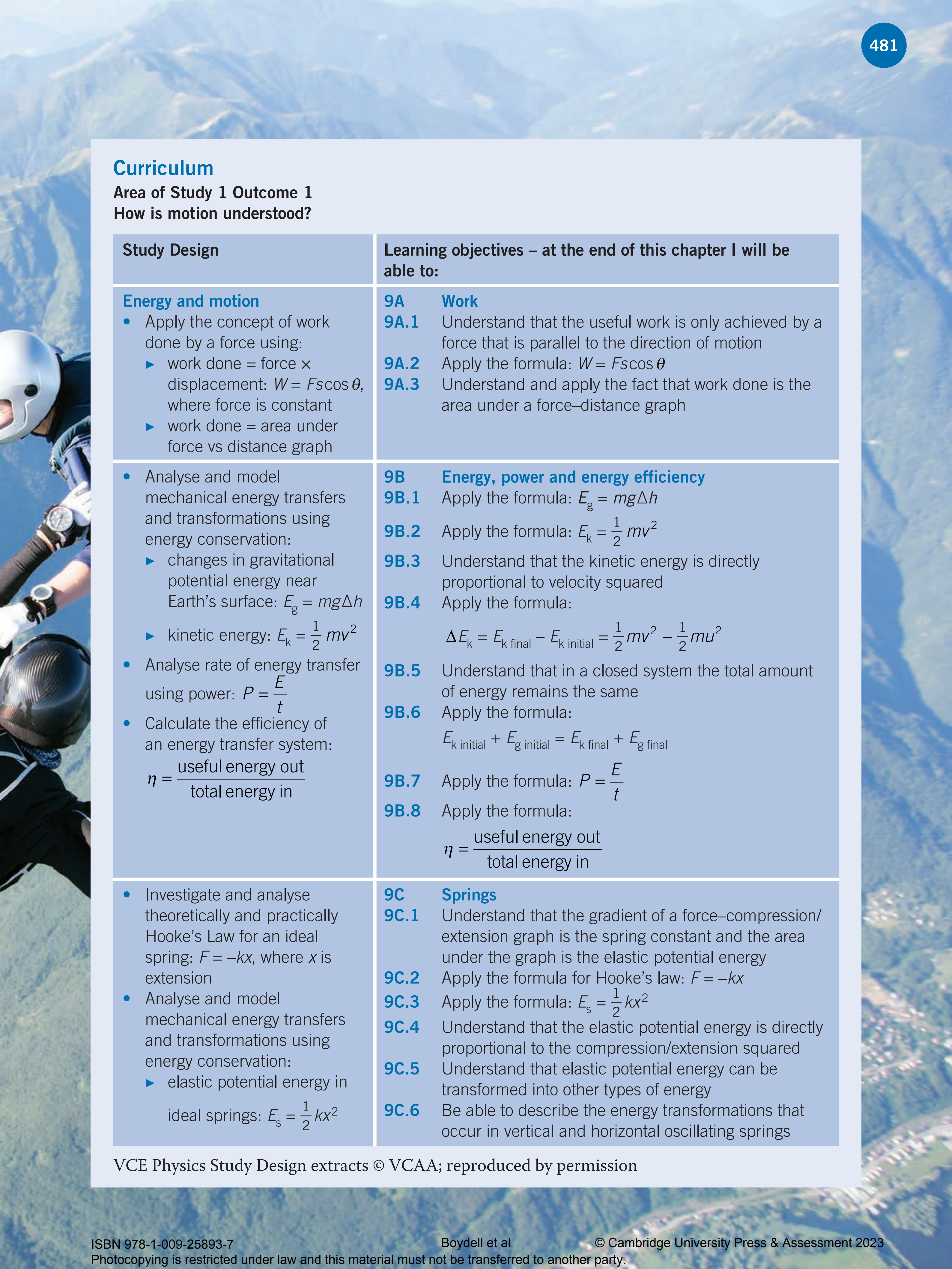

Curriculum

Area of Study 1 Outcome 1
How is motion understood?

Study Design	Learning objectives – at the end of this chapter I will be able to:
Energy and motion • Apply the concept of work done by a force using: ▸ work done = force × displacement: $W = Fs\cos\theta$, where force is constant ▸ work done = area under force vs distance graph	**9A Work** **9A.1** Understand that the useful work is only achieved by a force that is parallel to the direction of motion **9A.2** Apply the formula: $W = Fs\cos\theta$ **9A.3** Understand and apply the fact that work done is the area under a force–distance graph
• Analyse and model mechanical energy transfers and transformations using energy conservation: ▸ changes in gravitational potential energy near Earth's surface: $E_g = mg\Delta h$ ▸ kinetic energy: $E_k = \frac{1}{2}mv^2$ • Analyse rate of energy transfer using power: $P = \frac{E}{t}$ • Calculate the efficiency of an energy transfer system: $\eta = \frac{\text{useful energy out}}{\text{total energy in}}$	**9B Energy, power and energy efficiency** **9B.1** Apply the formula: $E_g = mg\Delta h$ **9B.2** Apply the formula: $E_k = \frac{1}{2}mv^2$ **9B.3** Understand that the kinetic energy is directly proportional to velocity squared **9B.4** Apply the formula: $\Delta E_k = E_{k\ final} - E_{k\ initial} = \frac{1}{2}mv^2 - \frac{1}{2}mu^2$ **9B.5** Understand that in a closed system the total amount of energy remains the same **9B.6** Apply the formula: $E_{k\ initial} + E_{g\ initial} = E_{k\ final} + E_{g\ final}$ **9B.7** Apply the formula: $P = \frac{E}{t}$ **9B.8** Apply the formula: $\eta = \frac{\text{useful energy out}}{\text{total energy in}}$
• Investigate and analyse theoretically and practically Hooke's Law for an ideal spring: $F = -kx$, where x is extension • Analyse and model mechanical energy transfers and transformations using energy conservation: ▸ elastic potential energy in ideal springs: $E_s = \frac{1}{2}kx^2$	**9C Springs** **9C.1** Understand that the gradient of a force–compression/extension graph is the spring constant and the area under the graph is the elastic potential energy **9C.2** Apply the formula for Hooke's law: $F = -kx$ **9C.3** Apply the formula: $E_s = \frac{1}{2}kx^2$ **9C.4** Understand that the elastic potential energy is directly proportional to the compression/extension squared **9C.5** Understand that elastic potential energy can be transformed into other types of energy **9C.6** Be able to describe the energy transformations that occur in vertical and horizontal oscillating springs

Glossary

Closed system
Efficiency
Elastic limit
Elastic material
Elastic potential energy
Energy
Equilibrium position
Gravitational potential energy
Hooke's law
Ideal spring
Open system
System
Work

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Concept map

9A Work

Work done on an object can cause a change in kinetic energy and gravitational potential energy

9B Energy, power and energy efficiency

Kinetic energy and gravitational potential energy can be transformed from one form into another, including into elastic potential energy and then back again

9C Springs

Elastic potential energy is utilised extensive in our daily lives as well as in nature

See the Interactive Textbook for an interactive version of this concept map interlinked with all concept maps for the course.

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Work

Study Design:
- Apply the concept of work done by a force using:
  - work done = force × displacement: $W = Fs\cos\theta$, where force is constant
  - work done = area under force vs distance graph

Glossary:
Work

ENGAGE

A solution to climate change

Burning fossil fuels releases an abundance of anthropogentic (of human origin) greenhouse gases into the atmosphere, many of which capture thermal energy and raise the average temperature of Earth. This leads to the destruction of habitats, more extreme weather events, increased difficulty growing crops, rising sea levels and numerous secondary effects.

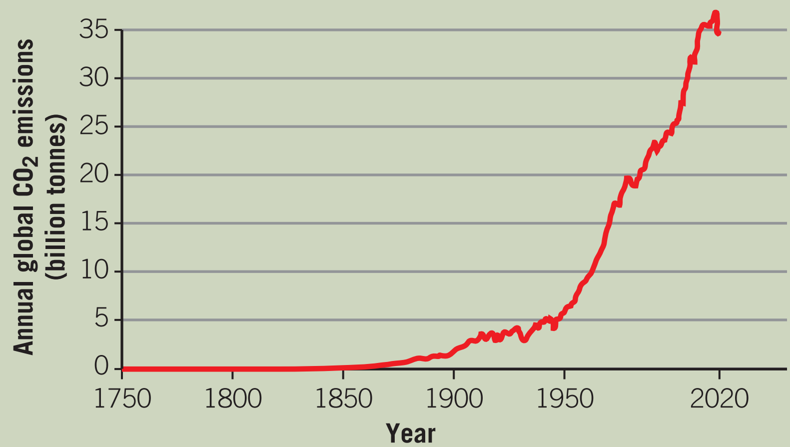

Figure 9A–1 Annual global carbon dioxide emissions, 1750–2020

The solution to our energy crisis is complex, more complex than to simply say we have to stop burning fossil fuels. The energy derived from fossil fuels can drive a country's economy; the richer the country, the more fossil fuels that country tends to emit.

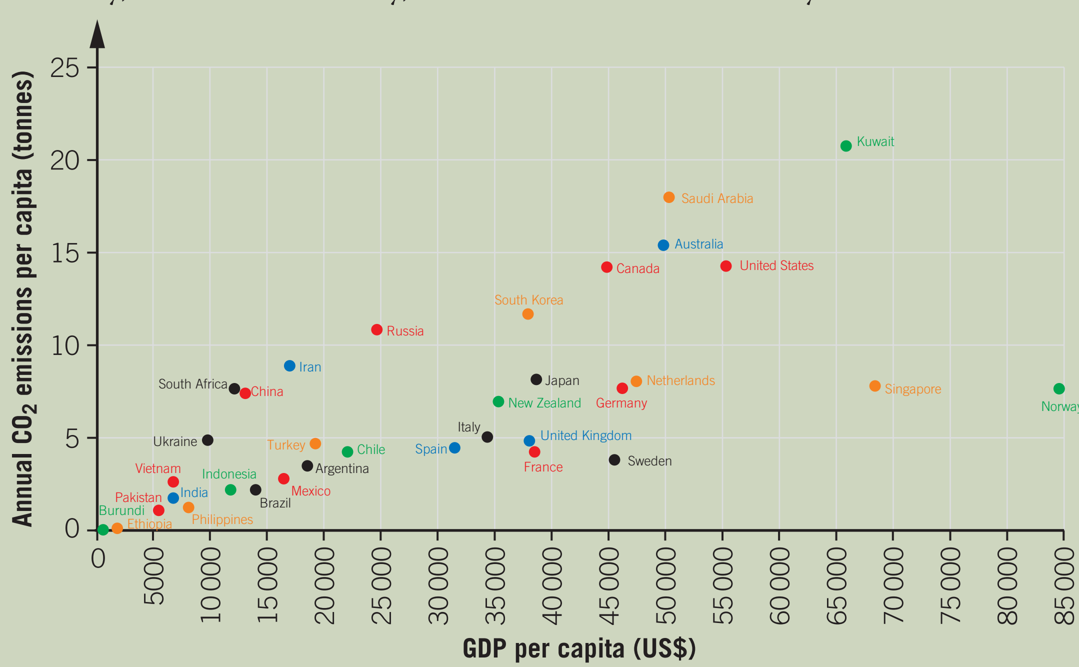

Figure 9A–2 Carbon dioxide emissions per capita vs GDP per capita for selected countries

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Emissions from rich countries only account for 37% of the total carbon dioxide emissions, and burning fossil fuels is an invariable by-product of a country trying to escape poverty. Making things more energy efficient is essential to economic progress, but it may have unintended consequences. For example, the fuel efficiency of aircraft almost doubled between 1960 and 2008; this was one of the many factors that decreased the cost of aeroplane tickets and increased the number of people flying per year.

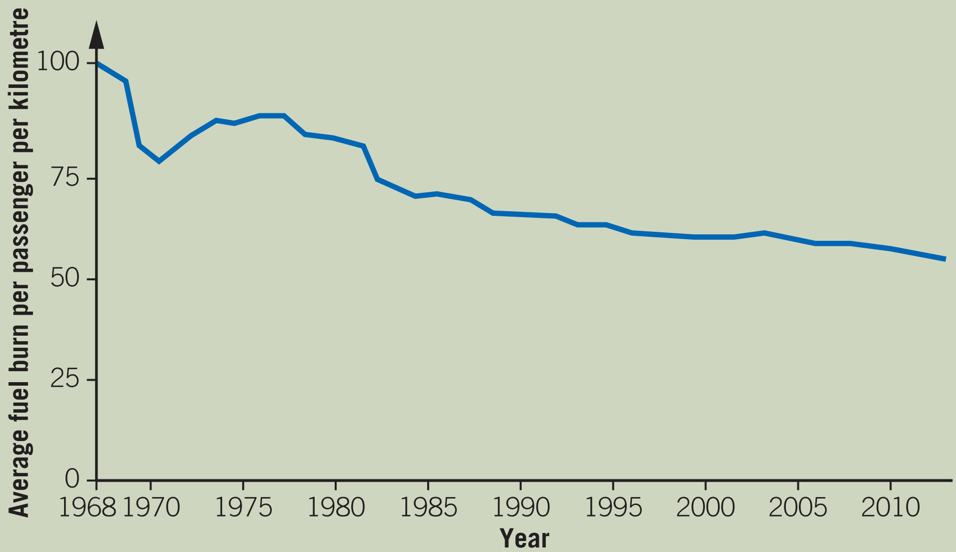

Figure 9A–3 The average fuel burned per passenger per kilometre for new commercial jet aircraft, 1968 to 2014. The figure for 1968 is set as the 100 index and values for each year are proportional to that. Most significantly, the average fuel burned for a new aircraft fell by 45% from 1968 to 2014.

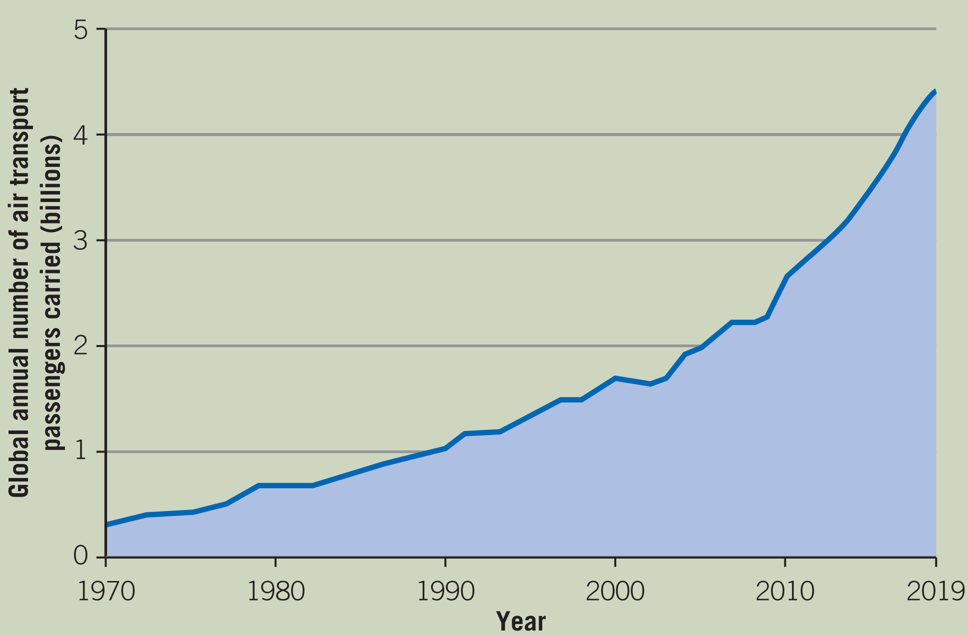

Figure 9A–4 The global annual number of air transport passengers carried, 1970 to 2019

Innovations such as carbon capture, safer nuclear power plant designs, new batteries and sustainable concrete production that will all help address the problem.

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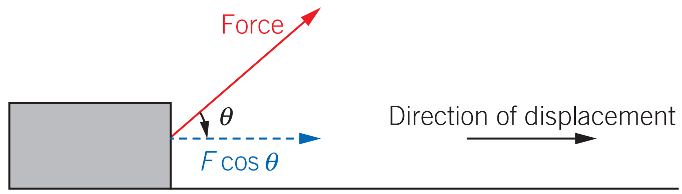
EXPLAIN

How is work calculated?

Work the amount of energy transferred from one object or system to another

Work is the amount of energy transferred by a force from one object or system to another. Work is a scalar quantity. The amount of work done on an object can be calculated by multiplying the displacement by the force that is applied parallel to the direction of displacement. Imagine a box being pulled along a frictionless floor as shown below



This can be expressed mathematically as follows.

Formula 9A–1 Work

$$W = Fs\cos\theta$$

Where:

W = Work done by the force (J)

F = Magnitude of the force (N)

s = Displacement of the object (m)

θ = Angle between the force and the direction of displacement (°)

Although work is a scalar quantity, it can still be positive or negative because the energy can be given to an object or taken away from an object. Take a bowling ball, for example: while your hand is in contact with the bowling ball, energy is being given to the ball. Once the ball has been released by your hand, a small rolling friction force acts on the ball in the opposite direction to its motion. Therefore, the work done can be considered negative.

When a force performs no work

It is possible to apply a constant force on an object and not transfer any energy to the object. For example, if you hold an object in a fixed position, you are applying a constant force on the object. You can feel the effort of holding the object, but no energy is being transferred to it. This is because there is no displacement of the object and, as a result of $W = Fs\cos\theta$, since the displacement is zero the work is also zero.

Worked example 9A–1 Work pushing a box

A man pushes a box of mass 46 kg horizontally along the ground with a force of 500 N. The box encounters a frictional force of 50 N. Calculate the amount of work done on the box to push it 32 m.

a Calculate the work done on the box by the pushing force.

b Calculate the work done against the box by the friction force.

c Calculate the energy given to the box.

Solution

a $W_{push} = F_{push}s\cos\theta = (500)(32)\cos 0° = 16\,000$ J

b $W_{friction} = F_{friction}s\cos\theta = (50)(32)\cos 180° = -1600$ J

c $W_{total} = W_{push} + W_{friction} = (16\,000) + (-1600) = 14\,400$ J

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Worked example 9A–2 Work towing

A cable-towed kneeboarder is being pulled with a force of 250 N and the towing cable makes an angle of 22° to the horizontal. A diagram of this situation is shown below.

If the kneeboarder travels 163 m in a straight line in the direction of the force, calculate the amount of work done by the cable on the kneeboarder.

Solution

Note that the net force is acting at an angle of 22° to the direction of travel.

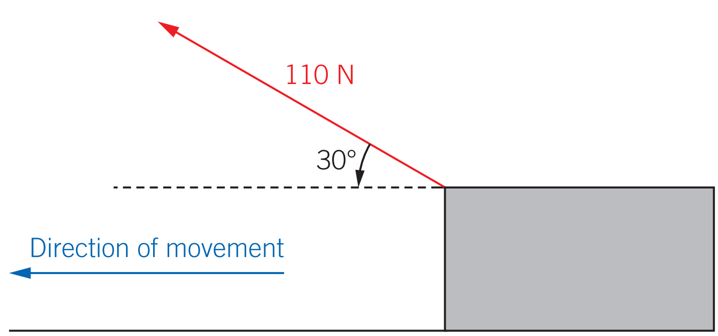
$$W = Fs\cos\theta = (250)(163)\cos 22° = 3.78 \times 10^4 \text{ J}$$

Check-in questions – Set 1

WORKSHEET 9A–1 WORK

1 A factory worker pushes a box along a smooth frictionless surface with a constant force of 55 N. If the worker is pushing parallel to the direction of motion and pushes the box 36.5 m, how much work have they done?

2 A block of mass 150 kg is pulled across a smooth floor with a force of 110 N at an angle of 30° to the horizontal. There is no frictional force. Calculate the work done on the block if it is moved a distance of 20 m. A diagram of this situation is shown below.



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Force–distance graphs

The work done can also be determined by analysing a force–distance graph. A force–distance graph displays force component on the y-axis and distance on the x-axis, as shown in the following diagram.

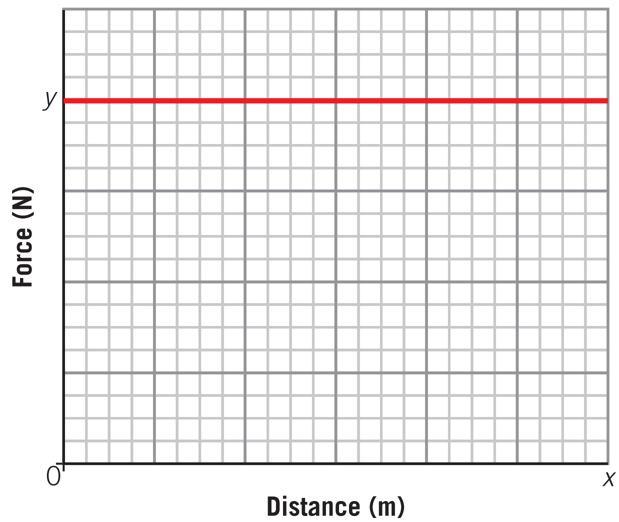
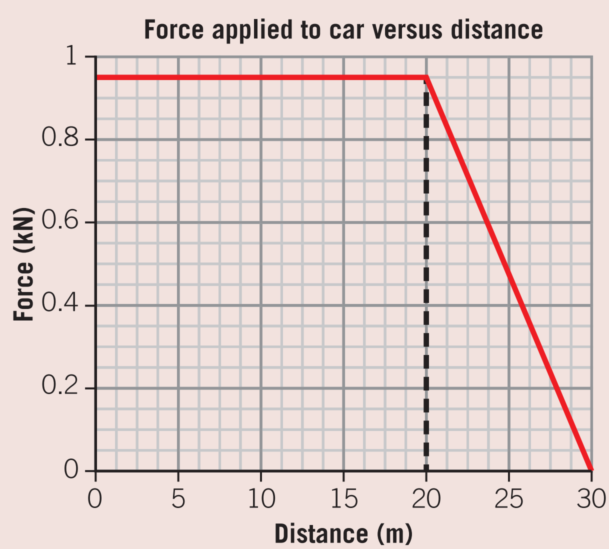


Figure 9A–5 Example of a force-distance graph with a constant force y applied over a distance x.

The work done can be determined by calculating the area under the graph. To calculate the work done in the above diagram above, y force would have to be multiplied by x distance; as the force is being multiplied by the distance, the product will always be the work done in joules.

Worked example 9A–3 Work from force–distance graph

A broken-down car is pushed with a force of 0.95 kN in the direction of displacement for 20 m. The person who is pushing the car then tires and their force in the direction of displacement reduces at a constant rate to zero over the next 10 m. A force–distance graph of this situation is shown on the right.



Calculate the work done by the person pushing the car.

Solution

The work done is the area under the graph, this graph would need to be broken up into a rectangle and a triangle as shown. (Note: kN must be converted into N.)

$$\text{total area} = \text{total work}$$

$$= \left(0.95 \times 10^3\right)(20) + \frac{1}{2}\left(0.95 \times 10^3\right)(10)$$

$$= 2.38 \times 10^4 \text{ J}$$

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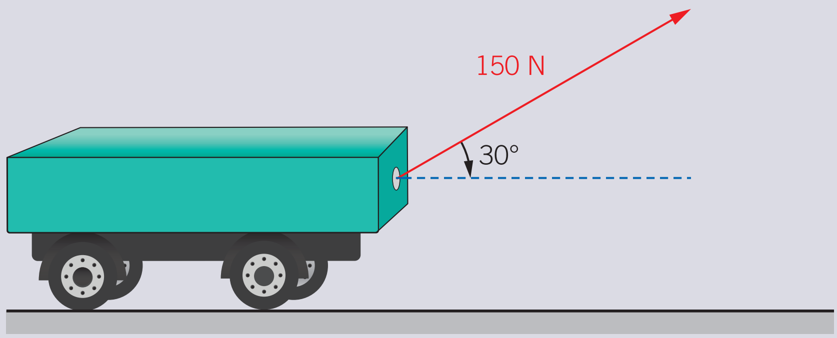
9A SKILLS

Finding forces that are parallel to the direction of motion
To successfully find the amount of useful work done, you must be able to find the component of a force that acts parallel to the direction of motion. Finding the correct component requires a good understanding of trigonometry. Consider the following question.

Question

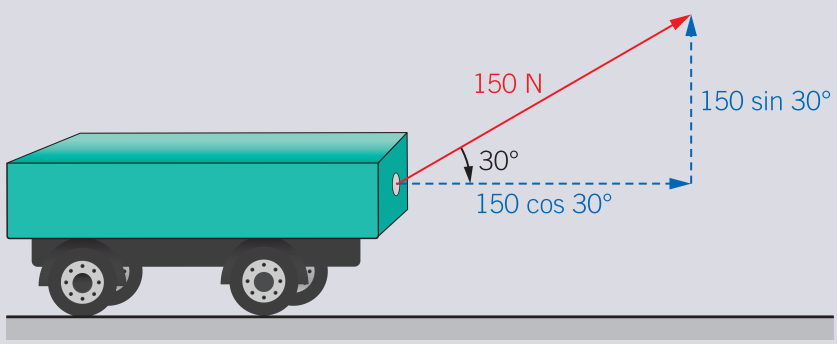
A child pulls a toy cart with a string. The tension in the string is 150 N and the string forms an angle of 30° to the horizontal. A diagram of this situation is shown below.



Calculate the work done if the child pulls the toy for 122 m.

Solution

The first step is to break up the force into its horizontal and vertical components, as shown below.



Then, identify the component that you need. As the cart is moving horizontally, the component that you need is the horizontal component.

$$W = Fs\cos\theta = (150)(122)\cos 30° = 1.58 \times 10^4 \text{ J}$$

This skill can be applied to many areas of study. For example, it can assist in finding the horizontal and vertical components of velocity in projectile motion, finding the force that is perpendicular to the pivot point when creating a torque, and understanding acceleration down a slope and many other situations.

VIDEO 9A–1 SKILLS: FINDING FORCES THAT ARE PARALLEL TO THE DIRECTION OF MOTION

LINK **7A** CONCEPTS USED TO MODEL MOTION

LINK **8B** NEWTON'S LAWS OF MOTION

LINK **8C** EQUILIBRIUM

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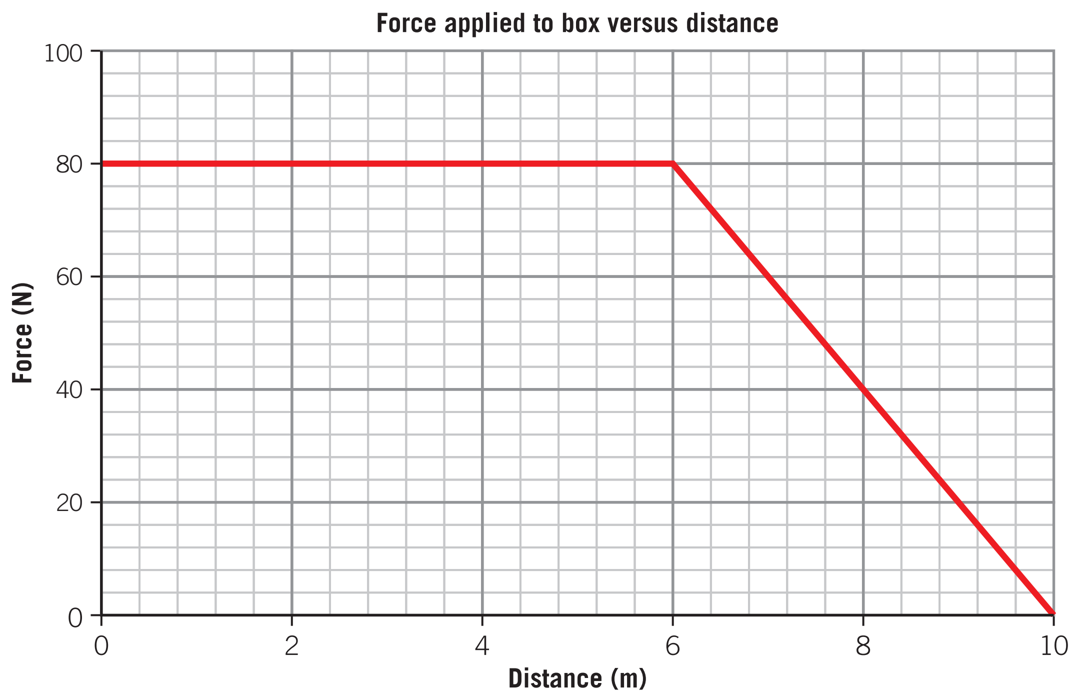
Section 9A questions

Multiple-choice questions

1 A student pushes a box with a constant force of 80 N, in the direction of motion, for 6 m. The student then pushes the box a further 4 m and in this 4 m the student reduces the force on the box at a constant rate until the force becomes zero. A force–distance graph of this situation is shown below.



The work done on the box by the student is

A 38 400 J
B 640 J
C 560 J
D 275 J

2 A train of mass 1650 kg travels 2.45 km in a straight line. The engine produces a constant force of 3000 N. The work done by the engine on the train is

A 7.35×10^3 J
B 4.04×10^6 J
C 4.95×10^6 J
D 7.35×10^6 J

3 A student holds a physics textbook above her head for 2 minutes. Which of the following statements is correct?

A No work is done because there is no displacement.
B Over the 2 minutes, the energy in the student's arms is given to the physics book.
C Work is done to the books to hold the book up, which is why the student gets tired.
D Work is done on the student's stationary joints and muscles.

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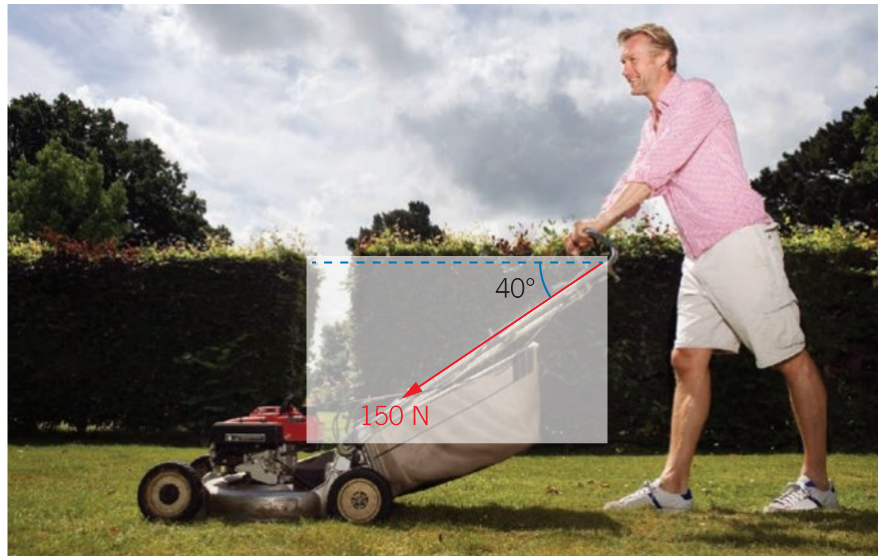
4 A man is mowing his lawn with a lawnmower of mass 35 kg. The man applies a force of 150 N down the handle, which makes an angle of 40° to the horizontal, as shown in the diagram right.

If the man pushes the lawnmower a distance of 5 m, the amount of work that he has done is

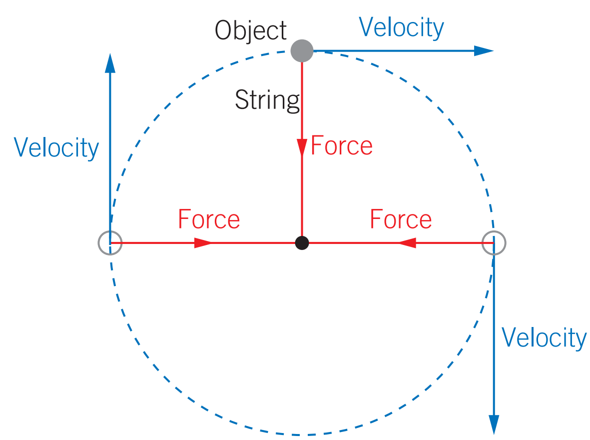
A 750 J
B 575 J
C 482 J
D 250 J



5 A student swings an object in circles on the end of a string. When the mass is swinging, the velocity and the force are always at right angles as shown in the diagram below.

Which of the following statements it true?

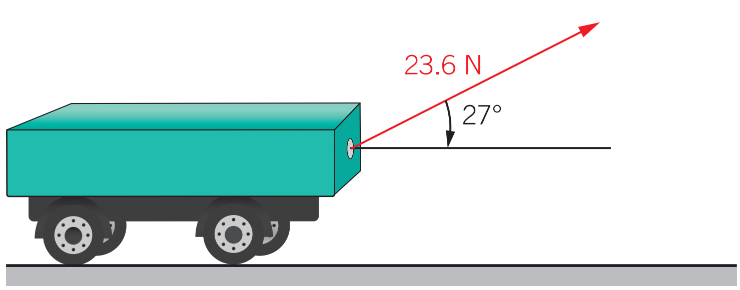
A Work is done to change the direction of the object.
B Work is done to keep the object in circular motion.
C Work is done on the student's muscles, which is why they get tired.
D No work is done on the object.



Short-answer questions

6 A weightlifter lifts a 60 kg mass from the ground up over their head. When the weight is over the weightlifter's head it is 2.15 m above the ground. Calculate the work that the weightlifter has done on the bar.

7 A child pulls a cart a distance of 55.4 m, with a force of 23.6 N at an angle of 27°.



a Calculate the force that is parallel to the direction of travel.
b Calculate the work done by the child.

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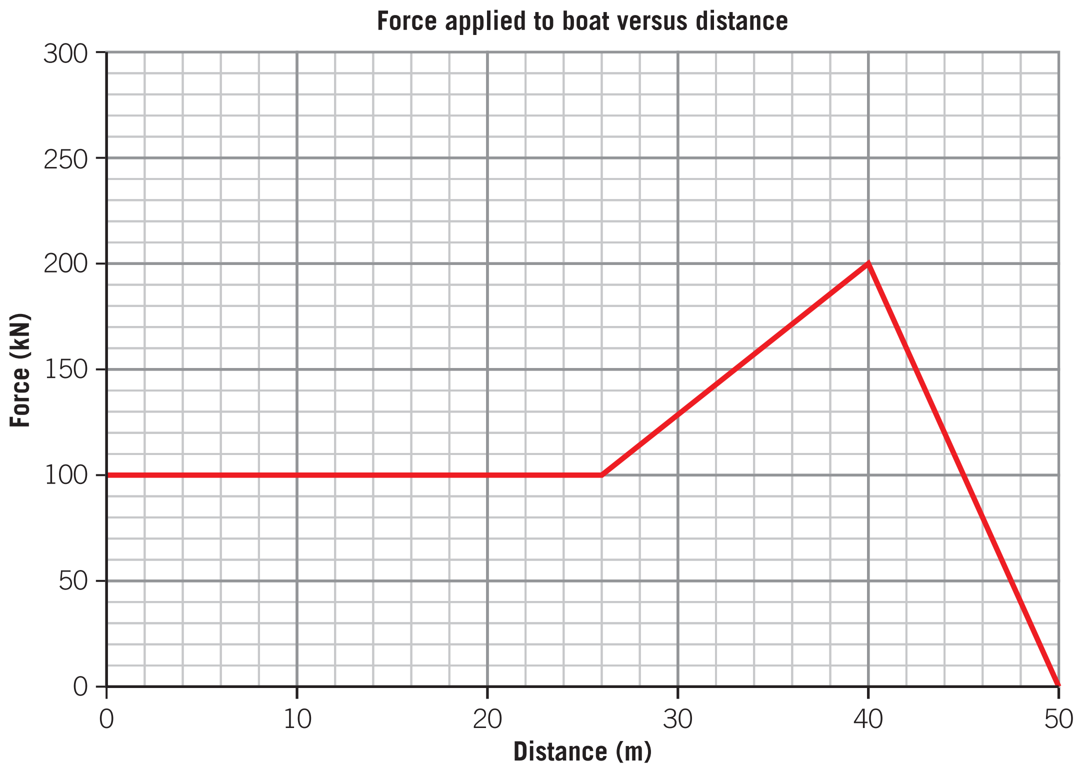
8 A shopper is pushing a shopping trolley back to his car. The shopper pushes the trolley with a force of 100 N for the first 20 m; he then increases his force at a constant rate over the next 40 m to 200 N. The shopper then continues to push the trolley with a force of 200 N for 20 m before reducing his force to zero at a constant rate over the next 20 m.

- **a** Sketch the force–distance graph of this situation. Your graph should include labelled *x*- and *y*-axes with units and an accurate scale.
- **b** Calculate the work done by the shopper on the trolley.

9 A tugboat is attached to a large ship via a rope that pulls in the same direction as the direction that the boat is moving. The graph displaying how the tugboat pulls on the ship as a function of the distance travelled is displayed below.



- **a** Which is greater: the work done in the first 30 m or the work done in the last 20 m? Justify your answer with calculations.
- **b** If instead of pulling parallel to the direction of travel, the rope was pulling at an angle to the horizontal, what effect would this have on the force required if the same amount of work was done?

10 A race car that has a mass of 1.29×10^3 kg accelerates at a constant rate of 9000 m s^{-2}. Ignore the effects of air resistance in this question.

- **a** What is the magnitude of the force driving the car forward?
- **b** If the car travels for 450 m while accelerating, calculate the work done on the car.

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Energy, power and energy efficiency

Study Design:

- Analyse and model mechanical energy transfers and transformations using energy conservation:
  - changes in gravitational potential energy near Earth's surface: $E_g = mg\Delta h$
  - kinetic energy: $E_k = \frac{1}{2}mv^2$
- Analyse rate of energy transfer using power: $P = \frac{E}{t}$
- Calculate the efficiency of an energy transfer system: $\eta = \frac{\text{useful energy out}}{\text{total energy in}}$

Glossary:

Closed system
Efficiency
Energy
Gravitational potential energy
Open system
System

ENGAGE

Land diving in Vanuatu

Every year on the small island of Pentecost in Vanuatu, the local people perform the ritual of land diving at a festival called 'Naghol' as a rite of passage. Tribe members as young as five years risk their lives jumping off the top of towers with just two jungle vines attached to their feet.

The towers are constructed with wood that is held together with vines. These towers can be up to 30 metres tall. As the land divers climb the tower, they are storing gravitational potential energy. At the top of the tower, the diver has stored energy that is roughly equivalent to a 1-tonne car moving at 25 km h^{-1}. When the diver jumps, he is accelerated down to Earth by gravity and will reach velocities approaching 85 km h^{-1}. The diver's fall is arrested by the vines that are carefully selected by a village elder. The jumping is thought to bring a good yam crop and provide security to the community the higher the jump, the bigger the blessing.

Figure 9B–1 A local from Pentecost Island performs a land dive.

Energy the measurable property of a body or system with the ability to do work

VIDEO 9B–1 ENERGY TRANSFORMATIONS

EXPLAIN

What is energy?

Energy is defined as the measurable property of a body or system with the ability to do work. Energy can be transformed from one form of energy into another, the same type of energy can be transferred from one object to another, and energy cannot be created or destroyed.

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Gravitational potential energy

Gravitational potential energy the amount of energy an object has stored due to its position in a gravitational field; measured in joules (J)

Gravitational potential energy is the amount of energy that an object has stored due to its position in a gravitational field. For objects that are close to the surface of Earth it is assumed that the strength of the gravitational field is a constant, 9.8 $N\,kg^{-1}$.

Formula 9B–1 Gravitational potential energy

$$E_g = mg\Delta h$$

Where:

E_g = Gravitational potential energy (J)

m = Mass (kg)

g = Gravitational field strength (9.8 $N\,kg^{-1}$ on the surface of Earth)

Δh = Change in height (m)

Figure 9B–2 The diver on top of the cliff has a lot of gravitational potential energy, as they have done work against the gravitational field to reach the top of the cliff. When the diver jumps off, the gravitational field will do work on them and pull them down towards the ocean.

Worked example 9B–1 Work done by an elevator

An elevator moves a person who has a mass of 76.5 kg from the fifth floor of a tower, which is 18 m above the ground, to the 26th floor, which is 112 m above the ground. Calculate the work done on the person by the elevator.

Solution

The work done by the elevator on the person is equivalent to the change in gravitational potential energy of the person.

$$E_g = mg\Delta h$$
$$= (76.5)(9.8)(112 - 18)$$
$$= 7.05 \times 10^4 \text{ J}$$

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Kinetic energy

Kinetic energy is the energy of motion. The kinetic energy of a body can be calculated by:

Formula 9B–2 Kinetic energy

$$E_k = \frac{1}{2}mv^2$$

Where:

E_k = Kinetic energy (J)

m = Mass (kg)

v = Velocity (m s^{-1})

Worked example 9B–2 Kinetic energy of a car

Calculate the kinetic energy of a car of mass 1000 kg that is driving at 60 km h^{-1} along the Great Ocean Road.

Solution

All units should be converted to SI units:

$$v = \frac{60}{3.6}$$
$$= 16.67 \text{ m s}^{-1}$$
$$E_k = \frac{1}{2}mv^2$$
$$= \frac{1}{2}(1000)(16.67^2)$$
$$= 1.39 \times 10^5 \text{ J}$$

If the car in Worked example 9B–2 was to speed up, then the engine would need to do work to increase the car's velocity. If work is done on an object, then the work done will be equal to the increase in kinetic energy if no other forms of energy are available, such as thermal energy, light energy and gravitational potential energy. This can be shown by:

$$v^2 = u^2 + 2as$$
$$s = \frac{v^2 - u^2}{2a}$$
$$W = Fs\cos\theta$$
$$= (ma)\left(\frac{v^2 - u^2}{2a}\right)\cos 0°$$
$$= \frac{1}{2}mv^2 - \frac{1}{2}mu^2$$
$$= \Delta E_k$$

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Worked example 9B–3 Work done by car brakes

A car of mass 1050 kg that is travelling at 72 km h^{-1} along the Great Ocean Road passes through a town and slows to 45 km h^{-1}. Calculate the amount of work that the brakes do on the car to slow it down.

Solution

Convert all units to SI units:

$$u = \frac{72}{3.6} = 20 \text{ m s}^{-1}, v = \frac{45}{3.6} = 12.5 \text{ m s}^{-1}$$

$$W = \frac{1}{2}mv^2 - \frac{1}{2}mu^2$$

$$= \frac{1}{2}(1050)(12.5)^2 - \frac{1}{2}(1050)(20)^2$$

$$= -1.28 \times 10^5 \text{ J}$$

Note that the negative sign indicates that the energy is lost by the car.

As the kinetic energy is directly proportional to the square of the velocity, it requires more and more energy to increase the velocity by 1 m s^{-1}; the higher the initial velocity is, the more kinetic energy is required. The kinetic energy–velocity graph of a mass of 1 kg in Figure 9B–3 demonstrates this. To increase the velocity from 0 m s^{-1} to 1 m s^{-1} takes 0.5 J of energy. But to increase the velocity from 3 m s^{-1} to 4 m s^{-1} takes 8 – 4.5 = 3.5 J.

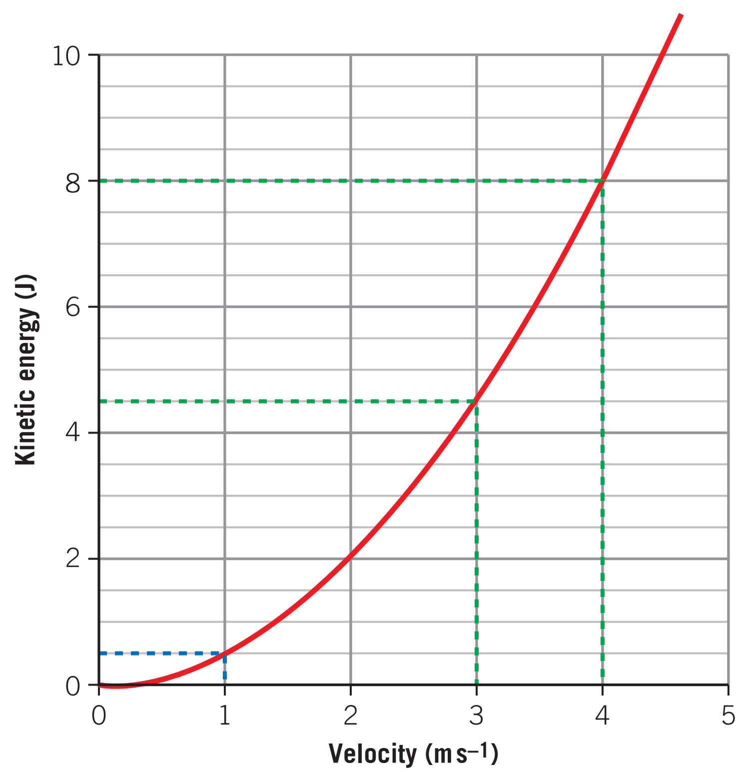

Figure 9B–3 The kinetic energy–velocity graph of an object of mass 1 kg. It takes far less energy to change the velocity of an object from 0 m s^{-1} to 1 m s^{-1} than it does to change the velocity of the same object from 3 m s^{-1} to 4 m s^{-1}.

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Energy transfers, transformations and the law of conservation of energy

Energy can be transferred from one object to another. For example, if you hit a golf ball with a golf club, the kinetic energy in the swinging golf club is partially transferred into the kinetic energy of the ball.

Energy can also be transformed from one form of energy into another, but it cannot be created or destroyed. Let's say you are riding on the roller-coaster that is shown in Figure 9B–4.

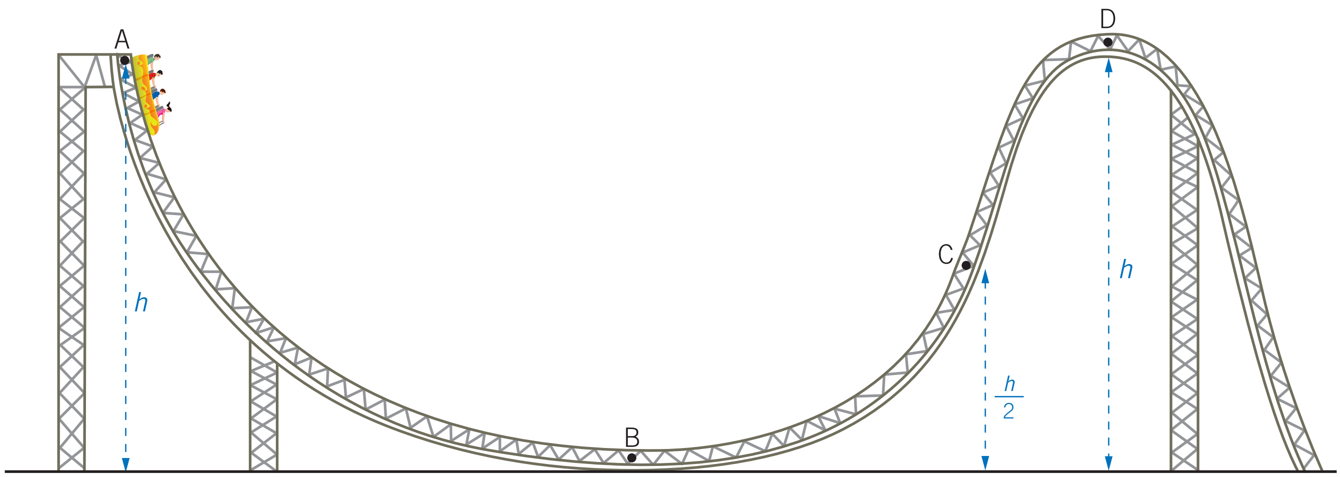

Figure 9B–4 A section of a theoretical roller-coaster track where friction and air resistance are ignored

At point A, you would have the maximum amount of gravitational potential energy and your kinetic energy will be at a minimum. Then as you fall from point A to point B, your gravitational potential energy will decrease as it is being transformed into kinetic energy. From point B to point C, the kinetic energy is being transformed into gravitational potential energy. Point C is exactly half the starting height, which means half of your initial energy will be kinetic and the other half will be stored as gravitational potential. Point D is exactly the same height as point A, and if the effects of friction and air resistance are ignored then the total energy should remain the same at all points during the roller-coaster ride. This means that at any point on the roller-coaster, or in any situation where gravitational potential energy and kinetic energy are being transformed, the following equation holds true:

$$E_{\text{k initial}} + E_{\text{g initial}} = E_{\text{k final}} + E_{\text{g final}}$$

$$\frac{1}{2}mv_i^2 + mg\Delta h_i = \frac{1}{2}mv_f^2 + mg\Delta h_f$$

When analysing the motion and energy of objects, we consider the **system** closed. A **closed system**, sometimes called an isolated system, does not allow transfer of mass or energy to the surrounding environment. This means that the total amount of energy within a closed system will remain the same. The physics of collisions is the only **open system** that is commonly discussed. Collisions are often inelastic, as much of the energy is lost as thermal energy and sound energy to the surrounding environment.

System
a collection of objects that can interact with each other

Closed system
a system that does not allow the transfer of mass or energy to the surrounding environment

Open system
a system that does allow the transfer of mass or energy to the surrounding environment

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Worked example 9B–4 Kinetic energy from gravity

A woman is on a ski route that starts 50 m vertically above its end point. Given that she starts from rest, calculate the speed of the woman when she is 30 m vertically above the end point. Ignore any effects due to air resistance and friction between her skis and the snow.

Solution

In this question, only some of the gravitational potential energy is being converted into kinetic energy, therefore:

$$\frac{1}{2}\cancel{m}v_i^2 + \cancel{m}g\Delta h_i = \frac{1}{2}\cancel{m}v_f^2 + \cancel{m}g\Delta h_f$$

$$v_f = \sqrt{2\left(\frac{1}{2}v_i^2 + g\Delta h_i - g\Delta h_f\right)}$$

$$= \sqrt{2\left(\frac{1}{2}(0)^2 + (9.8)(50) - (9.8)(30)\right)}$$

$$= 19.8 \text{ m s}^{-1}$$

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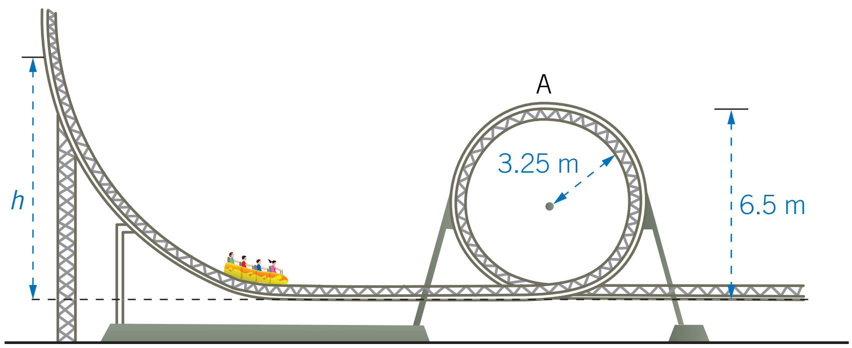
Check-in questions – Set 1

1 A cart on a roller-coaster that has a mass of 140 kg and is initially at rest, rolls down an incline and then goes around the loop on the inside of the track. When the cart is at point A, the top of the loop, the cart has a speed of 6.26 m s^{-1}. A diagram of this situation is shown below.



a Calculate the gravitational potential energy of the cart, relative to the horizontal track, when it is at point A.
b Calculate the kinetic energy of the cart at point A.
c What is the total energy in the system?
d Calculate the height, h, that the cart started from.

2 A train that has a mass of 2.00×10^6 kg is travelling at 27 km h^{-1} along a straight track.
a Calculate the kinetic energy of the train.
b If the train accelerates to 54 km h^{-1}, calculate the increase in the train's kinetic energy.

Power

A Mazda 3 hatchback and a V8 supercar, seen in Figure 9B–5, have approximately the same mass. If friction and drag are ignored, then the two cars will have the same kinetic energy at the same speed. This means that if both cars start from rest and accelerate to 100 km h^{-1}, it will take the same amount of energy to accelerate both of these two cars to this velocity. However, the Mazda 3 will take about 7.9 seconds to reach this speed while the V8 supercar can do it in approximately 3.6 seconds. The V8 supercar can increase the kinetic energy of the car much more quickly than the Mazda 3. Power is the rate of work done. As the V8 supercar can do work much more quickly than the Mazda 3, it is a much more powerful car.

Figure 9B–5 A Mazda 3 and a V8 supercar have approximately the same mass, but the V8 supercar is much more powerful than the Mazda 3.

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Power can be expressed mathematically as:

Formula 9B–3 Power

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

Where:

P = Power (W or J s^{-1})

E = Energy or work (J)

t = Time (s)

To calculate power, joules are divided by seconds to give the unit, J s^{-1}. This unit is also called the watt (W) after James Watt, the inventor of the steam engine.

Worked example 9B–5 Power and gravity

A diver of mass 63 kg climbs up from the ground level to the 10-metre diving platform in 95 seconds. It takes the diver 1.43 seconds to hit the water after they jump off the platform.

a Calculate the amount of gravitational potential energy that the diver has when they are standing on top of the diving platform.

b After jumping from the platform, how much kinetic energy does the diver have when they hit the water?

c Calculate the power of the diver as the diver climbs up the platform. Assume the diver climbs at a constant speed.

d Calculate the average power of the gravitational field as it pulls the diver down to the water.

Solution

a $E_g = mg\Delta h$

$= (63)(9.8)(10)$

$= 6.17 \times 10^3$ J

b As all of the gravitational potential energy will be converted into kinetic energy, the amount is 6.17×10^3 J.

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

$= \frac{6.17 \times 10^3}{95}$

$= 65.0$ W

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

$= \frac{6.17 \times 10^3}{1.43}$

$= 4.32 \times 10^3$ W

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Watt about friction?

If you drive down a straight stretch of road with a constant speed, your car is using energy because you are using fuel to maintain the constant speed of the car. But where is this energy going? It can't be going into the car because the velocity of the car is constant, which means the kinetic energy of the car is also constant. The energy is going into the car to turn its wheels, but that additional energy is immediately lost and given to the surrounding air particles and the road to overcome air resistance and friction. The work done to overcome the frictional forces and maintain a constant velocity is given below.

$$P = \frac{W}{\Delta t} \text{ and } W = Fs\cos\theta = Fs$$

Then:

$$P = F \times \frac{s}{\Delta t}$$
$$= Fv_{av}$$

Worked example 9B–6 Power of a car

Calculate the power of a car that maintains a constant velocity of 63 km h^{-1} when encountering a constant resistance forces of 577 N.

Solution

First, convert all units into SI units:

$$v = \frac{63}{3.6} = 17.5 \text{ m s}^{-1}$$

$$P = Fv_{av}$$
$$= (577)(17.5)$$
$$= 1.01 \times 10^4 \text{ W}$$

Check-in questions – Set 2

1 In 72 seconds, a kettle uses 1.80×10^5 J. What is the power rating of the kettle?
2 A car is moving at a constant velocity of 72 km h^{-1} and is experiencing an average total retarding frictional force of 2500 N. Calculate the power of the car.

WORKSHEET 9B–1 ENERGY, POWER AND ENERGY EFFICIENCY

Energy efficiency

Everything that we do requires energy – driving a car, using a computer, using an air conditioner. But how much of the energy that we put in are we getting back out as useful energy? The energy **efficiency** of something tells us, normally as a percentage, how much of the energy put in is useful and how much is wasted. For example, a combustion engine car is about 30% efficient; meaning that 30% of the energy that you put into your car is converted into the useful kinetic energy of the car. The other 70% of the energy is converted into other forms of energy such as sound and heat.

Efficiency the ratio of the energy output to the energy input of a system

The energy efficiency can be expressed mathematically as:

Formula 9B–4 Energy efficiency

$$\eta = \frac{\text{useful energy out}}{\text{total energy in}}$$

Where:

η = Energy efficiency

Worked example 9B–7 Power of an appliance

An electric toothbrush that has a power rating of 6 W runs for 2 minutes. If 194 J is transformed into useful kinetic energy of the brush, calculate the energy efficiency of the electric toothbrush.

Solution

First, convert all units into SI units:

$t = 2 \times 60 = 120$ s

Rearrange the power formula to get total energy in:

$$E = Pt$$
$$= (6)(120)$$
$$= 720 \text{ J}$$

Then, use the energy efficiency formula:

$$\eta = \frac{\text{useful energy out}}{\text{total energy in}} \times 100$$
$$= \frac{194}{720} \times 100$$
$$= 26.9\%$$

9B SKILLS

VIDEO 9B–2 SKILLS: UNDERSTANDING THE VARIABLES IN A FORMULA

Understanding how the variables in a formula relate to each other

When looking at a physics formula, it is useful to determine if variables are directly proportional or inversely proportional to each other.

When one variable is directly proportional to another it means that the ratio of the two variables is equal to a constant. Direct proportionality is represented by the symbol $\propto$.

For example, the formula for kinetic energy is:

$$E_k = \frac{1}{2}mv^2$$

In this formula, the variables relate to each other as follows.

The kinetic energy is directly proportional to the mass, $E_k \propto m$.

The kinetic energy is directly proportional to v^2, $E_k \propto v^2$.

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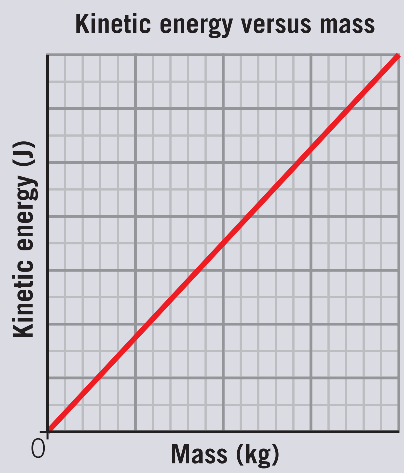
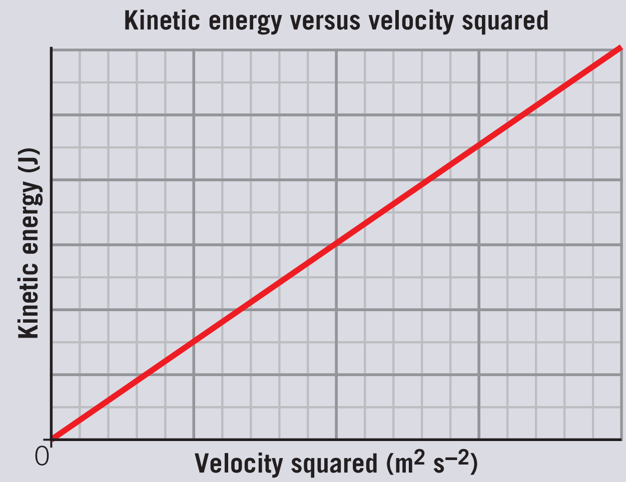
When two variables that are directly proportional to each other are represented on a graph, a straight line with a constant gradient will be produced, as shown below.





When one variable is inversely proportional to another, it means that as one variable goes up the other goes down. For example, consider the formula:

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

In this formula the variables relate to each other as follows.

- The power is directly proportional to the total energy, $P \propto E$.
- The power is inversely proportional to the time or directly proportional to one over the time, $P \propto \frac{1}{t}$.

Understanding proportionality can help to determine how an increase in one variable will affect the other variables. For example, $E_k \propto m$, so if mass doubles, the kinetic energy would also double, as shown below:

$$k = \frac{E_k}{m} = \frac{2E_k}{2m}$$

Where k is a constant.

Similarly, as $E_k \propto v^2$, this means that if the velocity doubles, then the kinetic energy would quadruple, as shown below:

$$k = \frac{E_k}{v^2} = \frac{4E_k}{(2v)^2} = \frac{4E_k}{2^2 v^2} = \frac{4E_k}{4v^2}$$

Question

The velocity of a cyclist increases from 5 m s^{-1} to 15 m s^{-1}. If the original kinetic energy is given by E_k, which of the following statements is true

A The kinetic energy of the cyclist is $2E_k$.
B The kinetic energy of the cyclist is $3E_k$.
C The kinetic energy of the cyclist is $6E_k$.
D The kinetic energy of the cyclist is $9E_k$.

Solution

D In this case, the velocity is tripled, which means the kinetic energy has increased by a factor of nine. This is because kinetic energy is directly proportional to the velocity squared not the velocity. This can be expressed mathematically as shown below:

$$k = \frac{E_k}{v^2} = \frac{xE_k}{(3v)^2} = \frac{xE_k}{3^2 v^2} = \frac{xE_k}{9v^2}$$

Therefore, $x = 9$, so the kinetic energy will increase by a factor of 9.

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Section 9B questions

Multiple-choice questions

1 A light-emitting diode (LED) uses 500 J of energy in total, 400 J is converted into light and the rest is converted into thermal energy and sound energy. What is the energy efficiency of this light globe?

A 80%
B 70%
C 30%
D 20%

2 A medium-sized fridge requires about 5000 W of power to run. The amount of energy that a 5000 W fridge would use in a day is

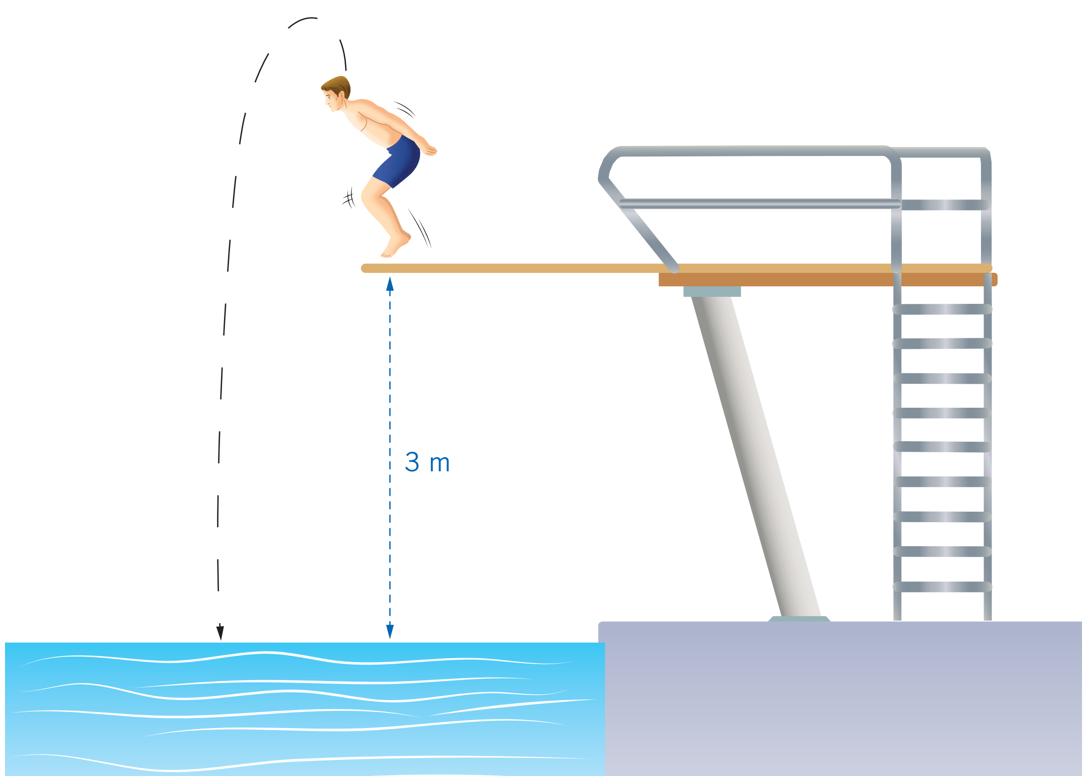
A 120 kJ
B 7.2 MJ
C 57.9 MJ
D 432 MJ

3 Calculate the work done for a cyclist to accelerate from 8 m s^{-1} to 12 m s^{-1}. The cyclist and bicycle have a combined mass of 97.5 kg.

A 195 J
B 780 J
C 3.90×10^3 J
D 5.85×10^3 J

Use the following information to answer Questions 4 and 5.

A diver is diving from the 3-metre diving board. He jumps up and leaves the diving board with a velocity of 5.55 m s^{-1} vertically up. A diagram of this situation is shown below.



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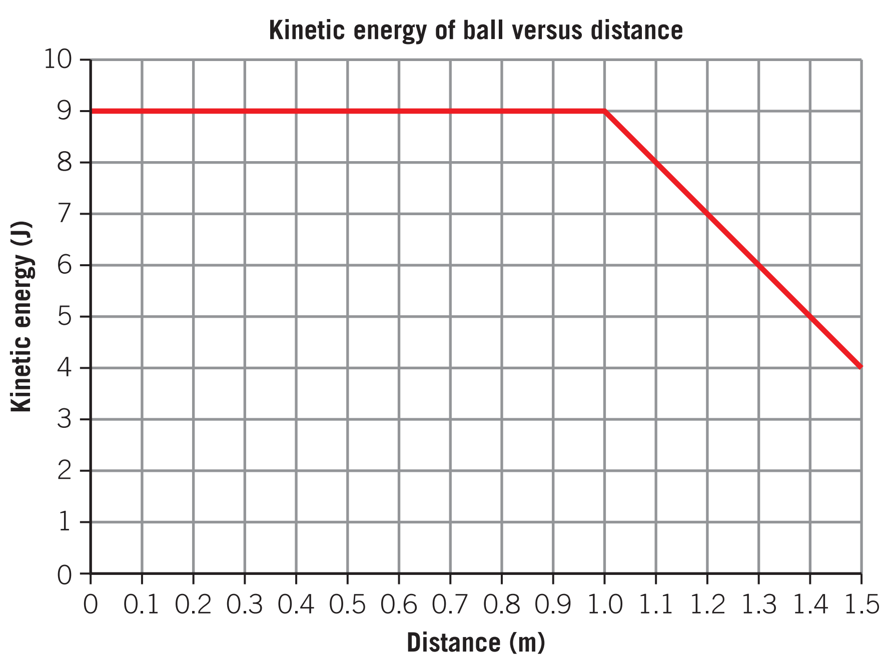
4 The maximum height that the diver will reach above the surface of the water
  A is 1.57 m.
  B is 3.28 m.
  C is 4.47 m.
  D Cannot be solved because the mass of the diver is not given.

5 If the diver has a mass of 63 kg, what is the final kinetic energy of the diver when he hits the water?
  A 1.55×10^3 J
  B 2.03×10^3 J
  C 2.82×10^3 J
  D 5.89×10^3 J

Short-answer questions

6 A person rides a motorbike at a speed of 153 km h^{-1} on a racetrack. The combined mass of the motorbike and the person is 185 kg.
  a How much kinetic energy does the motorbike and rider have?
  b When approaching the corner, the bike rider slows to a velocity of 63 km h^{-1}. Calculate the amount of work that the brakes do on the motorbike.

7 A smooth ball rolls on a table that is 1.5 m long; the first 1 m is highly polished and the next 0.5 m is rough. The kinetic energy–distance graph below shows how the kinetic energy of the ball changes as it moves along the table. The mass of the ball is 2.5 kg.



  a What is the initial velocity of the ball?
  b How much work was done to overcome the frictional forces of the rough area of the table?
  c When the ball reaches the edge of the table, it falls 1.27 m down to the floor. What is the total energy of the ball just before striking the floor? Assume no energy is lost to the surrounding environment as the ball falls.

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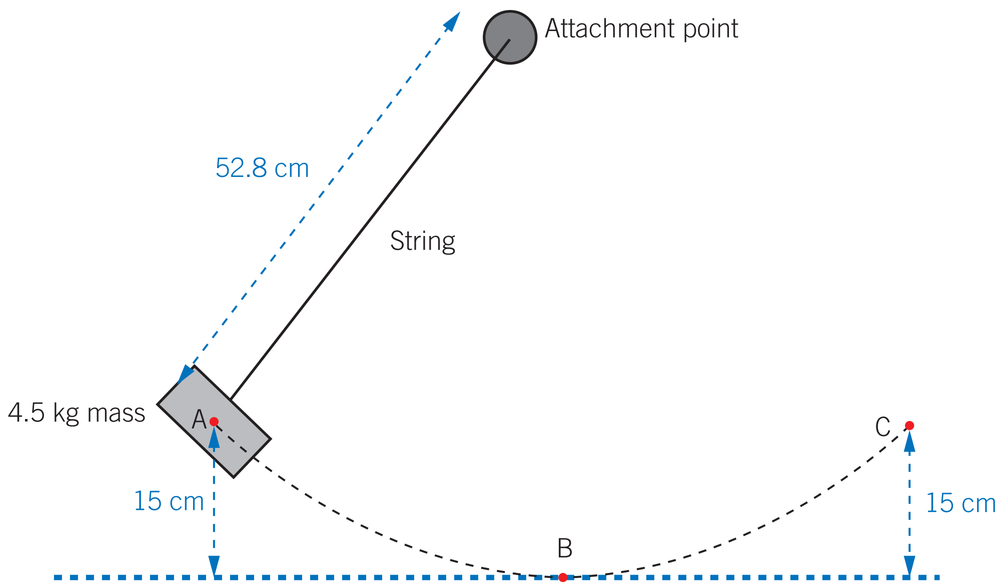
8 A pendulum of mass 4.5 kg is tethered to one end of a 52.8 cm string of negligible mass. The other end of the string is attached to a rigid attachment point. The pendulum is set to swing. Point A and point C are the highest positions in the pendulum's arc and point B is the lowest position. The highest and lowest positions are separated by a vertical distance of 15 cm. A diagram of this situation is shown below.



Calculate the velocity of the pendulum at point B.

9 A car is travelling along a road in Wilsons Promontory National Park at a velocity of 81 $km\,h^{-1}$ when a kangaroo jumps out onto the road. The driver brakes and slows down to a velocity of 40.5 $km\,h^{-1}$. The car and its contents have a total mass of 1153 kg.

a Calculate the kinetic energy of the car when it is travelling at 81 $km\,h^{-1}$.

b Calculate the amount of work that the brakes do on the car to slow it down.

10 A skydiver with a mass of 94.5 kg travels in a light aircraft up to an altitude of 4.20 km above the surface of Earth. She then jumps out of the aircraft and falls back towards Earth, releasing her parachute when she is 0.914 km above the surface of Earth.

a Calculate the gravitational potential energy of the skydiver just before she jumps out of the aircraft.

b Calculate the velocity of the skydiver just before she pulls her parachute. Assume that the skydiver has no initial velocity and ignore the effects of air resistance.

c In reality, skydivers quickly reach terminal velocity. Terminal velocity is the fastest possible velocity a skydiver can achieve and it occurs when the upward force of air resistance is equal to the downward pull of gravity. Calculate the power provided by Earth's gravitational field on an 80 kg skydiver who has a terminal velocity of 67 $m\,s^{-1}$.

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9C Springs

Study Design:

- Investigate and analyse theoretically and practically Hooke's Law for an ideal spring: $F = -kx$, where x is extension
- Analyse and model mechanical energy transfers and transformations using energy conservation:
  - elastic potential energy in ideal springs: $E_s = \frac{1}{2}kx^2$

Glossary:
Elastic limit
Elastic material
Elastic potential energy
Equilibrium position
Hooke's law
Ideal spring

ENGAGE

The amazing elasticity of tendons

The energy used in an animal's motion arises mostly from the muscular force generated to support the animal's weight and the work associated with moving the animal's centre of mass and body segments. When moving at high speeds, animals use bouncy gaits to conserve muscle work. At these higher speeds, the energy saving is mainly achieved by the storage and recovery of elastic potential energy in tendons and ligaments. Tendons are connective tissue mainly composed of collagen fibres that attach muscle to bone.

Figure 9C–1 Stewart McSweyn of Australia competes in the Men's 1500 metres in the Tokyo 2020 Olympic Games. When Stewart's foot contacts the ground, his Achilles tendon will elongate, storing elastic potential energy. As Stewart's centre of mass moves forwards, he will concentrically contract his gluteal muscles, quadriceps and calves to push backwards into the track. As this occurs, his Achilles tendon shortens, returning the energy that it has stored by also pushing back on the track. The track will then push Stewart forward.

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Tendons are remarkably efficient. Testing in human runners has found that the mechanical energy that our tendons return to us is very similar to other mammals and running birds, 5–13%. The mechanical energy is the energy from the muscular forces that generate and maintain movement. The exception to this is wallabies and kangaroos, which are more than twice as mechanically efficient as humans.

Figure 9C–2 Red kangaroos on the beach at Lucky Bay, Esperance, Western Australia, use their remarkably long tendons to bounce along, using very little energy

Wallabies and kangaroos have unusually long tendons that have the ability to store larger amounts of elastic potential energy. This allows kangaroos to hop at high speeds while using very little energy.

Elastic material a material that can store elastic potential energy and is able to return to its original shape once the energy is released

EXPLAIN

Elasticity

VIDEO 9C–1 USES OF SPRINGS

When an object compresses, extends or twists and then returns to its original shape, the material has stored energy by changing shape. Any material that can change shape and then return to its original shape is called an **elastic material**. All elastic materials have an **elastic limit**, this is the maximum stress that a material can be placed under without causing permanent deformation. Many solid materials are elastic, such as rubber, neoprene and steel. Materials that change shape permanently when deformed only slightly are referred to as plastic materials. Mud clay and plasticine are all examples of plastic materials.

Elastic limit the maximum deformation that can occur without causing permanent deformation

Hooke's law

Springs are used extensively in a range of machines and devices. Toys, pens, electronics, mattresses, medical devices, automatic watches, mining and drilling equipment and vehicles are just a few examples of where springs are used.

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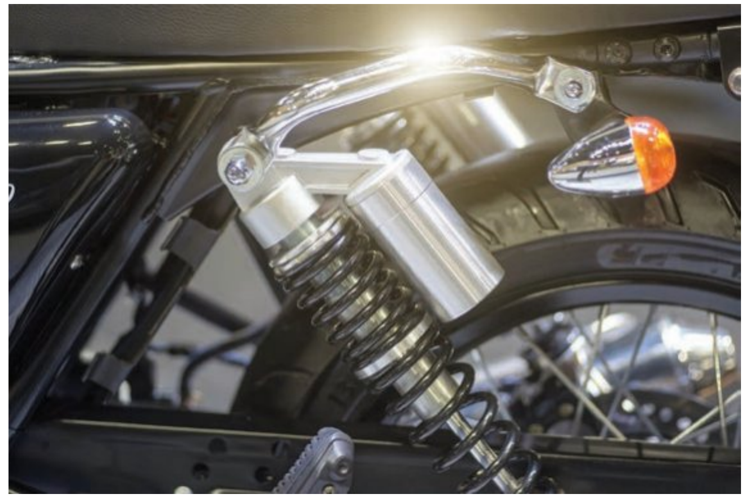

Figure 9C–3 Left: an automatic watch requires no batteries. When wearing the watch, a self-winding spring coverts the person's kinetic energy into elastic potential energy that is gradually released as motion on the hands of the watch. Right: springs are also used in vehicles to give the driver a smoother ride.

We have been able to utilise springs so effectively because we have known about their properties for over 300 years. In 1676 British physicist Robert Hooke first proposed **Hooke's law**, that in an **ideal spring**, the force applied to the spring is directly proportional to its extension or compression. Imagine a specific spring resting horizontally – when no force is applied to the spring there will be no extension in the spring. When 50 N of force is applied to this specific spring, it extends by 0.2 m; when 100 N of force is applied to the spring it extends by 0.4 m. A force–extension graph of the spring is shown in the figure above.

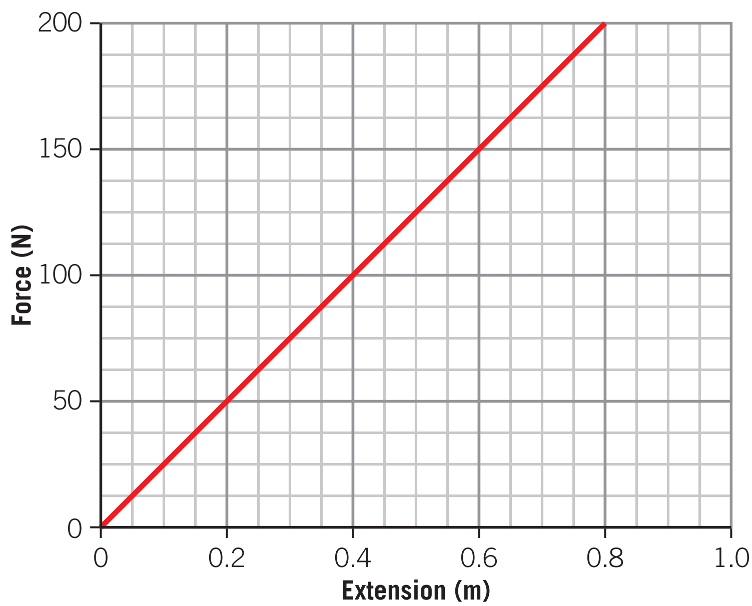

Figure 9C–4 Force versus extension graph for an ideal spring with a spring constant of $k = 250\ \text{N m}^{-1}$.

Hooke's law in an ideal spring, the force applied to the spring is directly proportional to its extension or compression

Ideal spring a hypothetical spring that is considered frictionless and mass-less and that obeys Hooke's law

The constant linear relationship between the force applied and the extension highlights Hooke's law, that force is directly proportional to extension. The gradient of this graph is known as the spring constant, k, and as you are dividing newtons by metres the unit for the spring constant is N m^{-1}. The gradient, and therefore the spring constant for the spring, in the graph above can be calculated as follows:

$$\begin{aligned}\text{gradient} &= k \\ &= \frac{\text{rise}}{\text{run}} \\ &= \frac{200-0}{0.8-0} \\ &= 250\ \text{N m}^{-1}\end{aligned}$$

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The spring constant gives an indication of the stiffness of the spring; the higher the spring constant, the more force is required to extend or compress the spring and therefore the stiffer it is. For example, a spring that has a spring constant of 500 N m^{-1} would take twice as much force to extend it an equal amount as the spring with a spring constant of 250 N m^{-1}. This is shown in the graphs below.

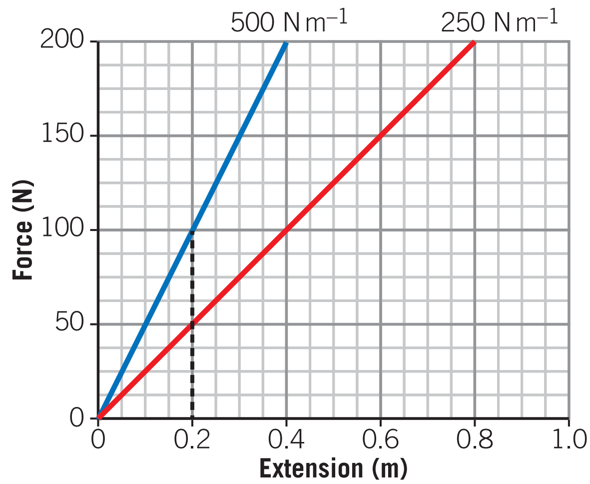

Figure 9C–5 Comparison of force versus extension graph for ideal spings with spring constants of $k = 250$ N m^{-1} (red) and $k = 500$ N m^{-1} (blue).

Hooke's law can be represented mathematically as follows:

Formula 9C–1 Hooke's law

$$F = -kx$$

Where:

F = Force (N)

k = Spring constant (N m^{-1})

x = Compression or extension of the spring (m)

There is a negative sign to indicate that the spring's restoring force acts in the opposite direction to the compression or extension. For simplicity, this book will omit the negative sign from this point onwards. This means that the formula will indicate the magnitude of the force on the spring and hence the magnitude of the force by the spring. While the above equation only refers to springs, the relationship holds true for all solid elastic materials.

Worked example 9C–1 Hooke's law and suspension

A car is driving over a speed bump in the road. The speed bump applies a force of 750 N to the car's shock-absorbing spring. The shock-absorbing spring has a spring constant of 1.34×10^4 N m^{-1}. Calculate the amount of compression in the spring as the car drives over the speed bump.

Solution

$$F = -kx$$

$$x = \frac{F}{k}$$

$$= \frac{750}{1.34 \times 10^4}$$

$$= 0.0560 \text{ m}$$

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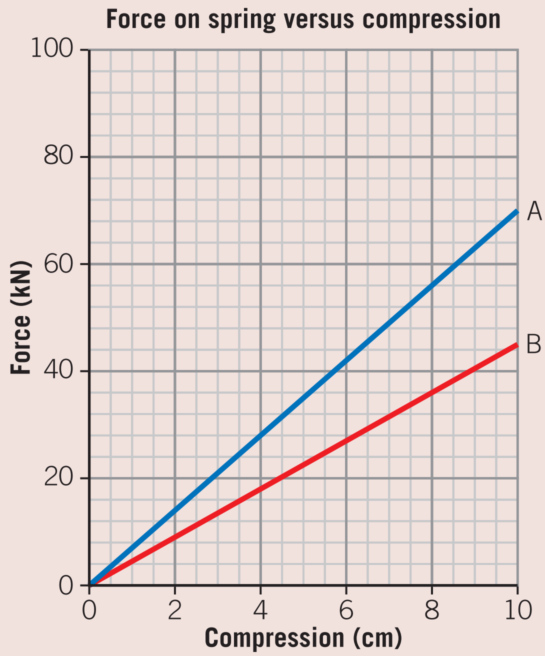
Worked example 9C–2 Reading a force–compression graph

A group of engineers is testing two springs, spring A and spring B, for use on mining equipment. The results of their tests are displayed on the force–compression graphs shown on the right.



a Calculate the spring constant of spring A and spring B and state which spring is stiffer.

b The engineers need to select a spring that is compressed by 70–80 cm when a force of 500 kN is applied to it. Which of the springs tested would be appropriate for use? Use a calculation to justify your answer.

Solution

a When looking at any graph, you must pay attention to the units. If they are not SI units, then you must convert them and then calculate the spring constant. In this example you, must convert kN into N.

$$k_A = \frac{(70 \times 10^3) - 0}{0.1 \times 0}$$

$$= 7.00 \times 10^5 \text{ N m}^{-1}$$

$$k_B = \frac{(45 \times 10^3) - 0}{0.1 - 0}$$

$$= 4.5 \times 10^5 \text{ N m}^{-1}$$

Spring A is stiffer as it has a greater spring constant.

b First, rearrange Hooke's law to make compression the subject. Then determine the compression of both springs when loaded with 500 kN.

$$x_A = \frac{F}{k}$$

$$= \frac{500 \times 10^3}{7 \times 10^5}$$

$$= 0.714 \text{ m}$$

$$x_B = \frac{F}{k}$$

$$= \frac{500 \times 10^3}{4.5 \times 10^5}$$

$$= 1.11 \text{ m}$$

Therefore, only spring A is appropriate for use.

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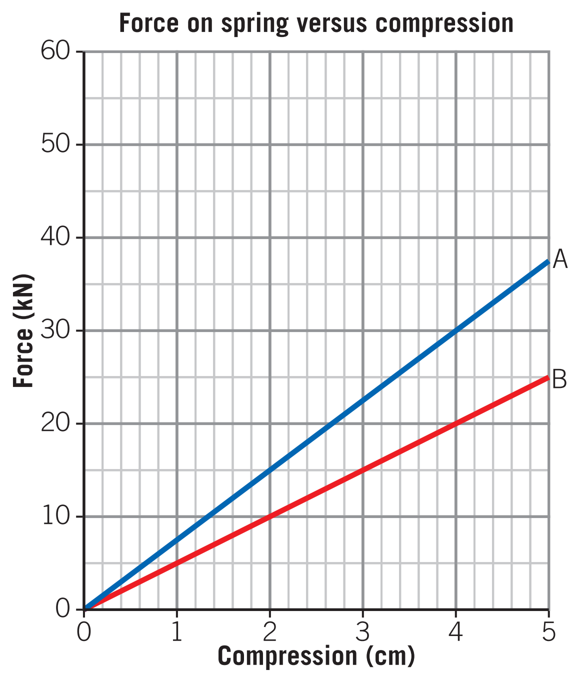
Check-in questions – Set 1

1 If 100 N of force is used to compress an ideal spring by 1 cm, what is the spring constant of that spring?

2 A car manufacturing company is looking for the stiffest spring that they can use for their new sports car. The springs that they can choose from are shown in the graph below.



Which spring should the car manufacturing company choose for the sports car and what is the spring constant of this spring?

Elastic potential energy

When an elastic material is compressed, extended or twisted, it stores energy. This stored energy is known as **elastic potential energy** or elastic potential energy. When the elastic potential energy is released, the object will return to its original shape. Imagine a spring that has a spring constant, k. A force–compression graph of the spring is shown on the right.

Elastic potential energy the energy stored in the material when it is deformed within its elastic limits

You should note that the values shown on the y-axis are a measure of force and values on the x-axis are a measure of distance (compression or extension).

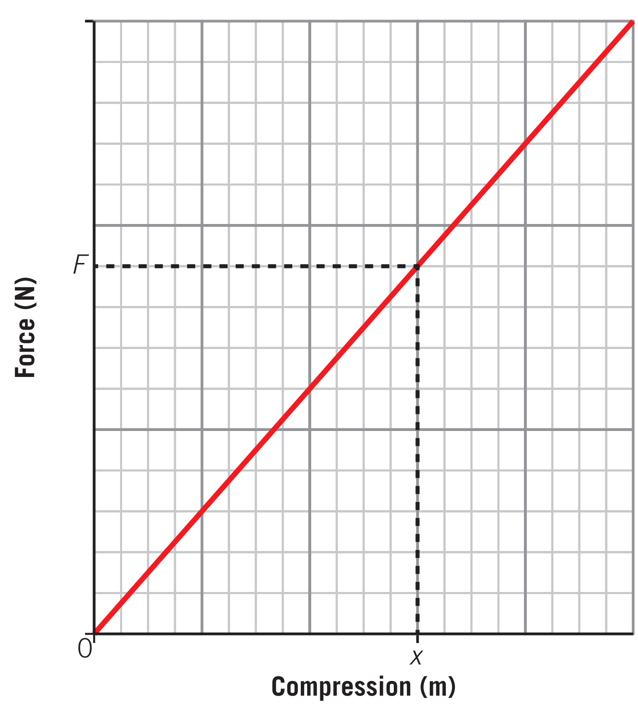


Figure 9C–6 The area under a force versus compression graph for an elastic material is the elastic potential energy.

This means that this graph is just a special force–distance graph, and the area under a force–distance graph is work. This means that the area under a force–compression/extension graph is the work done to compress or extend the objects as well as the amount of elastic potential energy stored in the object. For the force–compression graph above, the elastic potential energy would be given by the area under the triangle; therefore:

$$\text{elastic potential energy} = E_s = \frac{1}{2}(F)(x)$$

Hooke's law states that $F = kx$. Therefore, the force, F, in the above equation can be substituted for kx as shown:

$$E_s = \frac{1}{2}(k)(x)(x)$$

$$E_s = \frac{1}{2}kx^2$$

Formula 9C–2 Elastic potential energy

$$E_s = \frac{1}{2}kx^2$$

Where:

E_s = Elastic potential energy or elastic potential energy (J)

k = Spring constant (N m^{-1})

Δx = Compression or extension (m)

Worked example 9C–3 Elastic energy of a spring

A spring, initially at rest, has a force of 3.44 kN applied to it. The spring has a spring constant of 2500 N m^{-1}.

a Calculate the change in length of the spring.

b Calculate the amount of elastic potential energy stored in the spring once the force has been applied.

Solution

a Convert all units to SI units.

$F = 3.44 \times 10^3$ N

Then rearrange the appropriate formula to make the change in length the subject. Substitute the appropriate values to solve the equation:

$$x = \frac{F}{k}$$

$$= \frac{3.44 \times 10^3}{2500}$$

$$= 1.38 \text{ m}$$

The change in length is 1.38 m.

b Select the appropriate formula and substitute the appropriate values in to solve the equation:

$$E_s = \frac{1}{2}kx^2$$

$$= \frac{1}{2}(2500)(1.38)^2$$

$$= 2.37 \times 10^3 \text{ J}$$

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Worked example 9C–4 Elastic potential from a graph

A spring to be used in a medical device is tested and produces the following force–extension data.

Calculate the elastic potential energy stored in the spring when it is extended by 2 cm.

Solution

The elastic potential energy can be found from the area under the graph.

First, convert all of the units to SI units:

$F = 5 \times 10^3$ N, $x = 0.02$ m

Then find the area under the graph:

$$E_s = (0.5)(5 \times 10^3)(0.02)$$
$$= 50 \text{ J}$$

This can also be done by finding the spring constant from the gradient of the graph and then solving the elastic potential energy formula, $E_s = \frac{1}{2}kx^2$.

When trying to extend a spring, it gets harder to change the shape of the spring the more you extend it. To extend a spring by 1 cm when it is resting does not take as much energy as extending the same spring by 1 cm when it is already stretched. This is because the more you stretch a spring, the greater the restoring force becomes and therefore more energy must be applied to overcome this force. This is also true when trying to compress a spring. This is shown graphically in Figure 9C–7, with a spring that has a spring constant of 200 N m^{-1}.

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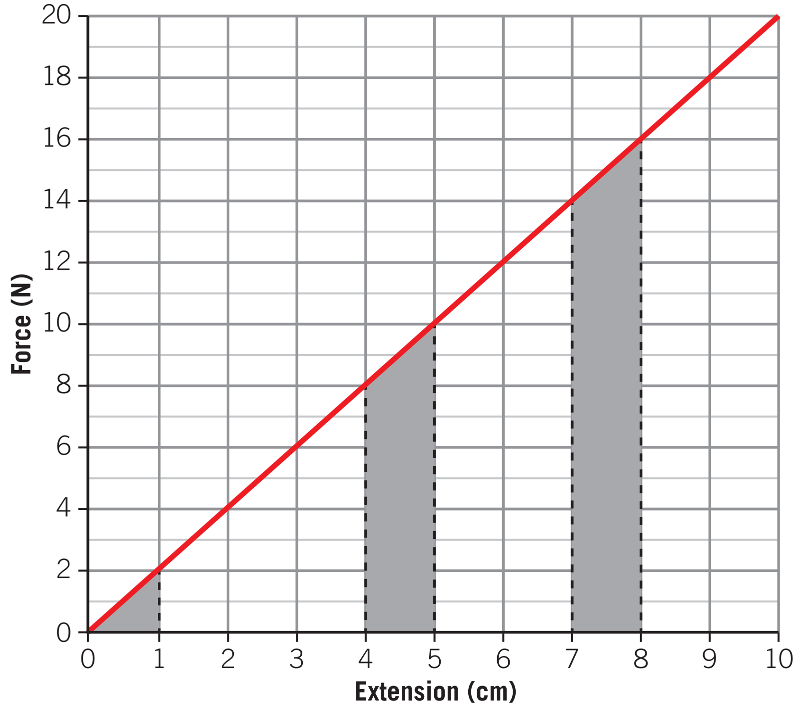

Figure 9C–7 The force versus extension graph for an ideal spring with spring constant $k = 200\ \text{N m}^{-1}$. The energy needed to extend the spring increases the more lengthened the spring becomes.

As the spring extends, it takes more and more energy to extend it by the same amount. The energy required to extend the spring by 1 cm is represented by the shaded region in the graph. It is clear that the longer the spring becomes, the more energy is required to extend the spring by 1 cm.

Therefore, when finding the change in elastic potential energy, you can either find the area under the graph or take away the elastic potential energy of the initial length, x_i, from the elastic potential energy of the final length, x_f:

$$\Delta E_s = \frac{1}{2}kx_f^2 - \frac{1}{2}kx_i^2$$

Worked example 9C–5 Energy released by a compressed spring

A spring of length 40 cm with a spring constant of $43.5\ \text{N m}^{-1}$ is initially compressed to 30 cm and is then released back to a length of 35 cm. Calculate the amount of energy released when the spring is released back to a length of 35 cm.

Solution

$$\Delta E_s = \frac{1}{2}kx_f^2 - \frac{1}{2}kx_i^2$$

$$= \frac{1}{2}(43.5)(0.05)^2 - \frac{1}{2}(43.5)(0.1)^2$$

$$= -0.163\ \text{J}$$

Note that there is a negative sign in front of the energy because the energy is being given out. If the spring was compressed by someone's hand, then slowly released by the same hand, the spring has done work on the hand.

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WORKSHEET 9C–1 SPRINGS

Check-in questions – Set 2

1 A student stretched an ideal spring by length L. The student then continues to stretch the spring so that it is extended by length of $2L$. When extended to length $2L$, explain which of the following statements is true.

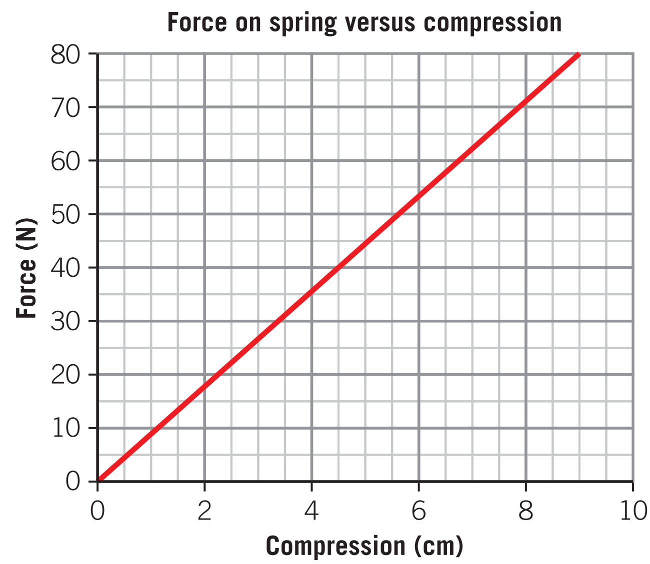
A The spring has twice as much energy when it is extended to length $2L$ compared to L.

B The spring has three times as much energy when it is extended to length $2L$ compared to L.

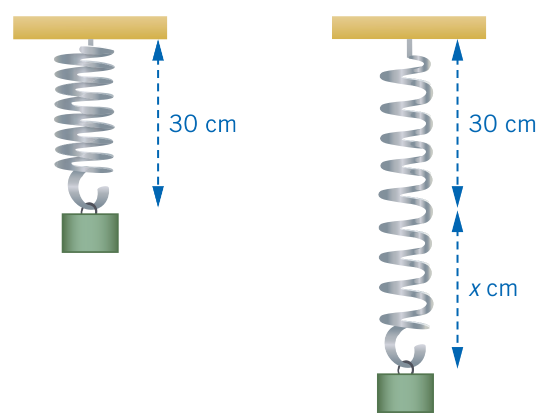
C The spring has four times as much energy when it is extended to length $2L$ compared to L.

D The spring has five times as much energy when it is extended to length $2L$ compared to L.

2 The force–compression graph of a spring that is used in pens is shown on the right. Use the graph to calculate the amount of elastic potential energy stored in the spring when it is compressed by 5 cm.



3 A group of students is conducting an experiment with an ideal spring that has a spring constant, k, of 21.8 $N\,m^{-1}$. The spring has an unstretched length of 30 cm. The students attach a mass of 300 g to the bottom of the spring and allow it to oscillate freely when it is released. When the spring is released, the spring has a maximum extension of x cm. The situation is shown to the right.



a Find the extension of the spring at its lowest point of oscillation. You can ignore the mass of the spring itself and frictional losses.

b When is the speed of the mass on the spring a maximum? Explain your answer.

c Calculate the extension of the spring when the velocity is a maximum.

d Calculate the maximum velocity of the spring throughout its oscillation.

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Energy transformations in a horizontal spring system

Imagine an ideal spring that works the same in compression and extension. The spring is lying horizontally on a frictionless surface, with one end fixed against a wall and the other end attached to a free object. If the object is pulled back and let go, it will oscillate about an **equilibrium position**. When the object is at the equilibrium position, it will have no net force on it. The object will have no net force on it because the spring is at its natural length, it is not compressed or extended, and the force due to gravity of the object is balanced by the normal force applied by the surface on the object.

Equilibrium position the position in a system where the net force on the oscillating object is zero

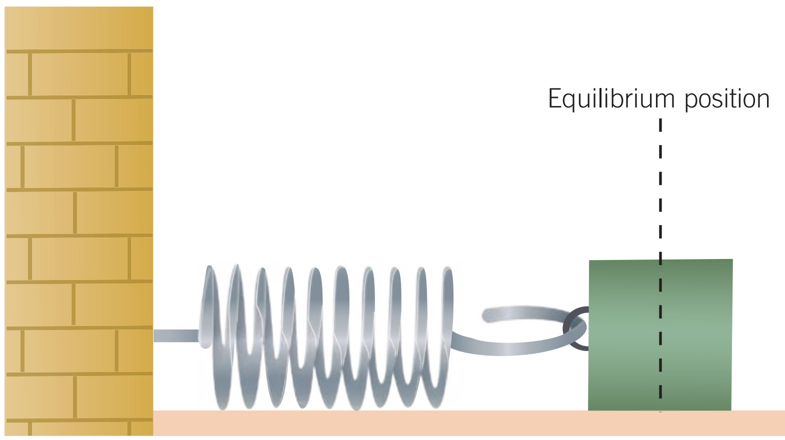


Figure 9C–8 An object attached to a horizontal spring has no net force at its equilibrium position.

As the spring oscillates, the kinetic energy and elastic potential energy will fluctuate between maximum values and zero. Since the total energy, E_T, will remain the same throughout the oscillation the sum of the kinetic energy, E_k, and elastic potential energy, E_s, at any given point will be equal to the total energy. This can been represented by the following formula:

$$E_T = E_k + E_s$$

Formula 9C–3 Kinetic energy in a horizontal spring system

$$E_T = \frac{1}{2}mv^2 + \frac{1}{2}kx^2$$

Where:

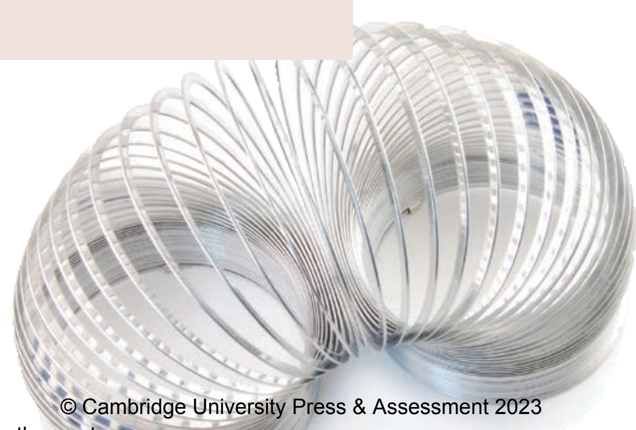
E_T = Total energy (J)

m = Mass (kg)

v = Velocity ($m\,s^{-1}$)

k = Spring constant ($N\,m^{-1}$)

x = Change in length of the spring (m)



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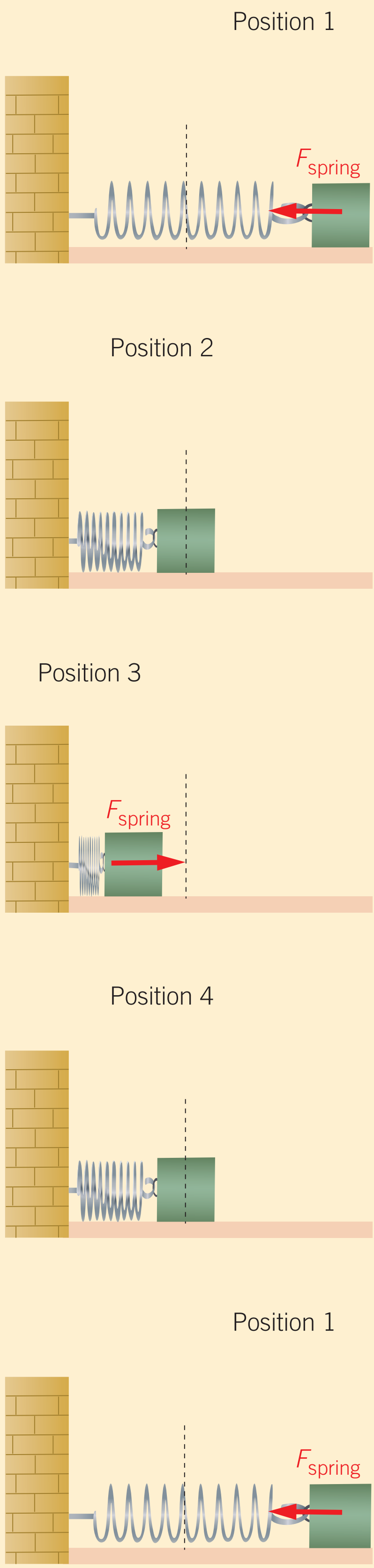

At position 1 the spring is fully extended, it is a point of maximum spring potential energy and zero kinetic energy.

As the object moves towards the equilibrium position (2) the kinetic energy increases and the spring potential energy decreases.

At the equilibrium positions (2 and 4) the spring will have maximum kinetic energy and zero spring potential energy.

Once the object passes the equilibrium position the spring begins to compress, slowing the object down. The kinetic energy will decrease while the spring potential energy increases.

At position 3 the spring potential energy will be a maximum and the kinetic energy will be zero.

The object will then gain kinetic energy and lose spring potential energy as it moves back to the equilibrium (4).

At the equilibrium position again the spring will have maximum kinetic energy and zero spring potential energy.

Once past the equilibrium the kinetic energy of the object will decrease and the spring potential energy will increase.

This decrease in kinetic energy will continue until the spring comes momentarily to rest at position 1, ready to repeat the cycle.

Figure 9C–9 The following shows one full oscillation of a horizontal spring. The dotted line represents the equilibrium position. It is important to remember that when the object is not on the equilibrium position the net force on the object will be towards the equilibrium position.

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Energy transformations in a vertical spring system

For a vertical spring system, imagine an ideal spring with one end fixed to a ceiling and the other end attached to an object that is free to move. If the object is dropped and allowed to move freely under the influence of gravity, it will oscillate about an equilibrium position. When the object attached to a vertical spring is at the equilibrium position, it will have no forces on it. This is because the upwards spring force will balance the downwards force due to gravity.

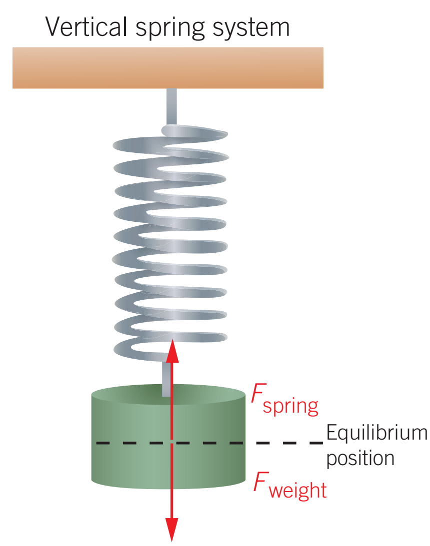

Figure 9C–10 An object attached to a vertical spring has no net force at its equilibrium position. The spring force F_{spring} balances the weight force F_{weight}.

The upwards spring force balancing the downwards force due to gravity is shown mathematically below:

Formula 9C–4 Kinetic energy in a vertical spring system

$$kx = mg$$

Where:

k = Spring constant ($N\,m^{-1}$)

x = Change in length of the spring (m)

m = Mass (kg)

g = Gravitational field strength (9.8 $N\,kg^{-1}$ on the surface of Earth)

The equilibrium position is the position of maximum kinetic energy. As the spring oscillates about the equilibrium position, the gravitational potential energy, elastic potential energy and kinetic energy will fluctuate between maximum values and zero.

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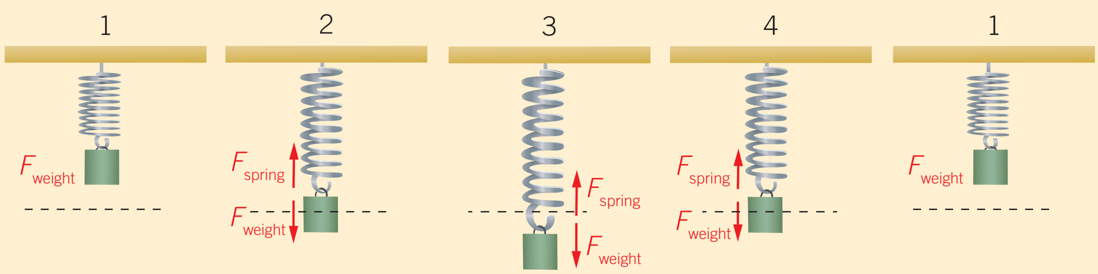
Before analysing the motion of a vertical spring system you must define the point of zero gravitational potential energy. It will be the lowest point of the spring's oscillation (position 3 in the diagram).

When the object is initially dropped (position 1), the spring is in its natural position, under no compression or extension. This means that the spring potential energy and kinetic energy are both equal to zero, while the gravitational potential energy is at a maximum.

→ As the object is pulled down by the force of gravity its spring potential energy and kinetic energy increase, while the gravitational potential energy decreases. At the equilibrium positions (2 and 4), the kinetic energy is a maximum.

→ Between positions 2 and 3, the object passes the equilibrium position, the kinetic energy starts to decrease, the gravitational potential energy continues to decrease, and the spring potential energy continues to increase.

→ *Continued below*



Continued from above →

At position 3 the kinetic energy and gravitational potential energy are both equal to zero, while the spring potential energy is at a maximum.

→ Between positions 3 and 4, the object then moves upwards, increasing both the kinetic energy and gravitational potential energy, while decreasing the spring potential energy.

→ At position 4, the object passes the equilibrium position, the kinetic energy starts to decrease, the gravitational potential energy continues to increase, and the spring potential energy continues to decrease, until the object returns to position 1 and the cycle repeats.

Figure 9C–11 One full oscillation of a vertical spring. The dotted line represents the equilibrium position. It is important to remember that, just like in a horizontal spring, when the objects are not at the equilibrium position then the net force on the objects will be towards the equilibrium position.

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Mathematical relationships in a vertical spring system

The gravitational potential energy lost by the object will be transformed into the elastic potential energy and kinetic energy of the system. This relationship can be represented by the formula:

$$E_g = E_s + E_k$$

$$mg\Delta h = \frac{1}{2}kx^2 + \frac{1}{2}mv^2$$

Since the change in height is equal to the change in length of the spring, Δh can be replaced with an x as shown below:

Formula 9C–5 Transformation of kinetic energy in a vertical spring system

$$mgx = \frac{1}{2}kx^2 + \frac{1}{2}mv^2$$

Where:

m = Mass (kg)
g = Gravitational field strength (9.8 $\mathrm{N\,kg^{-1}}$ on the surface of Earth)
x = Change in length of the spring (m)
k = Spring constant ($\mathrm{N\,m^{-1}}$)
v = Velocity ($\mathrm{m\,s^{-1}}$)

9C SKILLS

VIDEO 9C–2
SKILLS: HOW TO 'EXPLAIN' YOUR ANSWER

How to 'explain' your answer

Exams will commonly ask you to 'explain' your answer. To explain means to present accurate and concise evidence that supports your answer. Consider the following question.

Question

A mass, that is attached to an ideal spring, is dropped and allowed to oscillate freely in the vertical direction. When is the velocity of the mass at a maximum? Explain your answer. (3 marks)

Solution

- The velocity will be at a maximum at the equilibrium point, when the spring force is balanced by the force due to gravity. (1 mark)
- When the forces on the mass are balanced, the acceleration is zero. (1 mark)
- Therefore, before this point the mass would have been accelerating in the direction of travel and after this point the mass will begin to decelerate. (1 mark)

The answer is set out in three dot points; each dot point makes a distinct point and would be awarded one mark. When answering 'explain' questions, you should look at the number of marks and use that as a guide of how many points to make. Make sure that you are answering the question presented and not just writing a pre-prepared answer that is not specific to the question. Answers should be clear and concise. Remember that you will not be marked down for using dot points, in fact they can help you structure your answer.

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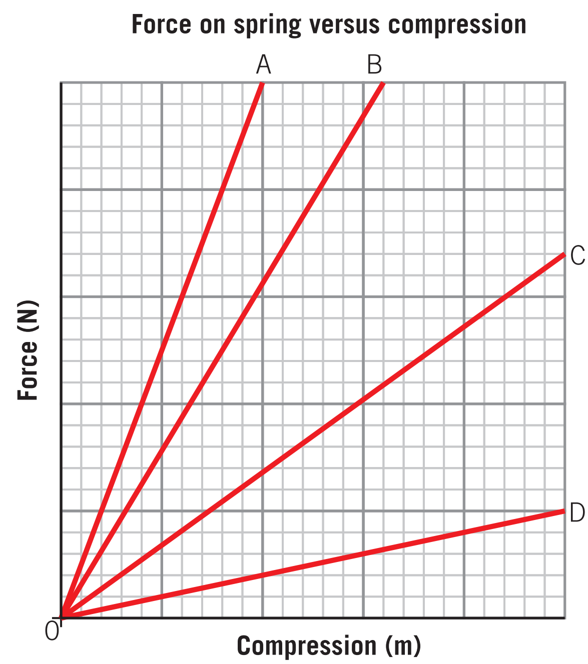
Section 9C questions

Multiple-choice questions

1 A car company is trying to get the stiffest spring for their latest sports car. They have a choice of four springs. The force-compression data of each spring is displayed on the graph below.

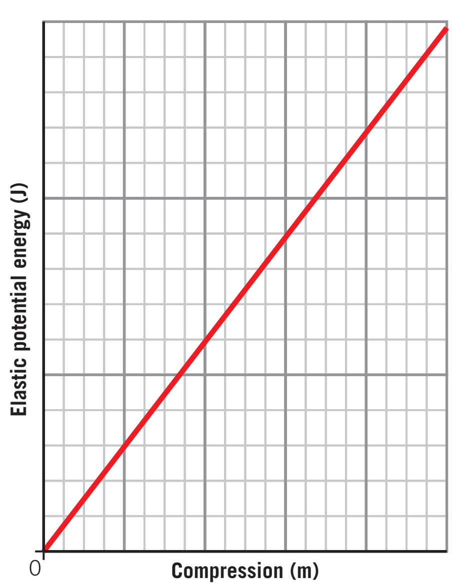


Which spring should the car company select?

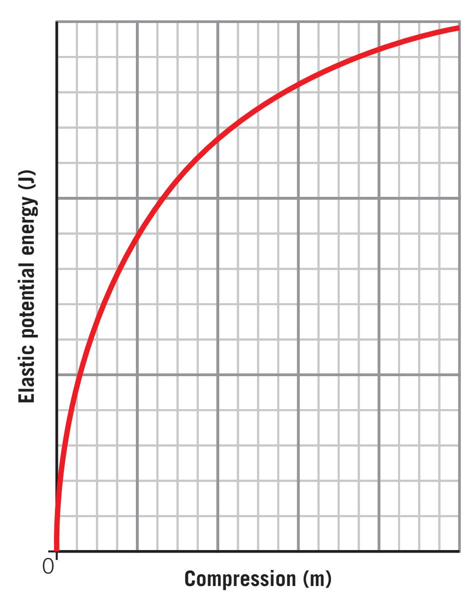
A A
B B
C C
D D

2 Which of the graphs below best represents the elastic potential energy–compression graph of an ideal spring?

A



B



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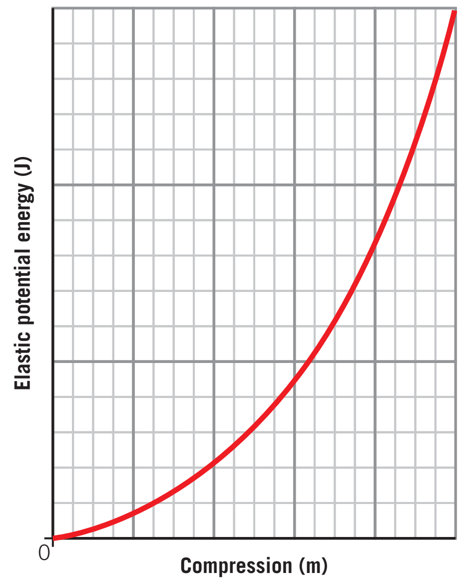
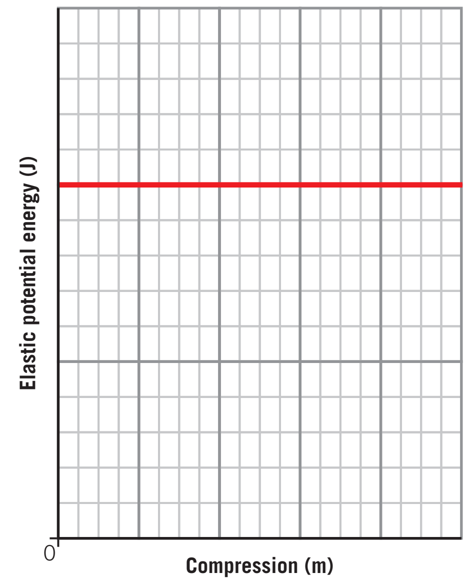
C

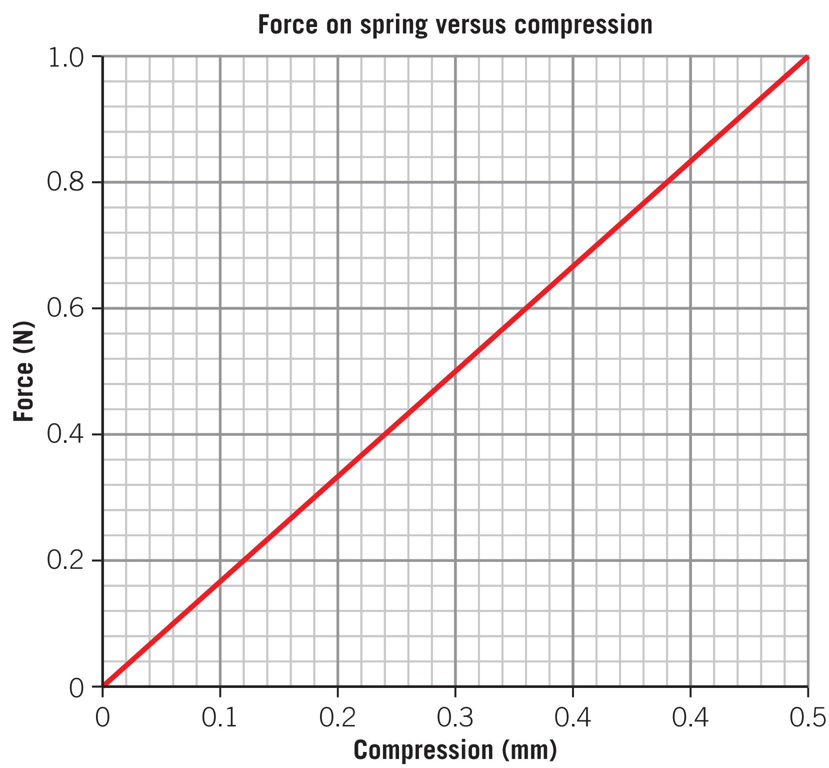


D



Use the following information to answer Questions 3 and 4.

A group of Swiss master watchmakers are testing the spring constant of a spring to be used in their watch. They measure the force against the compression of the spring and the results are shown on the right.



3 What is the spring constant of the spring?

- **A** 2000 $N\,m^{-1}$
- **B** 200 $N\,m^{-1}$
- **C** 20 $N\,m^{-1}$
- **D** 2 $N\,m^{-1}$

4 When the spring is compressed 0.3 mm, how much elastic potential energy is stored in the spring?

- **A** 9×10^{-8} J
- **B** 9×10^{-7} J
- **C** 9×10^{-6} J
- **D** 9×10^{-5} J

5 A spring that has a spring constant of 300 $N\,m^{-1}$ is already extended 10 cm. A student then stretches the spring an additional 2 cm. The amount of work that the student did to stretch the spring from 10 cm to 12 cm is equal to

- **A** 600 J
- **B** 0.66 J
- **C** 0.06 J
- **D** 0.03 J

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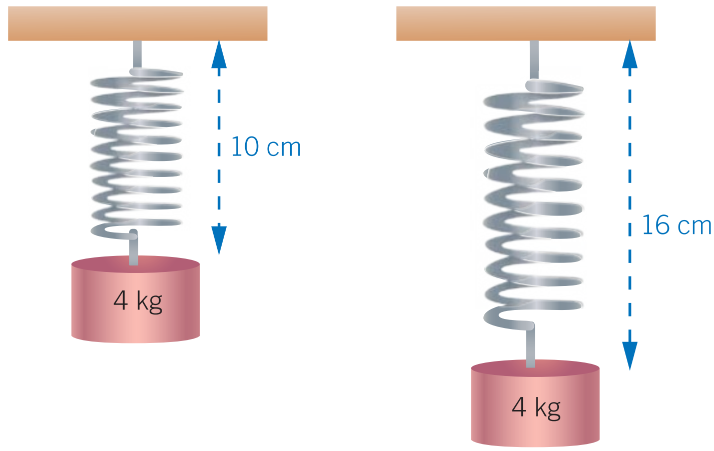
Short-answer questions

6 A spring with a natural (unextended) length of 10 cm is hung vertically and a mass of 4 kg is attached to the spring, which causes it to oscillate. At the lowest point of its oscillation, the spring has a total length of 16 cm. A diagram of this situation is shown below.

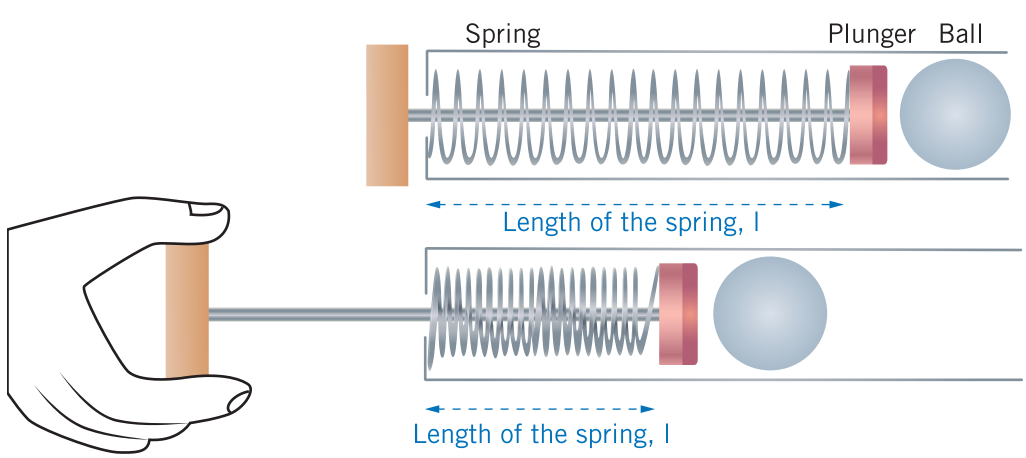


- **a** What is the length of the spring when the velocity is a maximum? Explain why this length corresponds to the maximum velocity.
- **b** Calculate the spring constant of the spring.
- **c** As the spring extends from 10 cm to 16 cm in length, describe the changes that occur in the gravitational potential energy of the mass and the elastic potential energy.
- **d** What is the maximum velocity of the mass throughout the oscillation?

7 A spring of length 0.150 m is extended by 0.05 m when a mass of 0.03 kg is hung on it.

- **a** What force does the mass exert on the spring?
- **b** How much work is done in extending the spring?
- **c** A student pulls the mass down a further 0.04 m. How much work does the student do?

8 A pinball machine uses a handle, spring and soft plunger in a cylinder to launch a ball into the machine. In the figure below, the top diagram shows the system in the rest position. In the lower diagram, a hand pulls back on the handle compressing the spring. The ball rolls back against the plunger due to the cylinder sloping very slightly downwards towards the handle end (ignore any gravitational effects).



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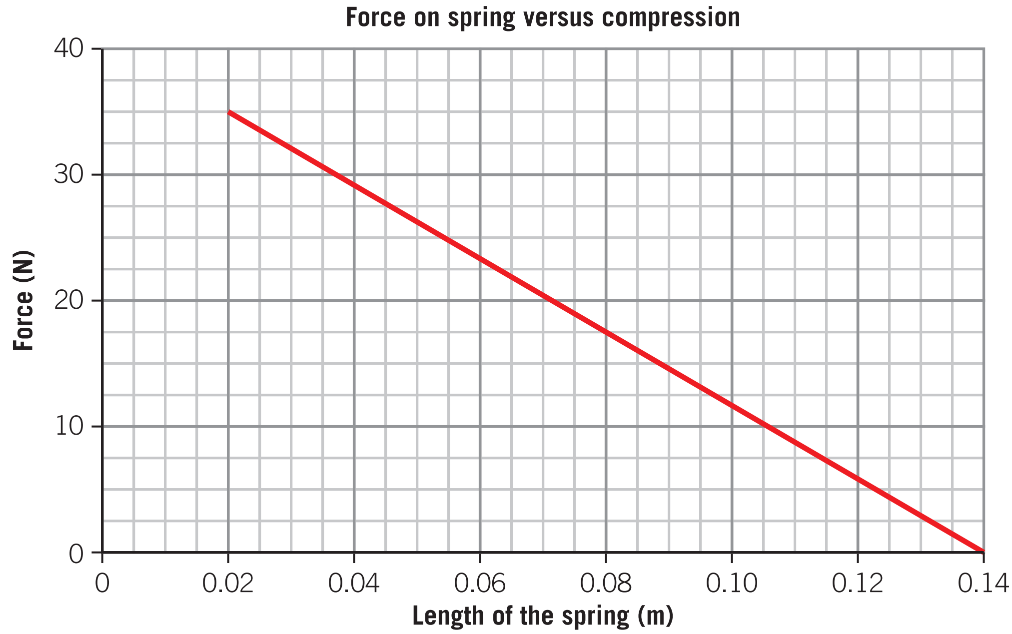
A force–length of the spring graph is shown below.



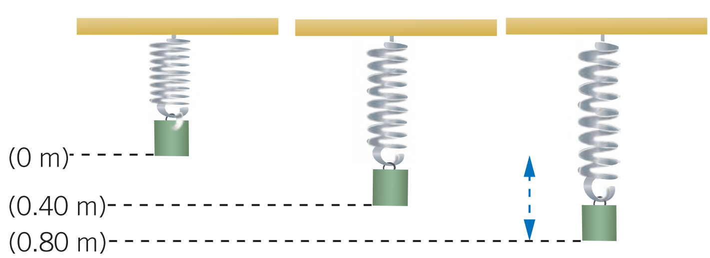
a What is the resting length of the spring?

b What is the spring constant for this spring?

c Calculate the work done to compress the spring from 0.14 m to 0.02 m.

d If the ball has a mass of 0.35 kg and the spring is compressed by 0.12 m, calculate the speed of the ball when the spring is released.

9 A mass of 2.0 kg is suspended from a spring, with spring constant $k = 50\ \text{N m}^{-1}$, as shown in the diagram below. It is released from the unstretched position of the spring and falls a distance of 0.80 m. Take the zero of gravitational potential energy at its lowest point and the gravitational field strength as $10\ \text{N kg}^{-1}$.

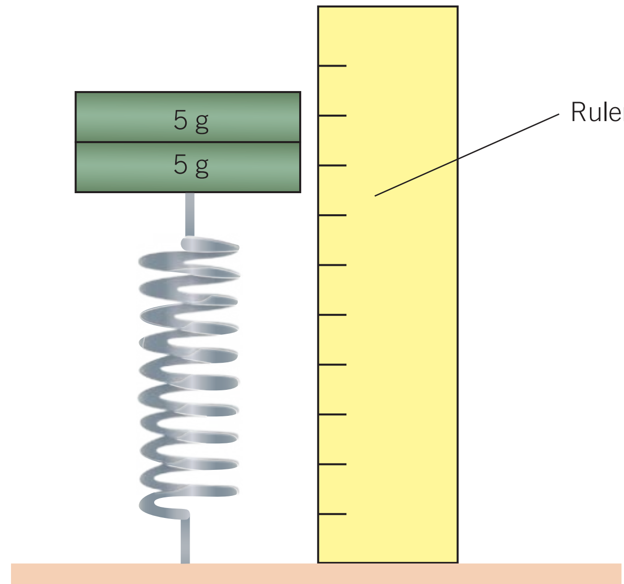


a Calculate the change in gravitational potential energy as the mass moves from the top position to the lowest position.

b Calculate the elastic potential energy at its lowest point.

c Calculate the speed of the mass at its midpoint (maximum speed).

10 A toaster manufacturer is testing springs for their latest toaster. In their design, a single spring is used in the toaster to pop a 38 gram piece of toast back up, once it has finished cooking. The engineers make and test two new springs. They test them by adding masses to springs and measuring how much the spring compressed due to the masses. The measurements are taken with a ruler that has markings every millimetre. A diagram of this situation is shown on the right.

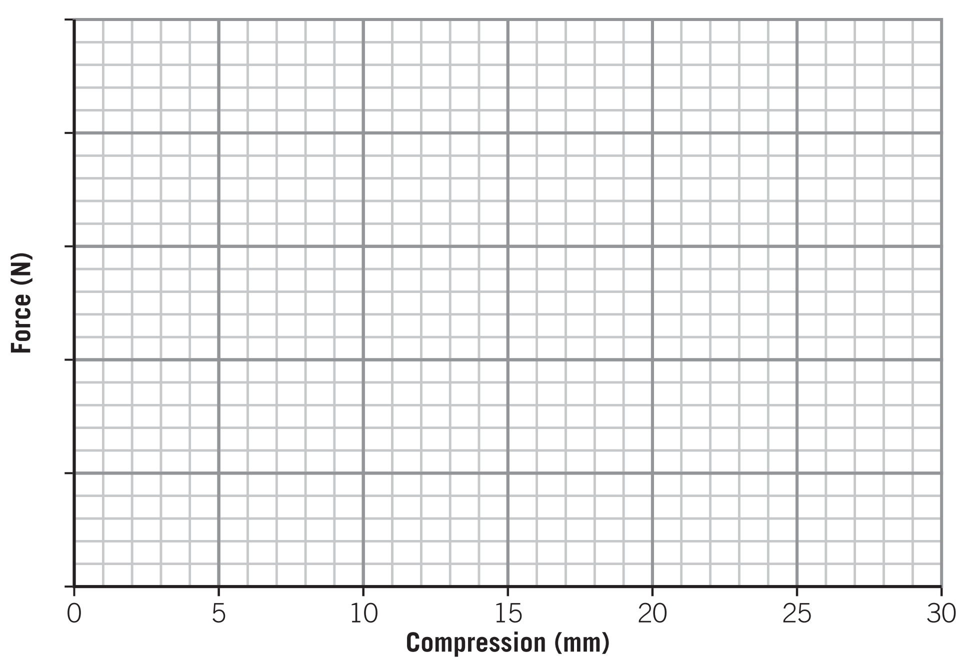


The results of their tests are shown in the table below (note that you can take gravity to be 10 $N\,kg^{-1}$ in this experiment).

Spring 1			Spring 2		
Compression (mm)	Mass (g)	Force (N)	Compression (mm)	Mass (g)	Force (N)
1.4	10		6.7	10	
2.9	20		13.3	20	
4.3	30		20.1	30	
5.7	40		26.6	40	

a Copy the table and complete the force columns of the engineer's results.

b Use the information provided in the table to graph the results on the set of axes provided below. Your graph should include an accurate scale, a line of best fit and error bars for the x-axis only.



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c List the independent and dependent variables.

d Use the line of best fit from your graph to determine the spring constant of spring 1 and spring 2.

e The engineers must consider how high the 38-gram piece of toast will be launched out of the toaster. In order to do this the engineers use the following equation to predict the height that the toast will achieve:

$$h = \frac{k\Delta x^2}{2mg}$$

Show how the engineers derived this equation.

f In the toaster, the spring will be compressed by 5 cm. Will spring 1 or spring 2 be most appropriate to use in the toaster? Use at least two calculations to justify your response.

g An engineer points out after the testing that there was a systematic error in their experiment. The engineer says that when the spring is placed vertically, it will be slightly compressed due to its own weight force. Comment on how this systematic error would affect the predicted value for the spring constant.

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Chapter 9 review

Summary

Create your own set of summary notes for this chapter on paper or in a digital document. A model summary is provided in the Teacher Resources, which can be used to compare with yours.

Checklist

In the Interactive Textbook, the success criteria are linked from the review questions and will be automatically ticked when answers are correct. Alternatively, print or photocopy this page and tick the boxes when you have answered the corresponding questions correctly.

	Success criteria – I am now able to:	Linked questions
9A.1	Understand that the useful work is only achieved by a force that is parallel to the direction of motion	2☐
9A.2	Apply the formula: $W = Fs\cos\theta$	1☐, 2☐, 14☐
9A.3	Understand and apply the fact that work is the area under a force–distance graph	6☐
9B.1	Apply the formula: $E_g = mg\Delta h$	19☐
9B.2	Apply the formula: $E_k = \frac{1}{2}mv^2$	4☐, 10☐, 13☐, 19☐
9B.3	Understand that the kinetic energy is directly proportional to velocity squared	10☐
9B.4	Apply the formula: $\Delta E_k = E_{k\ final} - E_{k\ initial} = \frac{1}{2}mv^2 - \frac{1}{2}mu^2$	7☐, 15☐
9B.5	Understand that in a closed system the total amount of energy remains the same	5☐, 11☐, 16☐, 19☐
9B.6	Apply the formula: $E_{k\ initial} + E_{g\ initial} = E_{k\ final} + E_{g\ final}$	5☐, 9☐, 11☐, 16☐, 19☐
9B.7	Apply the formula: $P = \frac{E}{t}$	3☐, 15☐
9B.8	Apply the formula: $\eta = \frac{\text{useful energy out}}{\text{total energy in}}$	14☐
9C.1	Understand that the gradient of a force–compression/extension graph is the spring constant and the area under the graph is the elastic potential energy.	12☐
9C.2	Apply the formula for Hooke's law: $F = -kx$	8☐, 11☐
9C.3	Apply the formula: $E_s = \frac{1}{2}kx^2$	11☐, 19☐
9C.4	Understand that the elastic potential energy is directly proportional to the compression/extension squared	17☐, 19☐
9C.5	Understand that elastic potential energy can be transformed into other types of energy	11☐, 12☐, 13☐, 17☐
9C.6	Be able to describe the energy transformations that occur in vertical and horizontal oscillating springs	18☐

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Multiple-choice questions

1 A toy electric car has an electric motor that applies a constant force of 200 N. If the car travels a distance of 325 m, the work that the motor does on the car is

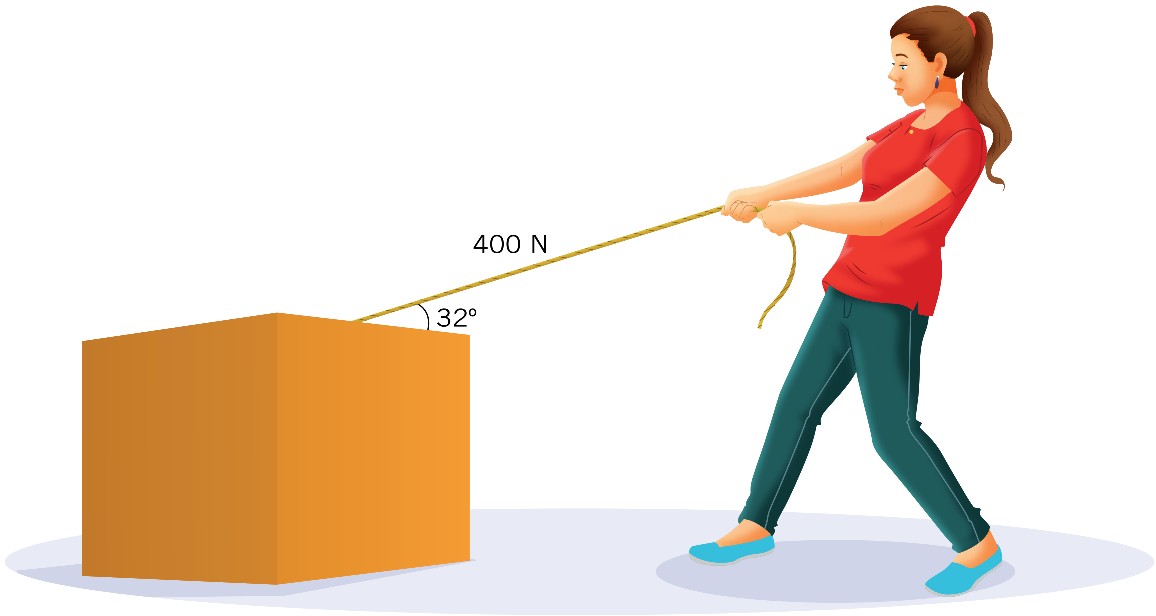
A 1.63 J

B 3.25×10^3 J

C 6.50×10^3 J

D 6.50×10^4 J

2 A woman is pulling a heavy box with a force of 400 N at an angle of 32° from the horizontal, as shown below.



How much work does the woman do on the box if she drags it 45 m in a straight line?

A 1.53×10^4 J

B 1.80×10^4 J

C 3.20×10^4 J

D 6.40×10^4 J

3 The current 1-hour cycling world record is 55.1 km, held by Sir Bradley Wiggins. To break this record, he held a power output of 440 W for the full hour. The amount of energy that he used for this hour is equal to:

A 440 J

B 2.64×10^4 J

C 2.42×10^5 J

D 1.58×10^6 J

4 How much kinetic energy does a car of mass 1110 kg, moving at a speed of 90 $\mathrm{km\,h^{-1}}$ have?

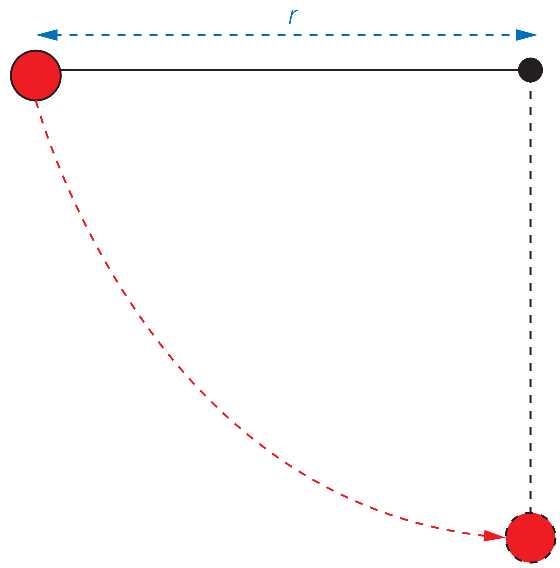
A 1.39×10^4 J

B 5.00×10^4 J

C 3.47×10^5 J

D 4.50×10^6 J

5 A pendulum with radius, r, is dropped from a horizontal position and moves down to a vertical position. A diagram of this situation is shown below.



The speed of the pendulum when it reaches the vertical position is equal to

A $\sqrt{\frac{gr}{2}}$

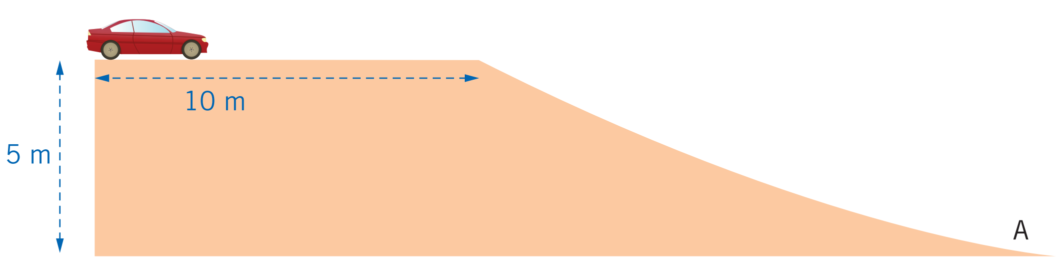
B $\sqrt{2gr}$

C gr

D $2gr$

Use the following information to answer Questions 6 and 7.

Some students wake up to find that the battery of their manual car is flat and they cannot start their engine. They find out that they can roll start their car as the motion of the wheels will transfer to the pistons, and if the car is moving fast enough it can cause the car to start. To do this, the students push the car straight for 10 m and then let it roll down a short hill. A diagram of this situation is shown below.



The force–displacement graph for the 10 m that the students push the car is shown next.

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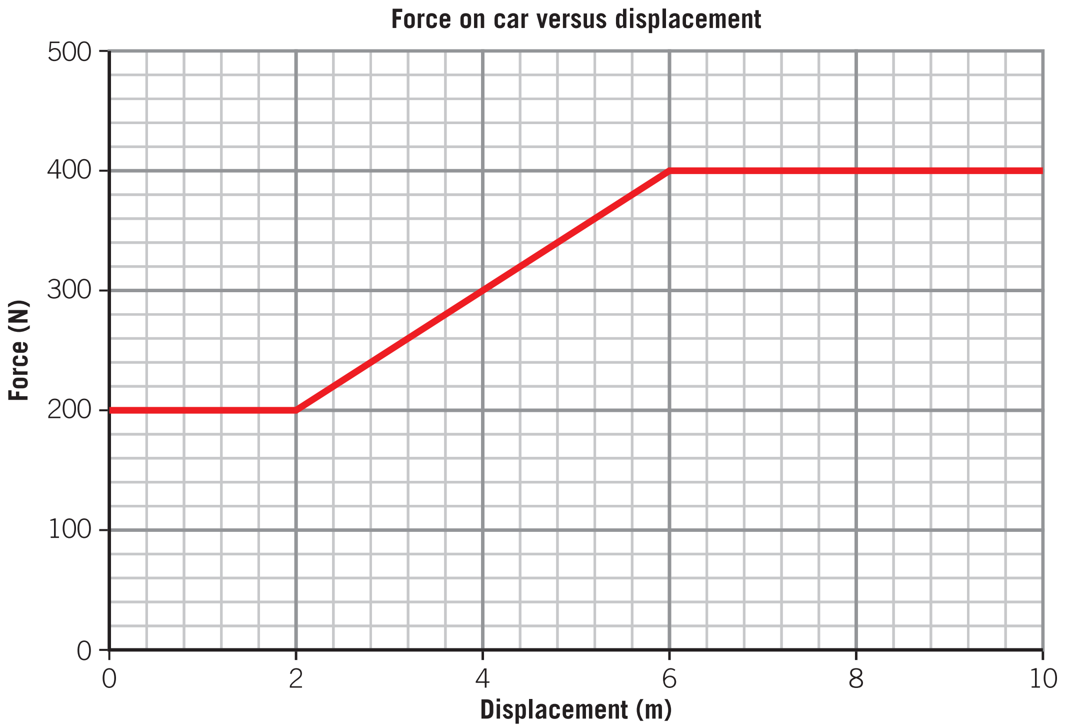


6 Which of the following is closest to the amount of work done to push the car to the edge of the hill.

A 320 J

B 3200 J

C 32000 J

D 320 000 J

7 Once the students have finished pushing the car, it goes over the edge of the hill with a speed of 9 $km\,h^{-1}$. Which of the following is closest to the speed of the car when it has rolled down the hill and passes point A. You can ignore air resistance in your calculations.

A 10.2 $km\,h^{-1}$

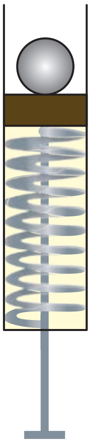
B 13.4 $km\,h^{-1}$

C 36.8 $km\,h^{-1}$

D 54.2 $km\,h^{-1}$

Use the following information to answer Questions 8 and 9.

A spring inside a cylinder launches a steel ball of mass 30 g into the air. Apply a force of 40 N is needed to compress the spring 0.2 m.



8 What is the spring constant of the spring?

A 800 $N\,m^{-1}$

B 400 $N\,m^{-1}$

C 200 $N\,m^{-1}$

D 100 $N\,m^{-1}$

9 If the spring is compressed by 25 cm, what is the maximum velocity achieved by the ball? Hint: You need to consider the slight change is gravitational potential energy as the spring pushes up the steel ball.

A 40.8 $m\,s^{-1}$

B 20.4 $m\,s^{-1}$

C 20.3 $m\,s^{-1}$

D 20.2 $m\,s^{-1}$

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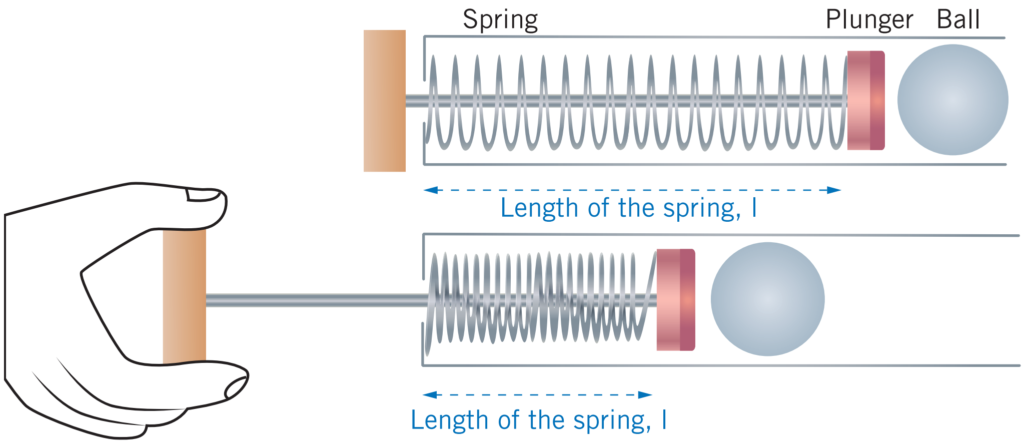
10 If a runner doubles their speed, then their kinetic energy will
- **A** stay the same.
- **B** double.
- **C** triple.
- **D** quadruple.

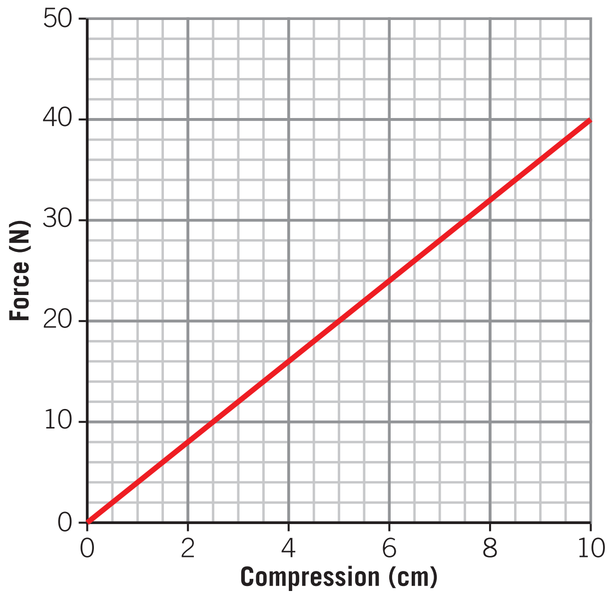
Short-answer questions

11 An archer fires a bow directly up. In order to do this, they pull the bow back by 25 cm. The bow has a spring constant of 500 $\mathrm{N\,m^{-1}}$ and the arrow has a mass of 18 g.
- **a** Calculate the force required by the archer to hold the bow in place. (2 marks)
- **b** Calculate the elastic potential energy stored in the bow when it is pulled back by 25 cm. (2 marks)
- **c** Calculate the maximum height achieved by the arrow from the point of its release. (3 marks)

12 A pinball machine uses a handle, spring and soft plunger to launch a ball into the machine. This is shown in the diagram below.



A force-compression graph of this spring is shown below.



- **a** Calculate the spring constant of this spring. (2 marks)
- **b** How much elastic potential energy is stored in the spring when the force on the spring is 30 N? (2 marks)

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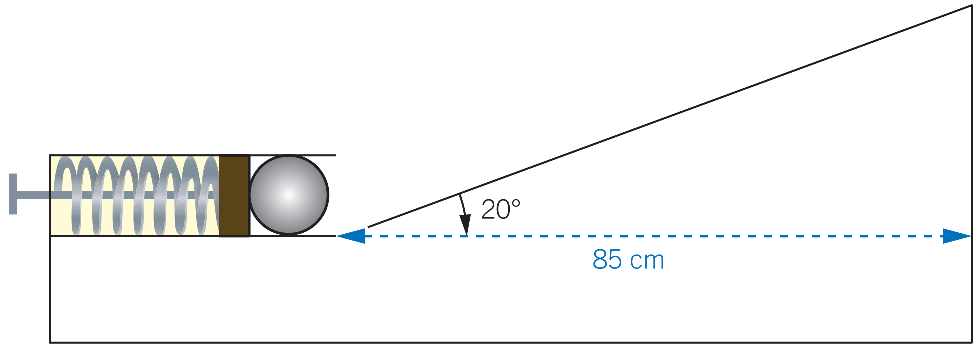
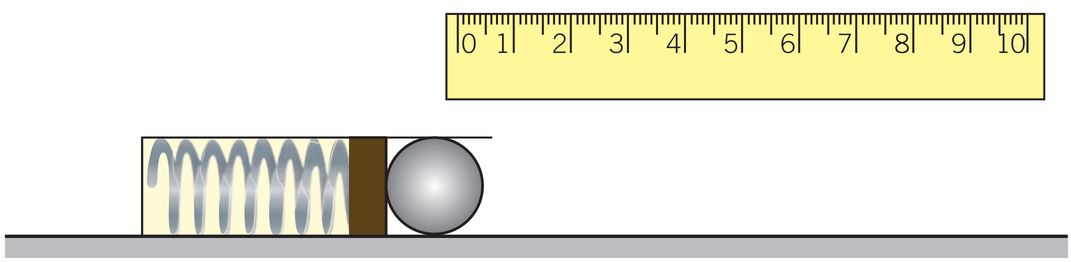
The same spring mechanism is used to launch a ball up an incline as shown below.



The ball has a mass of 0.150 kg.

c If the spring is compressed by 10 cm and then released, what is the velocity of the ball when it reaches the end of the incline? (3 marks)

13 Some arcade game designers are manufacturing a spring to launch a ball from a pinball machine. They test the spring by compressing it by varying amounts and placing a pinball of mass 80 g up to the compressed spring. Then they release the spring and measure the speed with which the pinball leaves the spring. They measure the velocity by timing how long it takes the ball to travel 10 cm and then apply the formula $v = \frac{d}{t}$. A diagram of this set-up is shown below.



The designers collect the results shown in columns 1 and 2 of the table.

Compression (m)	Compression squared (m^2)	Velocity ($m\,s^{-1}$)	Kinetic energy (J)
0.02		2.7	
0.04		5.5	
0.06		8.2	
0.08		11.0	

a Copy the table and complete the values for the compression squared and the kinetic energy. Round your answers to one decimal place. (3 marks)

b Draw a graph of the kinetic energy vs the square of the compression of the spring on a copy of the grid shown at the top of the next page. Include a line of best fit. (2 marks)

c Calculate the gradient of the line of best fit of your graph. (2 marks)

d Use your answer from part **c** to calculate the spring constant, *k*, of the spring. (3 marks)

e One of the designers states that the way they measured velocity is inaccurate. Other than inaccuracies in timing, explain why the measurement of the velocity is inaccurate, state its effect on the predicted values of the spring constant and suggest a way to reduce this error. (3 marks)

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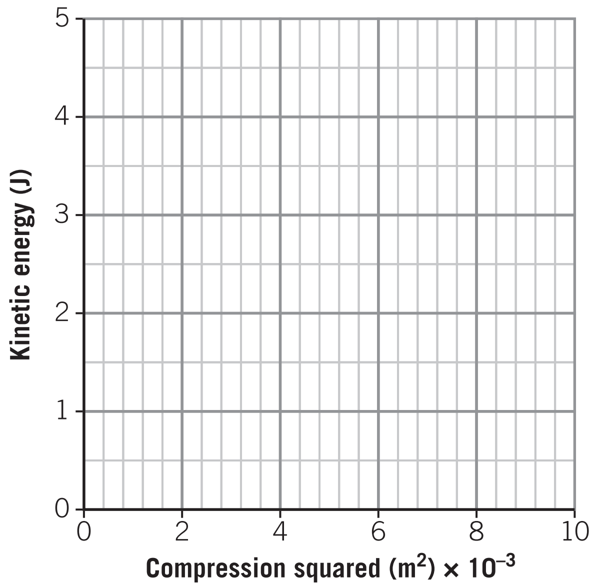
Make a copy of this grid to plot kinetic energy vs the square of the compression of the spring in Question 13b.



14 Blacksmiths use a giant pneumatic hammer to bend and shape large pieces of metal. It takes 1 GJ of energy for one strike of the hammer. When the hammer falls, it does so with a constant total force of 450 MN and covers a distance of 1.5 m.

a Calculate the work done by the hammer as it falls. (1 mark)

b Calculate the energy efficiency of the hammer. (2 marks)

15 A car of mass 960 kg accelerates from 45 km h^{-1} to 81 km h^{-1} in 3 seconds.

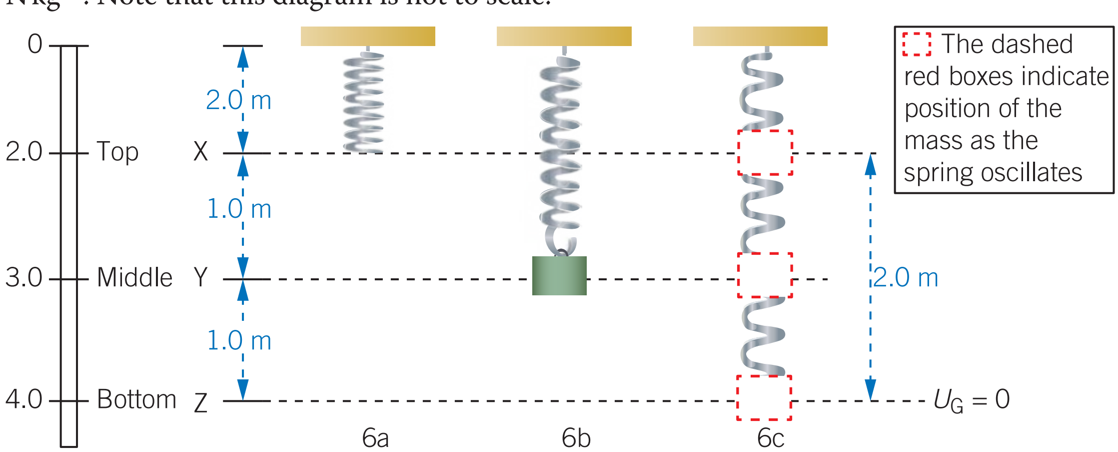
a Calculate the amount of work done on the car by the engine. (3 marks)

b Calculate the power of the car's engine during this time. (2 marks)

c If this car is 30% efficient and each millilitre (mL) of petrol contains 48.5 kJ of energy, calculate how many millilitres of fuel are used to accelerate the car. (3 marks)

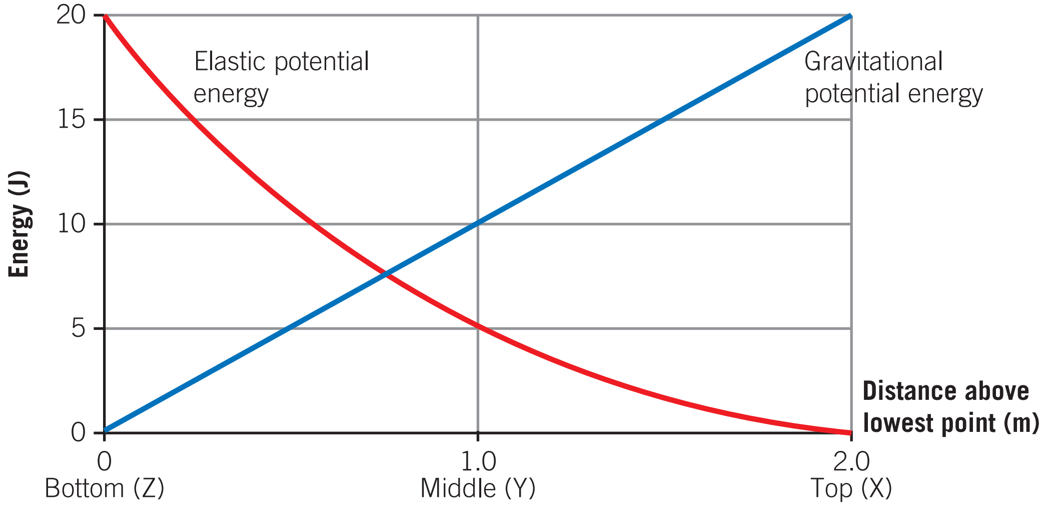
16 A person of mass 60 kg climbs a water slide that is 30.5 m tall. At the top of the slide, the person pushes off the railing, giving themselves an initial velocity of 0.56 m s^{-1}. Calculate the velocity of the person as they exit the bottom of the water slide. For this question, assume that friction is negligible. (2 marks)

17 Students hang a mass of 1.0 kg from a spring that obeys Hooke's law with k = 10 N m^{-1}. The spring has an unstretched length of 2.0 m. The mass then hangs stationary at a distance of 1.0 m below the unstretched position (X) of the spring, at Y, as shown at position 6b in the diagram below. The mass is then pulled a further 1.0 m below this position and released so that it oscillates, as shown in position 6c. Assume the gravitational field strength to be 10 N kg^{-1}. Note that this diagram is not to scale.



The zero of gravitational potential energy is taken to be bottom point, Z.

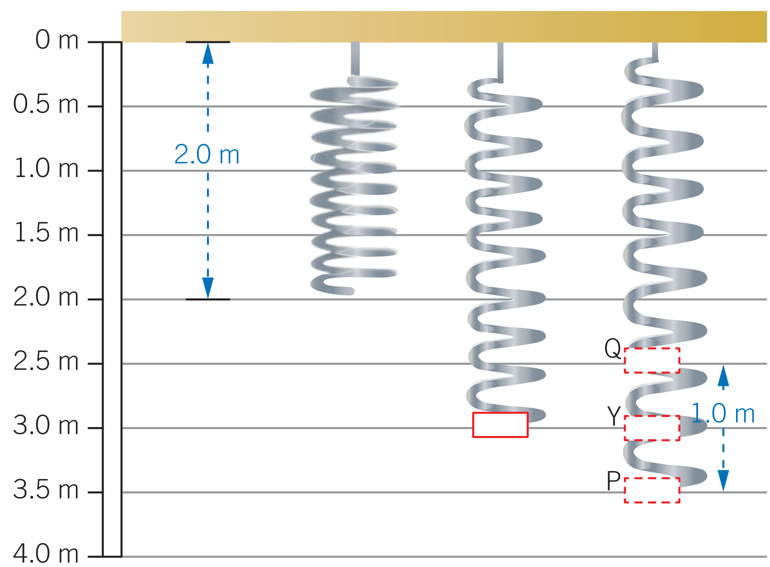
The elastic potential energy and gravitational potential energy are plotted on a graph, as shown in the diagram below.



a Calculate the total energy of the system when the mass is at its lowest point, Z. (1 mark)

b From the data in the graph, calculate the speed of the mass at its midpoint, Y. (2 marks)

Without making any other changes, the students now pull the mass down to point P, 0.50 m below Y. They release the mass and it oscillates about Y, as shown right.



The students now take the zero of gravitational potential energy to be at P and the zero of elastic potential energy to be at Q. They expect the total energy at P to be equal to the total energy at Q.

They prepare the following table.

Position	Gravitational potential energy, E_g	Elastic potential energy, E_s	Kinetic energy, E_k
Q	$E_g = mgh$ $= 1.0 \times 10 \times 1.0$ $= 10$ J	$E_s = 0$	$E_k = 0$
P	$E_g = 0$	$E_s = \frac{1}{2}k(\Delta x)^2$ $= \frac{1}{2} \times 10 \times 1.0^2$ $= 5.0$ J	$E_k = 0$

However, their calculation of the total energy ($E_g + E_s + E_k$) at Q (10 J) is different from their calculation of the total energy at P (5.0 J).

c Explain the mistake that the students have made. (3 marks)

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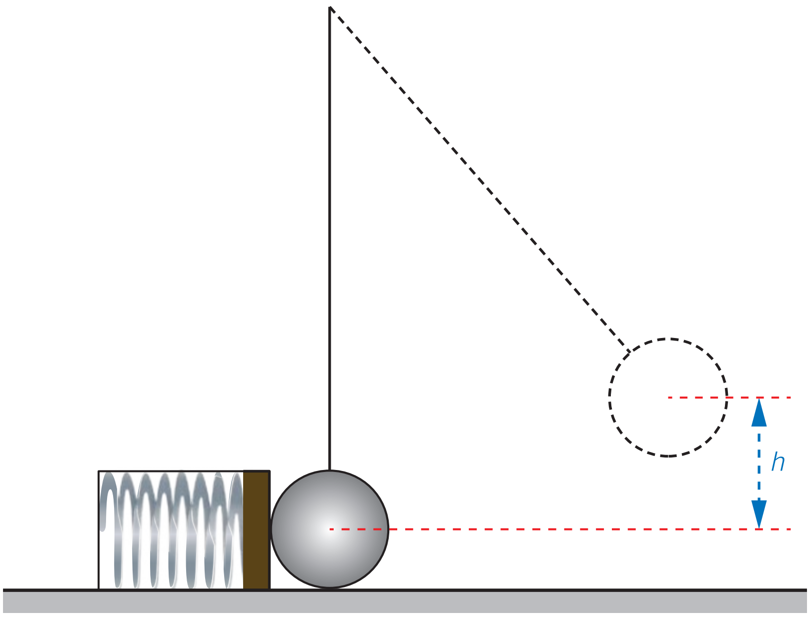
18 A spring fixed at one end and with a mass attached at the other end is placed horizontally on a polished surface that can be considered frictionless. The mass is then pulled, extending the spring, then released and allowed to oscillate freely. Describe the changes to elastic potential energy and kinetic energy that occur as the spring goes from a fully extended to a fully compressed position. The spring works the same in extension and compression. (5 marks)

19 Rob and Sophia have set up an energy transfer experiment. In this experiment, a steel ball, that has a mass of 45 g, is hung from the ceiling via a piece of string and then placed next to a loaded spring. The spring is compressed by 5 cm and is held in place by a force of 0.725 N. When the spring is released, it transfers all of its energy to the steel ball, which swings up in an arc. A diagram of this experimental set-up is shown below.



a Show that the elastic potential energy of the spring is 1.81×10^{-2} J when it is compressed by 5 cm. (2 marks)

b Calculate the velocity of the steel ball once the spring is fully extended. Assume that all of the energy of the spring is transferred to the ball. (2 marks)

c Determine the maximum height achieved by the ball. (2 marks)

d What is the velocity of the ball at its maximum height? Explain your answer. (2 marks)

e The students want to double the amount of initial spring potential energy. Rob suggests doubling the compression so that the elastic is compressed by 10 cm. Sophia disagrees and says that the spring need only be compressed to 7 cm. Who is correct? Justify your answer. (2 marks)

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Unit 2 Revision exercise

Multiple-choice questions

1 Which of the following is not a scalar?
A 20 m s^{-1}
B 9.8 m s^{-2} down
C 50 mL
D both A and B

2 When a male lion is running at its top speed of 80.5 km h^{-1}, it has a momentum of 4.25×10^3 kg m s^{-1}. What is the mass of the lion?
A 190 kg
B 165 kg
C 96.3 kg
D 52.8 kg

3 A 290 kg zebra that is travelling at 10 m s^{-1} has a kinetic energy of 1.45×10^4 J. The zebra then accelerates from 10 m s^{-1} to 20 m s^{-1}. The increase in kinetic energy is
A 1.45×10^4 J
B 2.90×10^4 J
C 4.35×10^4 J
D 5.80×10^4 J

4 An athlete in the Winter Olympics pushes on a bobsleigh with a constant force of 260 N for 30 m. If the athlete pushes parallel to the direction of motion, the amount of work done is
A 290 J
B 3900 J
C 5600 J
D 7800 J

5 In which of the following situations is the greatest amount of work being done?
A A 2500 kg satellite orbits Earth at a constant distance of 2000 km above Earth's surface.
B A person is holding a 200 kg weight at waist height.
C A person applies a force of 30 N for 0.25 m to slide a bag across a kitchen bench.
D A person applies a force of 400 N perpendicular to the direction of motion of a 250 kg object.

Use the following information to answer Question 6 and 7.

A soccer ball that has a mass of 450 g is kicked north against a brick wall at 10 m s^{-1}. The ball rebounds after the collision and travels south at 8.00 m s^{-1}.

6 The change in momentum of the soccer ball is
A 2 kg m s^{-1} south
B 8.1 kg m s^{-1} south
C 18.5 kg m s^{-1} south
D 8100 kg m s^{-1} south

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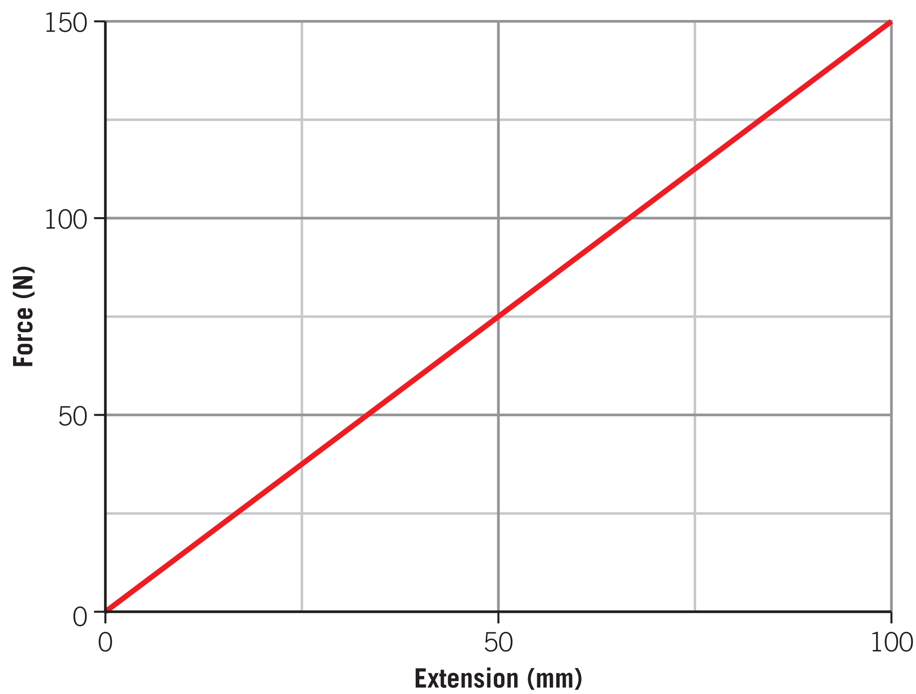
7 If the soccer ball is in contact with the wall for 5 ms, the average force that the ball applies to the wall is

A 6.17×10^{-3} N south
B 0.617 N south
C 1.62 N south
D 1620 N south

Use the following information to answer Question 8 and 9.

The graph below shows the force–extension graph for an ideal spring.



8 What is the spring constant of this spring?

A $1500\ \mathrm{N\,m^{-1}}$
B $150\ \mathrm{N\,m^{-1}}$
C $1.50\ \mathrm{N\,m^{-1}}$
D $1.50 \times 10^{-3}\ \mathrm{N\,m^{-1}}$

9 If the spring is extended by 100 mm in 1.5 seconds, how much power did the person extending the spring have?

A 150 W
B 15.0 W
C 7.50 W
D 5.00 W

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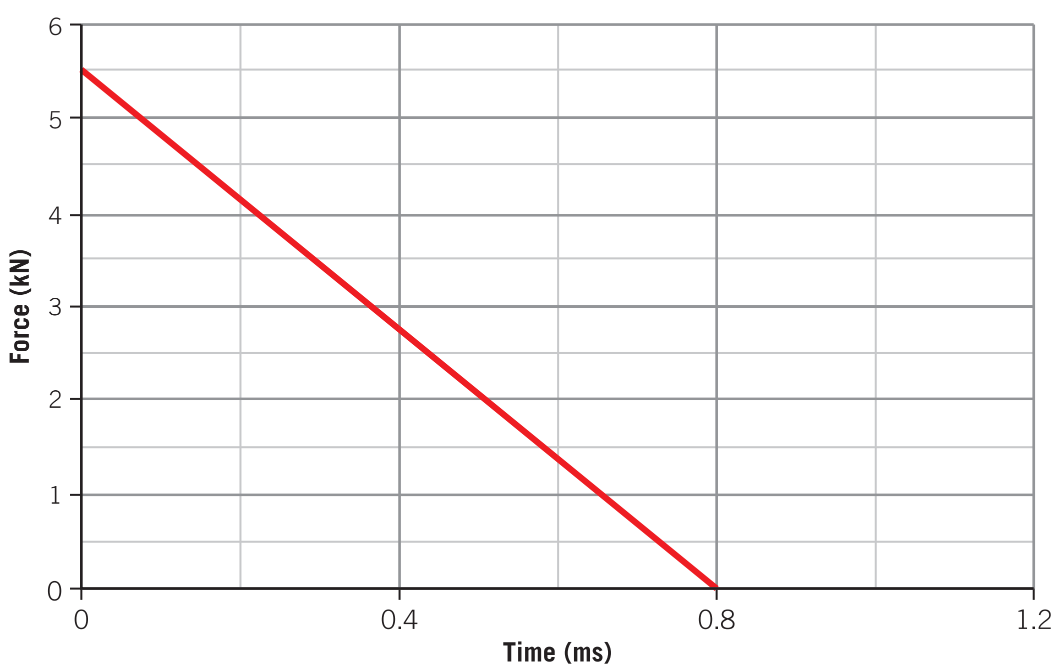
Short-answer questions

10 In a classroom demonstration a 50 g projectile is fired at 45 $m\,s^{-1}$ into a stationary 4 kg block of wood that is suspended by a string. When the projectile hits the block of wood, it lodges in it and the two objects move as one. Since the block is suspended by a string, it moves up as a result of the collision and reaches a maximum height of *h*. A diagram of this situation is shown below.

a Assuming that no energy is lost in the collision or due to air resistance, what is the theoretical maximum height, *h*, that the block and projectile system can reach? (2 marks)

The projectile contained a sensor that measured the force on it as a function of time. The force–time data was collected during the collision and is displayed on the force–time graph below. (Note: the *x*-intercept is 0.808 ms.)



b What is the change in momentum of the projectile if it is initially travelling south. Give a magnitude and direction in your answer. (3 marks)

c What is speed of the projectile–block system after the collision? (3 marks)

d Will the block reach its theoretical maximum height? Justify your answer. (3 marks)

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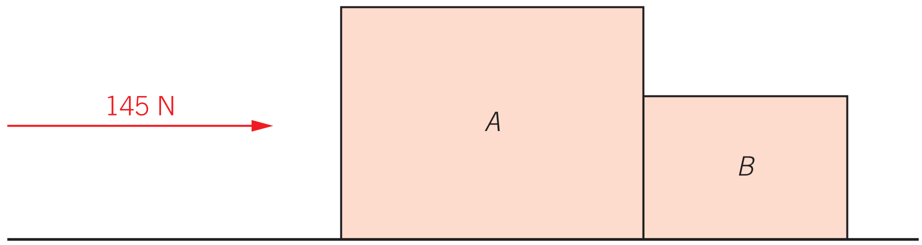
11 Two blocks, *A* and *B*, have masses of 15 kg and 7.50 kg respectively and are resting on a frictionless surface. An external force of 145 N north pushes on block *A*, which is in direct contact with block *B*. The two blocks move as one as a result of the external force. A diagram of this situation is shown below.



a Calculate the acceleration of the system. (2 marks)

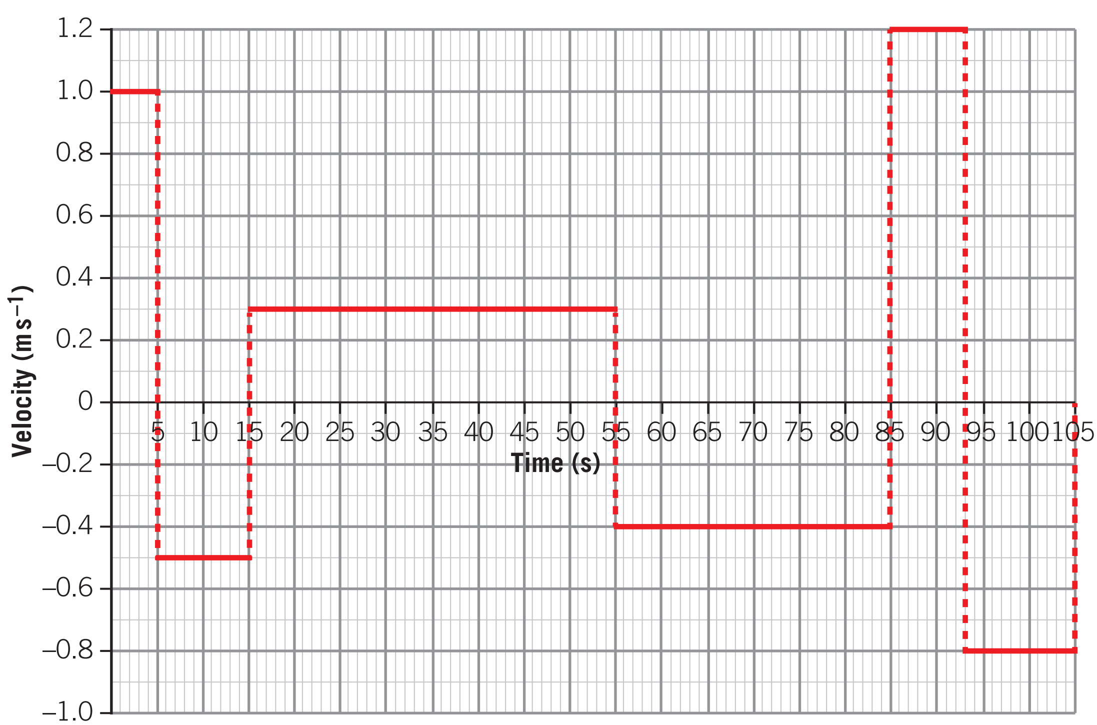
b Calculate the magnitude and direction of the force on block *A* due to block *B*. (3 marks)

12 In the 1970s the Australian Government passed laws to make wearing seatbelts while driving a vehicle compulsory. This led to a dramatic decrease in the number of road deaths.

a Explain, using Newton's laws of motion, why seatbelts help to protect the occupant during a car crash. (3 marks)

b Modern seatbelts have a mesh-like design that allows them to stretch slightly during a car crash. Explain, using your knowledge of motion concepts, why modern seatbelts are designed to stretch slightly in a collision. (3 marks)

13 On a Moon landing, an astronaut walked due east from the lunar module (a vehicle designed to take astronauts to and from the lunar surface), collected some Moon rocks and then walked back to the lunar module to deposit the rocks. The astronaut then made several more round trips, each time walking different distances east. The velocity–time graph for the astronaut is shown below.



a What was the total distance covered by the astronaut? (3 marks)

b How many trips did the astronaut make? (1 mark)

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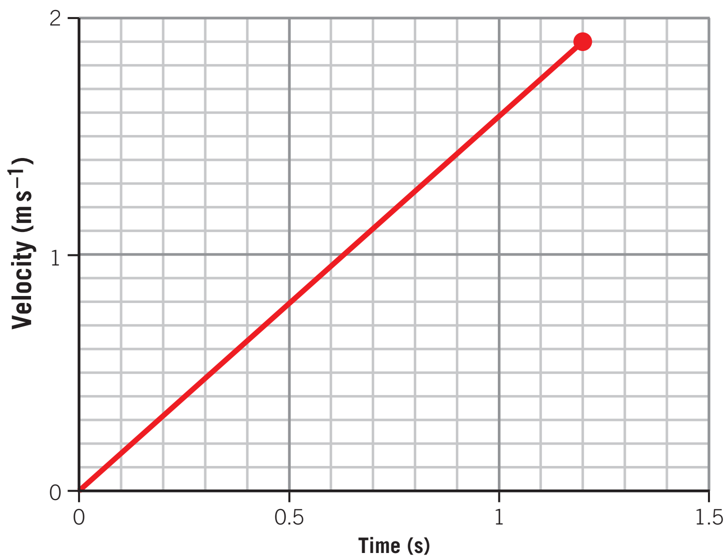
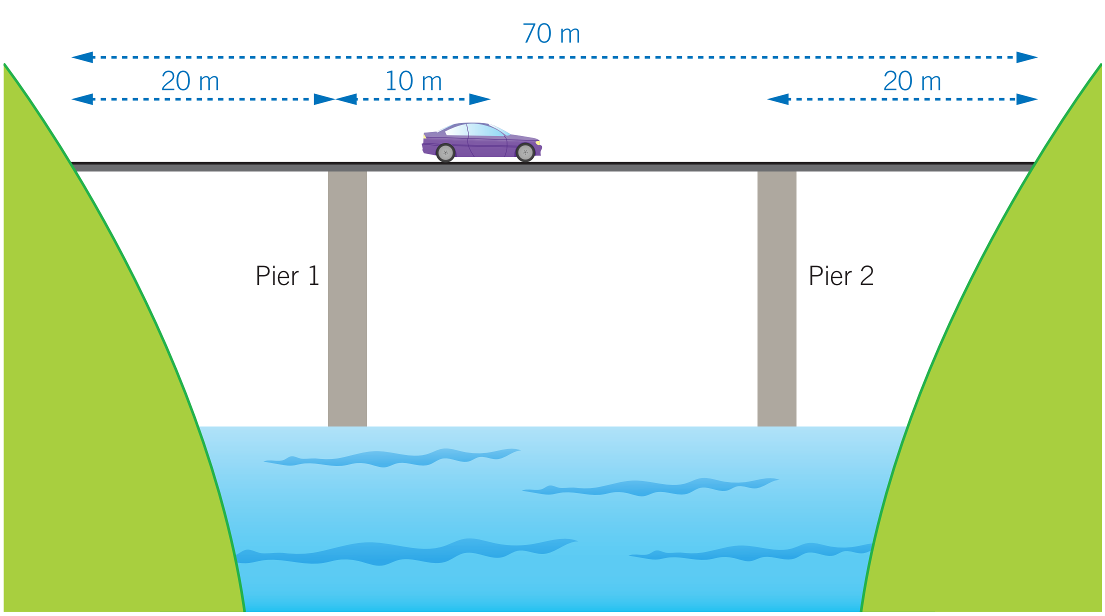
While walking, the astronaut drops a lunar rock that has a mass of 0.462 kg. His head camera captures a video of the falling rock and this video is used to accurately plot the velocity–time graph of the rock falling down for 1.2 seconds, which is shown below.



c If after 1.2 seconds the rock hits the surface of the Moon, calculate the height above the Moon's surface that the rock was dropped from. (2 marks)

d Use the graph to calculate the gravitational acceleration on the surface of the Moon. (2 marks)

14 A beam bridge is the simplest structural form of a bridge. It is composed of piers supporting a beam that allows traffic to pass over it. A group of engineers constructed a beam bridge to allow traffic to cross a river. The bridge has a uniform beam that spans 70 m and has a mass of 4.2×10^4 kg. The bridge is supported by two piers, the piers are positioned 20 m away from where the beam attaches to the land on both sides. A car that has a mass of 1250 kg is crossing the bridge. Consider the point when the car is 10 m away from the pier to the left, Pier 1, as shown in the diagram below.



a Calculate the upwards force that Pier 2 applies on the beam. (3 marks)

b Calculate the upward force that Pier 1 applies on the beam. (2 marks)

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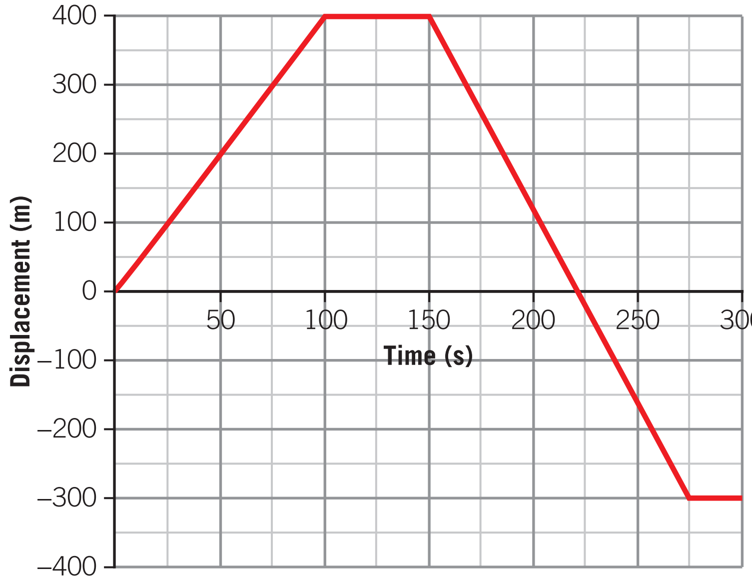
15 A trail runner is going on a training run. They run east from their starting position before reaching a turnaround point and run back west past the starting point. A displacement–time graph of the runner's journey is shown below.



a When was the runner stationary during the 300-second run? (1 mark)

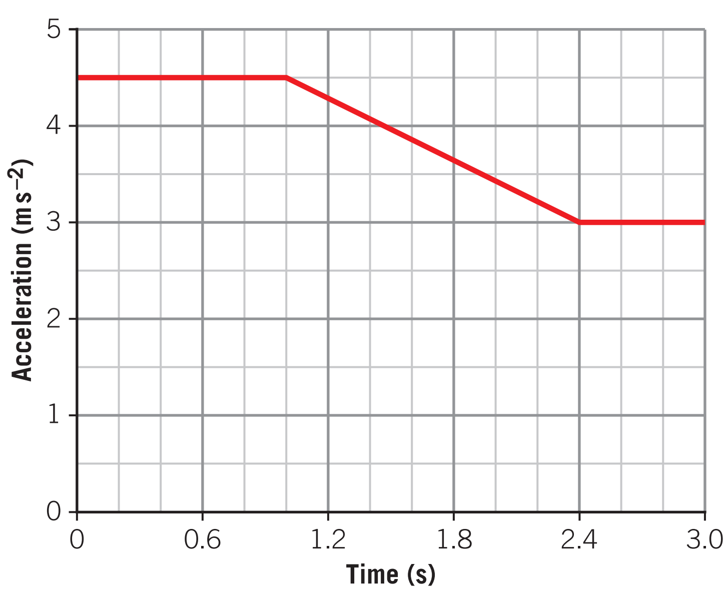
b When did the runner start running west? (1 mark)

c What is the total distance covered by the runner? (2 marks)

d What was the trail runner's maximum speed on the run? (2 marks)

e After the training run, the trail runner challenges their friend, Adam, to a race. Adam is not as fast as the trail runner so they agree that Adam will start 20 m back from the start line so that he can reach his top speed of 4.85 $m\,s^{-1}$. When Adam is in line with the trail runner, the trail runner sets off and accelerates at a constant rate of 4.22 $m\,s^{-2}$. How much time passes before the trail runner catches up with Adam? (3 marks)

After the race, the trail runner is tired but their watch has an accelerometer to measure acceleration as a function of time and they keen to test it out. The runner turns the accelerometer on and then sprints from rest for 3 seconds. The acceleration–time graph of their sprint is shown below.



f What is the trail runner's velocity at the end of the 3 seconds? (2 marks)

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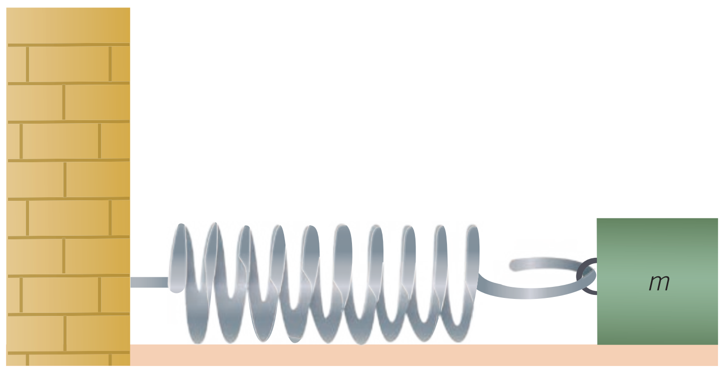
16 Two students are discussing the action and reaction pairs of forces as a person stands on the surface of Earth. Toby states that if the action force is the weight force of the person due to gravity then the reaction force is the force that the surface of Earth applies on the person. Georgia disagrees and states that the reaction force is the gravitational force of attraction that acts on Earth to the centre of the person. Who is correct? Justify your answer. (3 marks)

17 An ideal spring that has a spring constant of 650 $\mathrm{N\,m^{-1}}$ is attached horizontally to a wall and has a 1.48 kg mass, m, attached to it. The spring is then compressed by 1 cm and allowed to oscillate freely.



a What force does the spring exert when it is compressed by 1 cm? (1 mark)

b The spring is on a frictionless floor and oscillates continually. Explain how this back and forth motion is maintained. (4 marks)

c The period of the oscillation is the time taken for the mass to return to its original position. In this spring system, the period is 0.3 seconds. Assuming at $t = 0$ the spring has maximum compression, draw the kinetic energy–time graph for one complete oscillation. (3 marks)

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Appendix 1: Overview of online extra material

Unit 2 Options online

Curriculum

Unit 2: How does physics help us to understand the world?

Area of Study 2

Options: How does physics inform contemporary issues and applications in society?

See list below of options included

Options in the Interactive Textbook

The Interactive Textbook provides a concise resource for each of 11 options chosen from the list of 18 options in the study design. The eleven are:

- Option 2.1: How does physics explain climate change?
- Option 2.3: How do heavy things fly?
- Option 2.4: How do forces act on structures and materials?
- Option 2.8: How can human vision be enhanced?
- Option 2.9: How is physics used in photography?
- Option 2.10: How do instruments make music?
- Option 2.11: How can performance in ball sports be improved?
- Option 2.13: How do astrophysicists investigate stars and black holes?
- Option 2.14: How can we detect possible life beyond Earth's Solar System?
- Option 2.15: How can physics explain traditional artefacts, knowledge and techniques?
- Option 2.17: How does physics explain the origins of matter?

Content of the online resources for the options

- Learning objectives and success criteria
- Concise treatment of content
- Suggested activities and investigations
- Worked examples where required
- Links to further information and resources
- Questions linked to success criteria, with answers

Access in the Interactive Textbook

These optional resources are presented for students in downloadable PDF format. Navigate to the offline textbook (the PDF textbook) where they will be found in the contents list. Teachers' copies are located in the Teacher resources pane.

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Practical investigations online

Curriculum

Key science skills

- Develop aims and questions, formulate hypotheses and make predictions
- Plan and conduct investigations
- Comply with safety and ethical guidelines
- Generate, collate and record data
- Analyse and evaluate data and investigation methods
- Construct evidence-based arguments and draw conclusions
- Analyse, evaluate and communicate scientific ideas

Scientific investigation

- Scientific investigation methodologies
- Logbooks

Unit 2: How does physics help us to understand the world?

Area of Study 3 How do physicists investigate questions?

- Investigation design
- Scientific evidence
- Science communication

Key Science Skills in Senior Science

This section is an additional resource for generic key science skills used across all senior science subjects.

Practical investigations in VCE Physics

This section provides detailed coverage of Unit 2 Area of Study 3 How do physicists investigate questions?

Access in the Interactive Textbook

These optional resources are presented for students in downloadable PDF format. Navigate to the offline textbook (the PDF textbook) where they will be found in the contents list. Teachers' copies are located in the Teacher resources pane.

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Appendix 2: Formulas and data

Formula and data sheet

This formula and data sheet is based on the 2023–2027 Study Design, and when the official VCAA Formula Sheet is published, students should refer to that for assessment and examinations.

Motion and related energy transformations	
velocity; acceleration	$v = \frac{\Delta s}{\Delta t}$; $a = \frac{\Delta v}{\Delta t}$
equations for constant acceleration	$v = u + at$ $s = ut + \frac{1}{2}at^2$ $s = vt - \frac{1}{2}at^2$ $v^2 = u^2 + 2as$ $s = \frac{1}{2}(v + u)t$
Newton's second law	$\Sigma F = ma$
circular motion	$a = \frac{v^2}{r} = \frac{4\pi^2 r}{T^2}$
Hooke's law	$F = -k\Delta x$
elastic potential energy	$\frac{1}{2}k(\Delta x)^2$
gravitational potential energy near the surface of Earth	$mg\Delta h$
kinetic energy	$\frac{1}{2}mv^2$
Newton's law of universal gravitation	$F = G\frac{m_1 m_2}{r^2}$
gravitational field	$g = G\frac{M}{r^2}$
impulse	$F\Delta t$
momentum	mv
Lorentz factor	$\gamma = \frac{1}{\sqrt{1 - \frac{v^2}{c^2}}}$
time dilation	$t = t_o \gamma$
length contraction	$L = \frac{L_o}{\gamma}$
rest energy	$E_{rest} = mc^2$
relativistic total energy	$E_{total} = \gamma mc^2$
relativistic kinetic energy	$E_k = (\gamma - 1)mc^2$

Fields and application of field concepts	
electric field between charged plates	$E = \frac{V}{d}$
energy transformations of charges in an electric field	$\frac{1}{2}mv^2 = qV$
field of a point charge	$E = \frac{kq}{r^2}$
force on an electric charge	$F = qE$
Coulomb's law	$F = \frac{kq_1q_2}{r^2}$
magnetic force on a moving charge	$F = qvB$
magnetic force on a current carrying conductor	$F = nIlB$
radius of a charged particle in a magnetic field	$r = \frac{mv}{qB}$

Generation and transmission of electricity	
voltage; power	$V = RI;\ P = VI = I^2R$
resistors in series	$R_T = R_1 + R_2$
resistors in parallel	$\frac{1}{R_T} = \frac{1}{R_1} + \frac{1}{R_2}$
ideal transformer action	$\frac{V_1}{V_2} = \frac{N_1}{N_2} = \frac{I_2}{I_1}$
AC voltage and current	$V_{RMS} = \frac{1}{\sqrt{2}}V_{peak}$ $\quad I_{RMS} = \frac{1}{\sqrt{2}}I_{peak}$
electromagnetic induction	EMF: $\varepsilon = -N\frac{\Delta\Phi_B}{\Delta t}$ flux: $\Phi_B = B_\perp A$
transmission losses	$V_{drop} = I_{line}R_{line}$ $\quad P_{loss} = I^2_{line}R_{line}$

Wave concepts	
wave equation	$v = f\lambda$
constructive interference	path difference $= n\lambda$
destructive interference	path difference $= \left(n - \frac{1}{2}\right)\lambda$
fringe spacing	$\Delta x = \frac{\lambda L}{d}$
Snell's law	$n_1 \sin\theta_1 = n_2 \sin\theta_2$
refractive index and wave speed	$n_1v_1 = n_2v_2$

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The nature of light and matter	
photoelectric effect	$E_{k\ max} = hf - \phi$
photon energy	$E = hf$
photon momentum	$p = \frac{h}{\lambda}$
de Broglie wavelength	$\lambda = \frac{h}{p}$

Data	
acceleration due to gravity at Earth's surface	$g = 9.8\ \text{m s}^{-2}$
mass of the electron	$m_e = 9.1 \times 10^{-31}\ \text{kg}$
magnitude of the charge of the electron	$e = 1.6 \times 10^{-19}\ \text{C}$
Planck's constant	$h = 6.63 \times 10^{-34}\ \text{J s}$ $h = 4.14 \times 10^{-15}\ \text{eV s}$
speed of light in a vacuum	$c = 3.0 \times 10^{8}\ \text{m s}^{-1}$
universal gravitational constant	$G = 6.67 \times 10^{-11}\ \text{N m}^2\ \text{kg}^{-2}$
mass of Earth	$M_E = 5.98 \times 10^{24}\ \text{kg}$
radius of Earth	$R_E = 6.37 \times 10^{6}\ \text{m}$
Coulomb constant	$k = 8.99 \times 10^{9}\ \text{N m}^2\ \text{C}^{-2}$

Prefixes/Units			
p = pico = 10^{-12}	n = nano = 10^{-9}	μ = micro = 10^{-6}	m = milli = 10^{-3}
k = kilo = 10^{3}	M = mega = 10^{6}	G = giga = 10^{9}	t = tonne = 10^{3} kg

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Units

SI units

Internationally, the scientific community around the world agree to use the SI system of units. This is based on seven fundamental quantities and their units, from which all the other quantities can be calculated. It is essential that all quantities in physics are stated with a numerical value and a unit, such as:

boiling point of water = 373.15 K

Current is one such fundamental quantity, and the ampere is its fundamental unit. Until 2019, one ampere was defined as 'the constant current which, if maintained in two straight parallel conductors of infinite length of negligible circular cross section and placed one metre apart in a vacuum, would produce between these conductors a force equal to 2×10^{-7} newton per metre of length'. In 2018 the General Conference on Weights and Measures (CGPM) agreed that on May 20, 2019, the ampere would henceforth be defined such that the elementary charge would be equal to $1.602176634 \times 10^{-19}$ coulomb. Note: ten significant figures in this definition!

The seven fundamental SI quantities are mass (in kilograms, kg), time (in seconds, s), temperature (in kelvins, K), distance (in meters, m), electric current (in amperes, A), amount of substance (in mole, mol) and luminous intensity (in candela, cd). The definitions of the kilogram, the kelvin and the mole were all changed at the same time as current in 2019. Their new definitions are based on fixed numerical values of the Planck constant (h), the Boltzman constant (k) and the Avogadro constant (N_A) respectively.

All other units are derived from these seven base units.

Quantity	Unit
Mass	kilogram, kg
Length	metre, m
Time	second, s
Thermodynamic temperature	kelvin, k
Electric current	ampere, A
Amount of substance	mole, mol
Luminous intensity	candela, cd

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Prefixes

Knowing and converting between the following SI prefixes is an essential skill in this course.

Name	Value (×)	Examples
tera (T)	10^{12}	THz, terahertz
giga (G)	10^{9}	GHz, gigahertz
mega (M)	10^{6}	MHz, megahertz
kilo (k)	10^{3}	km, kilometre
(Base unit, no prefix)	10^{1}	metre, hertz, gram
centi	10^{-2}	cm, centimetres
milli (m)	10^{-3}	mm, millimetre
micro (μ)	10^{-6}	μm, micrometre
nano (n)	10^{-9}	nm, nanometre
pico (p)	10^{-12}	pm, picometre

See 1B Skills on page 18 and the 1B Skills video in the Interactive Textbook for examples of these calculations.

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Periodic table of the elements

Key: Atomic number 79 · Symbol of element Au · Relative atomic mass 197.0 · Name of element Gold

1 H 1.0 Hydrogen																	2 He 4.0 Helium
3 Li 6.9 Lithium	4 Be 9.0 Beryllium											5 B 10.8 Boron	6 C 12.0 Carbon	7 N 14.0 Nitrogen	8 O 16.0 Oxygen	9 F 19.0 Fluorine	10 Ne 20.2 Neon
11 Na 23.0 Sodium	12 Mg 24.3 Magnesium											13 Al 27.0 Aluminium	14 Si 28.1 Silicon	15 P 31.0 Phosphorus	16 S 32.1 Sulfur	17 Cl 35.5 Chlorine	18 Ar 39.9 Argon
19 K 39.1 Potassium	20 Ca 40.1 Calcium	21 Sc 45.0 Scandium	22 Ti 47.9 Titanium	23 V 50.9 Vanadium	24 Cr 52.0 Chromium	25 Mn 54.9 Manganese	26 Fe 55.8 Iron	27 Co 58.9 Cobalt	28 Ni 58.7 Nickel	29 Cu 63.5 Copper	30 Zn 65.4 Zinc	31 Ga 69.7 Gallium	32 Ge 72.6 Germanium	33 As 74.9 Arsenic	34 Se 79.0 Selenium	35 Br 79.9 Bromine	36 Kr 83.8 Krypton
37 Rb 85.5 Rubidium	38 Sr 87.6 Strontium	39 Y 88.9 Yttrium	40 Zr 91.2 Zirconium	41 Nb 92.9 Niobium	42 Mo 96.0 Molybdenum	43 Tc (98) Technetium	44 Ru 101.1 Ruthenium	45 Rh 102.9 Rhodium	46 Pd 106.4 Palladium	47 Ag 107.9 Silver	48 Cd 112.4 Cadmium	49 In 114.8 Indium	50 Sn 118.7 Tin	51 Sb 121.8 Antimony	52 Te 127.6 Tellurium	53 I 126.9 Iodine	54 Xe 131.3 Xenon
55 Cs 132.9 Caesium	56 Ba 137.3 Barium	57–71 Lanthanoids	72 Hf 178.5 Hafnium	73 Ta 180.9 Tantalum	74 W 183.8 Tungsten	75 Re 186.2 Rhenium	76 Os 190.2 Osmium	77 Ir 192.2 Iridium	78 Pt 195.1 Platinum	79 Au 197.0 Gold	80 Hg 200.6 Mercury	81 Tl 204.4 Thallium	82 Pb 207.2 Lead	83 Bi 209.0 Bismuth	84 Po (210) Polonium	85 At (210) Astatine	86 Rn (222) Radon
87 Fr (223) Francium	88 Ra (226) Radium	89–103 Actinoids	104 Rf (261) Rutherfordium	105 Db (262) Dubnium	106 Sg (266) Seaborgium	107 Bh (264) Bohrium	108 Hs (267) Hassium	109 Mt (268) Meitnerium	110 Ds (271) Darmstadtium	111 Rg (272) Roentgenium	112 Cn (285) Copernicium	113 Nh (280) Nihonium	114 Fl (289) Flerovium	115 Mc (289) Moscovium	116 Lv (292) Livermorium	117 Ts (294) Tennessine	118 Og (294) Oganesson

57 La 138.9 Lanthanum	58 Ce 140.1 Cerium	59 Pr 140.9 Praseodymium	60 Nd 144.2 Neodymium	61 Pm (145) Promethium	62 Sm 150.4 Samarium	63 Eu 152.0 Europium	64 Gd 157.3 Gadolinium	65 Tb 158.9 Terbium	66 Dy 162.5 Dysprosium	67 Ho 164.9 Holmium	68 Er 167.3 Erbium	69 Tm 168.9 Thulium	70 Yb 173.1 Ytterbium	71 Lu 175.0 Lutetium
89 Ac (227) Actinium	90 Th 232.0 Thorium	91 Pa 231.0 Protactinium	92 U 238.0 Uranium	93 Np (237) Neptunium	94 Pu (244) Plutonium	95 Am (243) Americium	96 Cm (247) Curium	97 Bk (247) Berkelium	98 Cf (251) Californium	99 Es (252) Einsteinium	100 Fm (257) Fermium	101 Md (258) Mendelevium	102 No (259) Nobelium	103 Lr (262) Lawrencium

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Glossary

Absorbed dose
the amount of energy absorbed by each kilogram of tissue that is irradiated; measured in grays (Gy)

Acceleration
the rate of change of velocity

Active
the 'live' wire in an AC supply; carries potential difference (often called voltage); coloured brown by internationally accepted convention

Activity
the number of radioactive nuclei that decay each second; measured in becquerel (Bq)

Alpha (α) particle
a radioactive decay product comprising two protons and two neutrons; the same as a He nucleus

Ammeter
an instrument used to measure the electric current in a circuit in amperes (A)

Ampere, amp (A)
the SI unit for electric current, a fundamental quantity

Amplitude, *A*
a measure of the size of vibrations in a wave as the maximum distance a point in the wave vibrates away from the neutral position; generally measured in metres (m)

Atmospheric window
the range of wavelengths of the electromagnetic spectrum that experience little to no absorption by atmospheric gases

Atomic number
the number of protons in the nucleus; given by the symbol *Z*

Back radiation
the amount of radiation emitted from the atmosphere back towards Earth's surface

Battery
a source or supply of electrical energy usually formed from a number of electric cells connected in series

Belt of stability
nuclei that have a neutron/proton ratio between 1:1 and 1.5:1

Beta (β) particle
a high-energy, high-speed electron (β^-) or positron (β^+) that is ejected from the nucleus by some radionuclides during a form of radioactive decay

Binding energy
the amount of energy required to split a nucleus into its individual nucleons

Binding energy curve
a graph of the average binding energy per nucleon versus mass number

Blackbody
a theoretical object that perfectly absorbs all radiation falling on it

Carbon dioxide (CO_2)
a common gas in the atmosphere that contributes to back radiation; it is produced by many chemical processes especially combustion and is absorbed by photosynthetic plants and microorganisms

Celsius (°C)
a unit of temperature on the Celsius temperature scale, where the boiling point of water is 100°C and the freezing point is 0°C

Centre of mass
the mean position of all the parts of a system, weighed according to their masses

Chain reaction
when neutrons, emitted from the fission of one atomic nucleus, initiate further fission in the surrounding atomic nuclei, and so on

Change of state
when a substance changes from one state (solid, liquid or gas) to another by absorbing or releasing energy

Charge
a property of matter that causes electric effects. Like charges repel, opposite charges attract.

Chromatic distortion
image distortion caused by light of different colours focusing at different points of an image

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Circuit breaker
a type of automatic switch in which a large current creates an electromagnet, which trips the switch and cuts the supply. It can be turned back on manually after a fault is corrected, without needing to be replaced like a fuse.

Climate
the long-term weather patterns or average weather in an area, typically over a period of 30 years

Closed system
a system that does not allow the transfer of mass or energy to the surrounding environment

Colour dispersion
the phenomenon in which white light is split into different light components as it moves from air (or a vacuum) into a medium such as glass

Compression
in longitudinal waves, a region where particles are most closely spaced

Condensation
the change of state from gas to liquid

Conduction
the process of thermal energy transfer though interactions between nearby atoms, molecules and electrons

Controlled chain reaction
for every two or three neutrons released by the fissile nucleus, only one neutron is allowed to strike another fissile nucleus

Control rods
rods made of materials that readily absorb neutrons

Convection
the process of thermal energy transfer through the movement of a fluid or gas

Coulomb (C)
the SI unit for charge. 1 C is equivalent to the combined charge of 6.25×10^{8} protons (or electrons) or the amount of charge that passes a point when a current of 1 A flows for a time of 1 s.

Critical angle
depends on the refractive index of the medium but is the angle that an incident ray of light will fully reflect at the surface of the medium

Critical mass
the smallest mass of a fissionable substance that will sustain a controlled chain reaction, when the rate of neutron loss equals the rate of neutron release by fission

Current
the net flow of electric charge, measured in amperes (A), where $1\ A = 1\ C\ s^{-1}$.

Daughter nucleus
a nucleus formed by the radioactive decay of another nucleus (the parent)

Decay chain
the sequence of stages a radioisotope passes through until it reaches a stable nucleus

Decay curve
a graph of the number of radioactive nuclei remaining in a substance versus time elapsed

Diode
a semiconductor with very large resistance to current flow in one direction, but very small in the other; a semiconductor device that will only allow electrical current to flow through it in one direction

Displacement
the shortest distance from one point to another

Dose equivalent
dose equivalent (Sv) = absorbed dose (Gy) × radiation weighting factor

Dose–risk relationship
the probability of incurring a severe radiation effect versus the dose of radiation received

Dosimeter
an instrument that measures personal exposure to ionising radiation over a given time period

Double insulated
two layers of insulation are used for added safety, typically on appliances that are not earthed. The layers are placed between the live parts and external metal parts of the appliance.

Earth
the wire or connection that provides a low resistance path for current to flow into the ground. It is the third wire in a plug or socket, usually green and yellow striped, and is attached to the external metal casing of an appliance for safety.

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Efficiency
the ratio of the energy output to the energy input of a system

Effective dose
applies to a specific organ or organs

Elastic collision
a collision in which the total kinetic energy is the same both before and after the collision

Elastic limit
the maximum deformation that can occur without causing permanent deformation

Elastic material
a material that can store elastic potential energy and is able to return to its original shape once the energy is released

Elastic potential energy
the energy stored in the material when it is deformed within its elastic limits

Electrical conductor
a material that allows electric charge to flow readily

Electrical potential energy
potential energy due to the concentration of charge in part of an electric circuit

Electric cell
a device that stores chemical energy, with the ability to produce an electric current when a circuit is created between the two terminals of the cell

Electric circuit
the pathway of electrical conductors that allows a continuous loop (or 'complete circuit') for electrons to flow through. A circuit with an open switch, or in some other way incomplete, is known as an 'open' circuit.

Electric field
a physical field that creates a force on all charged particles within the field. Produced by charged particles and changing magnetic fields. A changing electric field also produces a changing magnetic field.

Electric generator
a device that converts kinetic energy into electrical energy; usually a coil rotating in a magnetic field

Electromagnetic radiation
another term commonly used to refer to electromagnetic waves

Electromagnetic spectrum
the range of all types of electromagnetic waves, which have different wavelengths and frequencies

Electromagnetic switch
a switch that uses a magnetic field created by an electric current flowing through a coil of wire to move the switch toggle. Unlike a permanent magnet, the magnetic field will cease when the current stops.

Electromagnetic wave
a transverse wave made up of perpendicular changing electric and magnetic fields, which can propagate through space without the need of a medium

Electron
the lightest stable subatomic particle known. It carries a negative charge of 1.60×10^{-19} coulomb, which is considered the basic unit of electric charge.

Electrostatic force
a force that exists between charged particles, e.g. two positively charged protons

Element
a pure substance consisting only of atoms that all have the same numbers of protons in their nuclei

Energy
the measurable property of a body or system with the ability to do work

Enrichment
increasing the percentage of the fissile isotope of an element in a nuclear fuel

Equilibrium
the state where the sum of the translational and rotational forces on an object are equal to zero

Equilibrium position
the position in a system where the net force on the oscillating object is zero

Equivalent resistance
the value of a single resistor that could replace a number of individual resistors to give the same effect in the circuit

Evaporative cooling
the process of cooling that occurs in liquids when high-energy molecules evaporate and carry away energy from the system

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External radiation
the radiation source remains outside the body and irradiates us from the outside

Fibrillation
a dangerous state of rapid uncoordinated quivering contractions of heart muscle fibres that fail to pump blood

Fissile
elements that are capable of undergoing fission

Force diagram
a diagram that shows the relative magnitude and direction of all of the forces acting on a body. The forces are shown acting from the centre of mass of the object.

Free-falling
when a body is falling and the only force acting on the body is gravity

Frequency, *f*
the number of wavelengths of a wave that pass a fixed point in a second; measured in hertz (Hz)

Friction
a force that resists the relative motion of solid surfaces and fluid layers sliding against each other

Fuse
a piece of thin wire that acts as a safety device in a circuit by melting when too much current is passed through it, disconnecting the active wire from the circuit and preventing further damage

Fusion
the change of state from liquid to solid

Gamma ray
the region of the electromagnetic spectrum with the shortest wavelengths and highest frequencies

Geiger counter
an instrument for detecting the presence and intensity of ionising radiations

Genetic effects
chromosome aberrations and genetic mutations resulting from exposure to radiation

Gradient
the slope of a graph. The gradient of a straight line can be calculated as the rise divided by the run.

Gravitational field strength
a theoretical region of space around a mass where the gravitational force can be experienced by other masses. The gravitational field strength is expressed in N kg^{-1}, which is equivalent to the acceleration due to gravity in ms^{-2}.

Gravitational potential energy
the amount of energy an object has stored due to its position in a gravitational field; measured in joules (J)

Gray (Gy)
the SI unit of the absorbed dose of ionising radiation, corresponding to 1 J kg^{-1}

Greenhouse gas
a term used to classify gases that absorb and emit radiation in the infrared range

Half-life
the time taken for half of a group of unstable nuclei to decay

Heat
the flow of thermal energy between two bodies of different temperature

High-level waste
nuclear waste that needs to be stored for a very long time in shielded containers and continually cooled to stop overheating

Hooke's law
in an ideal spring, the force applied to the spring is directly proportional to its extension or compression

Ideal spring
a hypothetical spring that is considered frictionless and mass-less and obeys Hooke's law

Impulse
the change in momentum of an object, caused by a force acting for a certain amount of time

Inelastic collision
a collision in which the total kinetic energy is larger before the collision than after the collision. The 'missing' energy is often converted into other forms, such as thermal energy and sound energy

Inertia
a body's tendency to resist a change in its state of motion

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Infrared (IR)
the region of the electromagnetic spectrum between microwaves and red light; produced by sources of heat and is not visible to the human eye but can be detected as warmth on the skin

Insulator
a material that does not conduct electricity; has few or no free charges

Internal radiation
the radiation source irradiates us from inside our bodies

Ion
an atom or molecule that carries net positive or negative charge

Ionise
the removal or addition of electrons from a neutral atom

IPCC
Intergovernmental Panel on Climate Change

Isotope
a form of the same element with the same numbers of protons but different numbers of neutrons in their nuclei

Joule (J)
the SI unit of measurement for energy

Kelvin (K)
a unit of temperature on the Kelvin temperature scale, where the boiling point of water is 373.15 K and the freezing point is 273.15 K. 0 K corresponds to absolute zero.

Kilowatt-hour (kW h)
a unit of electrical energy based on a power of 1 kW running for 1 h, equivalent to 3.6 MJ; used on electricity supply meters and bills

Kinetic energy
the energy due to movement. It is measured in units of joules (J) and is a scalar quantity.

Law of conservation of momentum
for a collision involving two or more objects in a closed system the total momentum will remain the same

Light dependent resistor (LDR)
a semiconductor device whose resistance depends on the intensity of light shining on it

Light-emitting diode (LED)
a diode that lights up when current flows through it but since it is a diode current will not flow in the reverse direction

Load
the component(s) in a circuit where electrical energy is transformed into other forms of energy, e.g. thermal, light, kinetic energy

Longitudinal wave
a wave in which vibrations are parallel to the direction of travel

Low-level waste
nuclear waste usually stored on site for short periods of time and then released into the environment

Magnetic field
a physical field that creates a force on moving charged particles and magnetic materials within the field. Produced by changing electric fields and magnetic materials. A changing magnetic field also produces a changing electric field.

Magnitude
a number the defines only the size of a quantity

Mass
a body's resistance to acceleration when a force is applied.

Mass defect
change in mass of a nucleus created by fusion, or change in mass of the nuclei created in fission

Mass number
the sum of the number of protons and neutrons in the nucleus; given the symbol A

Medium
a substance or material that can carry the vibrations of a wave

Medium-level waste
nuclear waste requiring a longer storage time and requires shielding but not cooling

Melting
the change of state from solid to liquid

Methane (CH_4)
a gas that occurs in relatively small quantities in the atmosphere that contributes a large amount to back radiation; it is the main component of natural gas and commonly produced by cattle

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Microwave
the region of the electromagnetic spectrum with the longest wavelength after radio waves

Moderator
any material that slows neutrons down

Momentum, *p*
the product of an object's mass and velocity

Monochromatic
composed of a single frequency of light or other radiation

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

Neutral
the blue wire in an AC circuit that completes the circuit, providing a close to zero potential for current to flow

Neutrino
a neutral subatomic particle with a mass close to zero that rarely reacts with normal matter

Neutron
an uncharged particle in the nucleus of an atom

Non-fissile
elements that are not capable of undergoing fission

Normal
a line that extends from the surface of an object and is perpendicular to the tangent of the surface at that point

Normal force
the force that a surface applies to a body resting on it. The force is always applied perpendicular to the surface and prevents the body falling through the surface.

Nuclear decay
when the nucleus of an atom is unstable and spontaneously emits energy in the form of nuclear radiation

Nuclear energy
the energy released during nuclear fission or fusion

Nuclear fission
the process of splitting a large nucleus to form two smaller, more stable nuclei

Nuclear fusion
the process of joining together two small nuclei to form a larger, more stable nucleus

Nuclear transformation
the conversion of one nuclide into another nuclide

Nucleon
a proton or a neutron in a nucleus

Nucleus
the solid centre of an atom where most of the mass of an atom is concentrated

Ohmic resistor
a material that gives a straight-line I–V graph; i.e. it obeys Ohm's law

Ohm's law
for a particular type of material that gives a straight-line characteristic I vs V graph, meaning that $V = IR$ always holds for that material

Open system
a system that does allow the transfer of mass or energy to the surrounding environment

Optical fibre
a flexible transparent fibre made from glass and plastic that can carry digital signals by using the phenomenon of total internal reflection within

Origin
the initial point from where a body moves

Parabolic path
an approximately U-shaped plane curve that is mirror-symmetrical. This is the path taken by a projectile that is only under the influence of gravity.

Parallel
when two components are connected, creating alternative paths around an electric circuit

Parallel circuit
a circuit that contains junctions; the current drawn from the battery, cell or electricity supply splits before it reaches components and rejoins afterwards

Parent nucleus
the decaying nucleus is

Partial internal reflection
reflection of light at an interface where some of the light has also refracted across the surface

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Period, *T*
the time it takes for a wave to move one wavelength in the direction of travel; measured in seconds (s)

Periodic table
a table of the elements arranged in order of atomic number

Photon
a quantum of light or other electromagnetic radiation

Pivot point
the point that an object rotates around; also known as the axis of rotation

Plasma
a form of matter in which all the atoms are completely ionised – sometimes called the fourth state of matter

Positron
a positively charged subatomic particle having the same mass and magnitude of charge as the electron

Potential difference
the difference in electric potential between two points in a circuit; measured by a voltmeter when connected across a circuit component. A battery creates a potential difference across a circuit, which causes current to flow.

Potential (voltage) divider
a series circuit with two or more components; where the voltage is shared (or divided) between the components in the circuit

Potentiometer
a circuit device consisting of a three-terminal sliding or rotating contact (called the 'wiper'). Connections at one end and the wiper can be used to create a variable resistor. Often used as a volume control or light dimmer.

Power
the rate at which work is done; the rate at which energy is transformed; a scalar quantity measured in watts (W) or $J\,s^{-1}$

Proton
a positively charged particle in the nucleus of an atom

Quantitative
data that can be measured by the quantity

Radiation weighting factor
a factor by which the absorbed dose (Gy) is to be multiplied to obtain a quantity that expresses, on a common scale for all ionising radiation, the biological damage (Sv) to an exposed individual

Radioactive
any substance that spontaneously emits ionising radiation

Radioactive decay series
the sequence of stages a radioisotope passes through to become more stable. The chain ends when a stable isotope forms.

Radioactive isotope
any isotope of an element whose nuclei are unstable and dissipate energy by spontaneously emitting radiation

Radiocarbon dating
a method for determining the age of an object containing organic material by using the decay of radioactive carbon-14

Radiotherapy
a strategy to target cancerous tumours with maximum effect by using large doses of lethal (to the targeted cells) radiation while minimising collateral damage to healthy cells

Radio wave
the region of the electromagnetic spectrum with the longest wavelength and lowest frequencies

Rarefaction
in waves, a region where particles are most spread out

Reflection
a change in the direction of a wave crest as it meets the surface between two media that results in the wave travelling back into the medium it came from

Refraction
the change in direction of a wave moving from one medium (or vacuum) to another medium (or vacuum) caused by the wave changing speed

Refractive index
a measure of how much slower light travels through a medium compared to in a vacuum; given the symbol *n*

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Residual current device (RCD)
a device in the switchboard that activates circuit breakers when an imbalance between the active–neutral current is detected, protecting against electrocution

Resistance
a measure of how much an object or material impedes the flow of current; measured in units of ohms (Ω)

Resultant vector
a single vector that is equivalent to the sum of two or more vectors

Rotational equilibrium
when a system is not rotating, the sum of the torques is equal to zero

Rotational force
a force that can cause an object to rotate about an axis of rotation

Scalar
a quantity that is fully described by a magnitude (it doesn't need a direction)

Semiconductor
a material that conducts electricity only partially, or only under particular conditions

Series
when circuit components are connected one after another in a continuous loop so that the same current passes through each component

Series circuit
when circuit components are connected one after the other in a continuous loop, so that the same current passes through each component

Short-circuit
an accidental connection in a circuit or an appliance in which a conductor is placed across a potential difference so that an excessive current flows, possibly causing dangerous heating or electric shock

Sievert (Sv)
the SI unit of dose equivalent (the biological effect of ionising radiation), equal to an effective dose of a joule of energy per kilogram of recipient mass.

Snell's law
a law that describes mathematically the link between the angle of refraction, the angle of incidence and the refractive indices of each medium

Specific heat capacity
the energy required to raise the temperature of 1 kg of a material by 1 K; units are $J\,kg^{-1}\,K^{-1}$. Its value depends on the material being heated. It is given the symbol *c*.

Specific latent heat
the energy needed to be absorbed or released per kilogram of a substance to cause a change of state, in units $J\,kg^{-1}$. It depends on both the substance and the change of state. It is given the symbol *L*.

Strong nuclear force
the force that holds the nucleons together in a nucleus of an atom. It acts only over very short distances (10^{-15} m).

Subcritical
when the rate of neutron loss is greater than the rate of neutron release by fission

Supercritical
when the rate of neutron loss is less than the rate of neutron release by fission

System
a collection of objects that can interact with each other

Thermal energy
the sum of all the random potential and kinetic energies of the atoms and molecules that make up an object or a system

Thermistor
a thermal resistor, a non-ohmic semiconductor device whose resistance changes with temperature; two main types: NTC (negative thermal coefficient) increases *R* with decreasing temperature, is the most common type. PTC (positive thermal coefficient) increases *R* with increasing temperature, is made for special jobs.

Thermonuclear bomb
a two-stage nuclear weapon with an initial fission stage, which then triggers a much larger fusion explosion

Tokamak
a device that uses a very strong magnetic field to confine plasma in the shape of a torus (donut-shaped ring)

Torque
a measure of how much of a force acting on an object is causing it to rotate

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Total internal reflection
the phenomenon where all the light at a surface is reflected with no refraction. It occurs when light moves from a medium of higher refractive index to a medium of lower refractive index at an angle of incidence greater than or equal to the critical angle.

Transducer
a device that receives input signal as one form of energy and converts it to a different form of energy output

Transformer
a device that transfers energy via an alternating current (AC) from one circuit to another, usually with an increase or decrease (step-up or -down) in potential difference (voltage)

Translational equilibrium
occurs when the velocity of an object is constant. This means that the net force acting on the object is equal to zero.

Translational force
a force that can cause an object to change its position

Translational kinetic energy
the energy associated with an object of mass, m, travelling with speed, v

Transmutation
a change in the structure of atomic nuclei that converts one element into another element

Transverse wave
a wave in which vibrations are perpendicular to the direction of travel

Transuranic
an element with more than 92 protons

Ultraviolet (UV)
the region of the electromagnetic spectrum between visible light and X-rays

Uncontrolled chain reaction
every two or three neutrons released by the fissile nucleus, are allowed to strike other fissile nuclei. This grows exponentially to produce a massive explosion.

Vaporisation
the change of state from liquid to gas

Vector
a quantity that is described by both a magnitude (how big it is) and a direction it

Velocity
the rate of change of displacement

Visible light
the region of the electromagnetic spectrum between 700 nm and 400 nm,; it is the only region that can be detected by our eyes

Volt (V)
the SI unit of measurement for potential difference, denoted by the symbol V

Voltmeter
an instrument used to measure potential difference (in V) between two points in a circuit

Watt (W)
the unit of power defined as 1 watt = 1 joule per second

Wavelength, λ
the distance between repeated parts of a wave shape; measured in metres (m)

Weak nuclear force
the force responsible for radioactive beta decay

Wien's law
an equation that relates the peak wavelength emitted and the temperature of an ideal blackbody

Work
the amount of energy transferred from one object or system to another

X-ray
the region of the electromagnetic spectrum between UV and gamma rays; they have the second shortest wavelengths and second highest frequencies

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