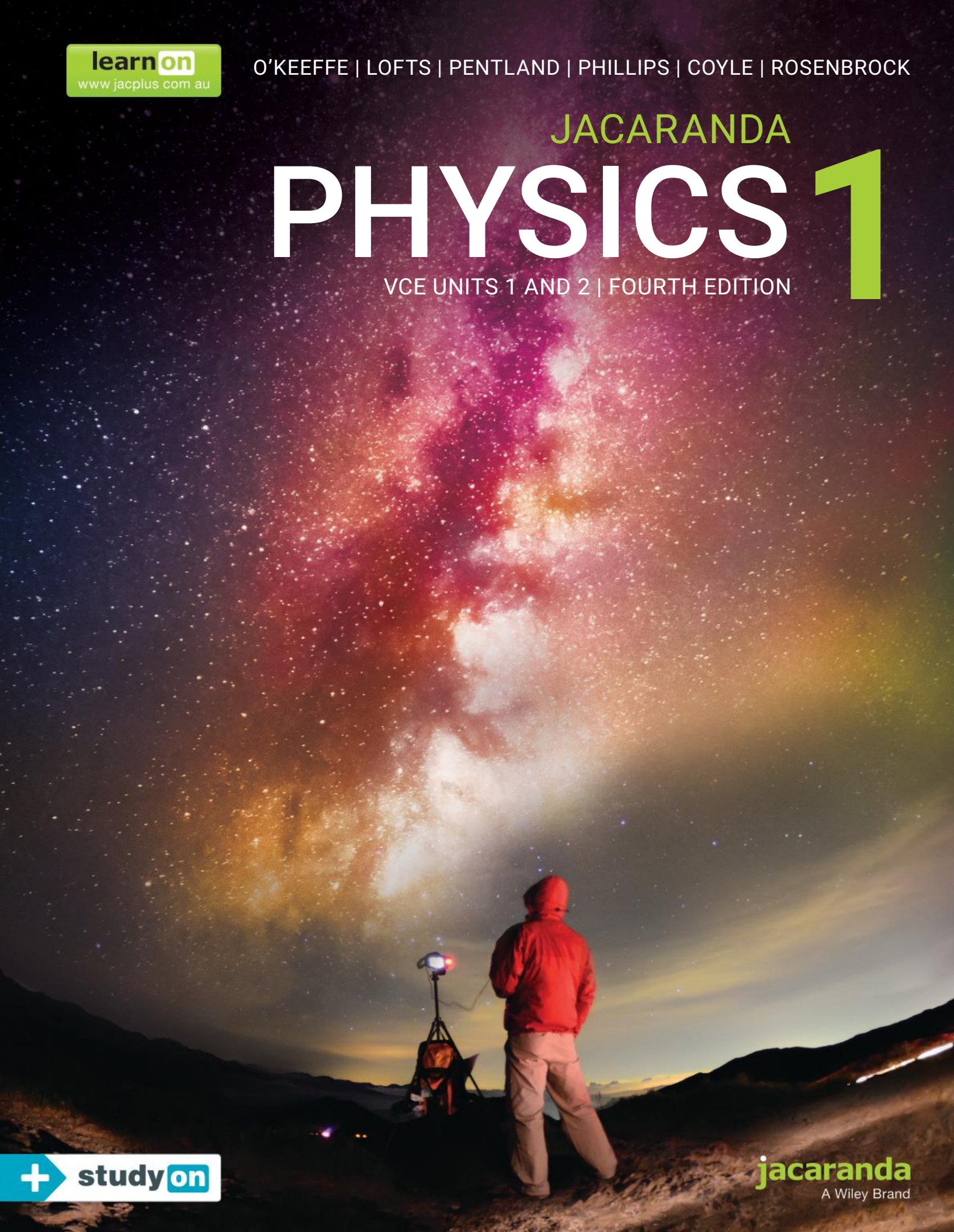


JACARANDA PHYSICS 1

VCE UNITS 1 AND 2 | FOURTH EDITION



JACARANDA

PHYSICS 1

VCE UNITS 1 AND 2 | FOURTH EDITION

JACARANDA
PHYSICS 1
VCE UNITS 1 AND 2 | FOURTH EDITION

DAN O'KEEFFE

GRAEME LOFTS

JANE COYLE

MICHAEL ROSENBROCK

ROSS PHILLIPS

PETER NELSON

BARBARA MCKINNON

PETER PENTLAND

GARY BASS

DANIELA NARDELLI

PAM ROBERTSON

JILL TACON

JON PEARCE

CONTRIBUTING AUTHORS

MURRAY ANDERSON

MOSES KHOR

This edition published 2020 by
John Wiley & Sons Australia, Ltd
42 McDougall Street, Milton, Qld 4064

Typeset in 11/14 pt Times LT Std

© Clynton Educational Services Pty Ltd (Graeme Lofts), Dan O’Keefe, Peter Pentland, Ross Phillips, Gary Bass, Daniella Nardelli, Pam Robertson, Jill Tacon and Jon Pearce 2020

The moral rights of the authors have been asserted.

ISBN: 978-0-7303-7315-5

Previous editions of this title have been published as follows.

Physics 1 VCE Units 1 and 2 and eBookPLUS

© Clynton Educational Services Pty Ltd (Graeme Lofts), Dan O’Keefe, Peter Pentland, Ross Phillips, Gary Bass, Daniella Nardelli, Pam Robertson, Jill Tacon and Jon Pearce 2015

Jacaranda Physics 1 Third Edition

© Clynton Educational Services Pty Ltd (Graeme Lofts), Dan O’Keefe, Peter Pentland, Ross Phillips, Gary Bass, Daniella Nardelli, Pam Robertson, Jill Tacon and Jon Pearce 2008

Jacaranda Physics 1 Second Edition

© Clynton Educational Services Pty Ltd (Graeme Lofts), Dan O’Keefe, Peter Pentland, Ross Phillips, Gary Bass, Daniella Nardelli, Pam Robertson, Jill Tacon and Jon Pearce 2003

Jacaranda Physics 1

© Clynton Educational Services Pty Ltd (Graeme Lofts), Dan O’Keefe, Peter Pentland, Pam Robertson, Barry Hill and Jon Pearce 1996

Reproduction and communication for educational purposes

The Australian *Copyright Act 1968* (the Act) allows a maximum of one chapter or 10% of the pages of this work, whichever is the greater, to be reproduced and/or communicated by any educational institution for its educational purposes provided that the educational institution (or the body that administers it) has given a remuneration notice to Copyright Agency Limited (CAL).

Reproduction and communication for other purposes

Except as permitted under the Act (for example, a fair dealing for the purposes of study, research, criticism or review), no part of this book may be reproduced, stored in a retrieval system, communicated or transmitted in any form or by any means without prior written permission. All inquiries should be made to the publisher.

Trademarks

Jacaranda, the JacPLUS logo, the learnON, assessON and studyON logos, Wiley and the Wiley logo, and any related trade dress are trademarks or registered trademarks of John Wiley & Sons Inc. and/or its affiliates in the United States, Australia and in other countries, and may not be used without written permission. All other trademarks are the property of their respective owners.

Front cover image: © Denis Belitsky/Shutterstock; © maxchu / Getty Images

Illustrated by various artists, diacriTech and Wiley Composition Services

Typeset in India by diacriTech

Printed in Singapore by
Markono Print Media Pte Ltd

All activities have been written with the safety of both teacher and student in mind. Some, however, involve physical activity or the use of equipment or tools. **All due care should be taken when performing such activities.** Neither the publisher nor the authors can accept responsibility for any injury that may be sustained when completing activities described in this textbook.



A catalogue record for this
book is available from the
National Library of Australia

10 9 8 7 6 5 4 3 2 1

CONTENTS

About this resource	ix
Acknowledgements	xi

UNIT 1 WHAT IDEAS EXPLAIN THE PHYSICAL WORLD?	1

AREA OF STUDY 1 HOW CAN THERMAL EFFECTS BE EXPLAINED?

1 Thermodynamic principles	3
1.1 Overview	3
1.2 Explaining heat using the kinetic theory	4
1.3 Measuring and converting temperature	9
1.4 Transferring heat	13
1.5 Thermal equilibrium and the laws of thermodynamics	18
1.6 Specific heat capacity	22
1.7 Review	30
2 Thermodynamics and climate science	35
2.1 Overview	35
2.2 Earth's energy systems	37
2.3 The enhanced greenhouse effect	45
2.4 Climate models	54
2.5 Investigating issues related to thermodynamics	56
2.6 Review	58

AREA OF STUDY 1 REVIEW

Practice examination	64
Practice school-assessed coursework	69

AREA OF STUDY 2 HOW DO ELECTRIC CIRCUITS WORK?

3 Concepts used to model electricity	70
3.1 Overview	70
3.2 Electric circuits	71
3.3 Current	76
3.4 Voltage	83
3.5 Energy and power in an electric circuit	86
3.6 Resistance	91
3.7 Review	103
4 Circuit analysis	112
4.1 Overview	112
4.2 BACKGROUND KNOWLEDGE Electric circuit rules	113
4.3 Series and parallel circuits	119
4.4 Non-ohmic devices in series and parallel	130
4.5 Power in circuits	135
4.6 Review	137

5 Using electricity and electrical safety	145
5.1 Overview	145
5.2 Household electricity and usage	146
5.3 Electrical safety	153
5.4 Review	161

AREA OF STUDY 2 REVIEW

Practice examination	167
Practice school-assessed coursework	174

AREA OF STUDY 3 WHAT IS MATTER AND HOW IS IT FORMED?

6 Origins of atoms	176
6.1 Overview	176
6.2 Early developments of the Big Bang Theory	177
6.3 Further developments of the Big Bang Theory	186
6.4 Measurements of the universe	189
6.5 The formation of the first atoms	195
6.6 Review	203

7 Particles in the nucleus	207
7.1 Overview	207
7.2 The discovery of subatomic particles	208
7.3 Nuclear radiation	221
7.4 Types of nuclear radiation	227
7.5 Review	235

8 Energy from the atom	242
8.1 Overview	242
8.2 Energy from mass	243
8.3 Energy from the nucleus	247
8.4 Energy from accelerating charges	256
8.5 Review	261

AREA OF STUDY 3 REVIEW

Practice examination	266
Practice school-assessed coursework	271

UNIT 2 WHAT DO EXPERIMENTS REVEAL ABOUT THE PHYSICAL WORLD? **273**

AREA OF STUDY 1 HOW CAN MOTION BE DESCRIBED AND EXPLAINED?

9 Analysing motion	275
9.1 Overview	275
9.2 Describing movement	276
9.3 Analysing motion graphically	287
9.4 Equations for constant acceleration	299
9.5 Review	305

10 Forces in action	313
10.1 Overview	313
10.2 Forces as vectors	314
10.3 Newton's First Law of Motion	325
10.4 Newton's Second Law of Motion	327

10.5 Newton's Third Law of Motion	337
10.6 Forces in two dimensions	342
10.7 Momentum and impulse	351
10.8 Torque	360
10.9 Equilibrium	362
10.10 Review	368

11 Energy and motion 374

11.1 Overview	374
11.2 Impulse and momentum	375
11.3 Work and energy	381
11.4 Energy transfers	385
11.5 Efficiency and power	397
11.6 Review	402

AREA OF STUDY 1 REVIEW

Practice examination	408
Practice school-assessed coursework	413

AREA OF STUDY 2 OPTIONS: OBSERVATION OF THE PHYSICAL WORLD

- online only

 - 12 What are stars?
 - 13 Is there life beyond Earth's solar system?
 - 14 How do forces act on the human body?
 - 15 How can AC electricity charge a DC device?
 - 16 How do heavy things fly?
 - 17 How do fusion and fission compare as viable nuclear energy power sources?
 - 18 How is radiation used to maintain human health?
 - 19 How do particle accelerators work?
 - 20 How can human vision be enhanced?
 - 21 How do instruments make music?
 - 22 How can performance in ball sports be improved?
 - 23 How does the human body use electricity?

24 Practical investigation	430
24.1 Overview	430
24.2 Key science skills in Physics	431
24.3 BACKGROUND KNOWLEDGE Variables	440
24.4 Concepts specific to investigation, key terms and representations	442
24.5 Scientific research methodologies and techniques	446
24.6 Health and safety guidelines	454
24.7 Methods of organising, analysing and evaluating primary data	457
24.8 Models and theories to understand observed phenomena	469
24.9 Nature of evidence and key findings of investigations	472
24.10 Conventions of scientific report writing and scientific poster presentation	474
24.11 Review	485
Glossary	495
Appendix 1: Periodic table	502
Appendix 2: Astronomical data	504
Answers	505
Index	542

ABOUT THIS RESOURCE

Jacaranda Physics has been reimaged to provide students and teachers with the most comprehensive resource on the market. This engaging and purposeful suite of resources is fully aligned to the VCE Physics Study Design (2016–2021).

Formats

Jacaranda Physics is now available in print and a range of digital formats, including:

Print	learnON	eBookPLUS	PDF	eGuidePLUS
				
Printed textbook with free digital access code inside	learnON is our immersive and flexible digital learning platform	The eBookPLUS is an electronic version of the student text	Downloadable PDFs available with eBookPLUS	The eGuidePLUS includes everything from the eBookPLUS with additional resources designed for teachers

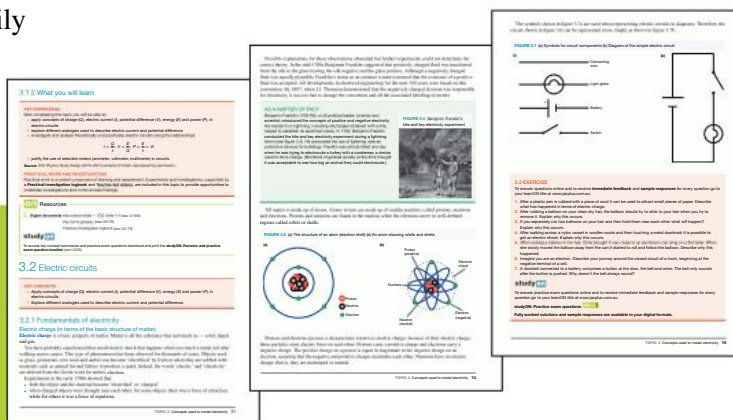
Fully aligned to the VCE Physics Study Design

Have confidence that you are covering the entire VCE Physics Study Design (2016–2021), with:

- tailored exercise sets at the end of each sub-topic
- additional background information easily distinguished from curriculum content
- practice SACs clearly linked to each outcome
- practice exams for each area of study.

Key concepts approach

Students can easily understand which aspect of the Study Design they are studying with Key Knowledge dot points highlighted at the start of each topic and broken down into Key Concepts in each sub-topic.



Engaging resources and rich media

A variety of online and offline resources to encourage students of all learning styles, including:

- videos and interactivities embedded at the point of learning
- practical investigations complete with printable logbook
- a variety of worksheets and activities allow students to apply their knowledge of the content.

Teacher-led videos

Videos of both sample problems and practical investigations led by experienced teachers allow students to better consolidate their learning.



Inspiring students to become independent learners

This resource, on the immersive digital platform learnON, encourages self-driven student learning through:

- fully worked solutions for every question providing students with immediate feedback
- progress tracked automatically in learnON allowing students to reflect on their learning, and enabling students to highlight areas of strength and weakness
- topic summary, key terms and practice questions at the end of every topic
- sample problems with fully worked solutions set out in the THINK–WRITE format.

The screenshot shows the 'studyON: practice exam questions' interface. It includes sections for 'learnON questions' and 'Textbook questions'. Below these is a 'My Results' section with a donut chart showing 80% completion. A table lists questions with their status, marks, and time. A question preview for 'Q5' is shown on the right, asking about the Law of Conservation of Energy.

studyon

Prepare for exams with every relevant past exam question since 2006! studyON is now included in learnON and as a printable exam revision booklet

A wealth of teacher resources

Jacaranda Physics empowers teachers to teach their class their way with the extensive range of teacher resources including:

- quarantined topic tests and SACs that are easily customisable
- practical investigation support with demonstrative videos, laboratory information, expected results and risk assessments
- work programs
- curriculum grids.

Test Maker

Create custom tests for your class from the entire question pool — including all subtopic, topic review and past VCAA exam questions

The screenshot shows the 'Create Assignment' interface. It includes a 'Select your content' section with a list of topics and exercises. Below this is a 'Select questions to assign' section with a list of questions and a 'SHOW QUESTIONS' button. A question preview for 'Q5' is shown on the right, asking about the process of chemiluminescence.

The screenshot shows the 'Results' interface. It includes a '1. Choose assignment type' section with 'PRACTICE' and 'ASSESSMENT' options. Below this is a '2. Select students' section with a list of students. A '3. Filter further' section is also present. The main part of the interface shows a table of student performance data with columns for 'Total', 'Biological sciences', 'Chemical sciences', 'Earth and space sciences', 'Physical sciences', and 'Science as a whole'.

Visibility of student results

Detailed breakdown of student results allows you to identify strengths and weaknesses across various topics and sub-topics.

ACKNOWLEDGEMENTS

The authors and publisher would like to thank the following copyright holders, organisations and individuals for their assistance and for permission to reproduce copyright material in this book.

VCE Physics Study Design content is copyright Victorian Curriculum and Assessment Authority (VCAA), reproduced by permission. VCE® is a registered trademark of the VCAA. The VCAA does not endorse this product and makes no warranties regarding the correctness or accuracy of its content. To the extent permitted by law, the VCAA excludes all liability for any loss or damage suffered or incurred as a result of accessing, using or relying on the content. Current VCE Study Designs and related content can be accessed directly at www.vcaa.vic.edu.au. Teachers are advised to check the VCAA Bulletin for updates.

Images

• Alamy Australia Pty Ltd: **73**/© Alamy Stock Photo; **253**/© blickwinkel; **73**/© ClassicStock / Alamy Stock Photo; **184**/© INTERFOTO / Alamy; **357**/© Javier Larrea; **160**/© sciencephotos; **243**/© Sueddeutsche Zeitung Photo; **147**/© Yevhen Rychko / Alamy Stock Photo; • ANSTO: **257**/© ANSTO; • ATLAS Experiment: **425**/ATLAS Experiment © 2014 CERN • Bhavesh Chauhan: **450 (top middle)**/© Bhavesh Chauhan; • Creative Commons: **358**/© Brady Holt; **151**/© EECA; **57 (top)**, **151**/© EECA / Commonwealth of Australia 2019; • Creatives Commons: **259**/© CK-12 Foundation - Christopher Auyeung; • Dan O'Keeffe: **430**/© Dan O'Keeffe; • European Space Agency Comm Dep: **196**/© ESA and the Planck Collaboration; • Getty Images: **229**/© Andrew Johnson; **1**/© lovelyday12 • Getty Images Australia: **319 (left)**/© LEMAIRE StÃ©phane / hemis.fr; **92**/© Science Source; • gmstockstudio: **56**/© gmstockstudio; • Image Addict: **79**/© imageaddict.com.au; • IPCC: **55**/© IPCC; • iStockphoto: **69**/© Lee Chin Yong; **273**/© Qiang Chen; **435**/© Stanislovas Kairys; • Jim Thalassoudis: **260**/© Jim Thalassoudis; • NASA: **419**/ ALMA ESO/NAOJ/NRAO / NASA / ESA **218**/© NASA; • NASA/ public domain: **188 (top)**, **197**/© NASA • Pixabay: **15 (b)**/ Ozgur Coskun; **421**/stokpic/229 images; **466 (b)**/Pixaline • Public Domain: **248**, **249**/© Atomic Heritage Foundation; **5**/© Public Domain; • Science Photo Library: **180 (middle)**/© Ann Ronan Picture Library; **179**/© Harvard College Observatory; **450 (top left)**/© MARTYN F. CHILLMAID; **11 (left)**/© Science Photo Library; • Shutterstock: **15 (a)**/© Juergen Faelchle; (b)/Ozgur Coskun; **81**, **84**, **93**/© (a) Vladimir A Veljanovski (b) Peter Pentland; **159**/ Caron Badkin; **256**/ Adrio Communications Ltd; **320**/© Alexandr Shevchenko; **420**/ design36; **422**/Everett Historical; **424**/ Semnic; **426**/ MJTH; **427**/ Halfpoint; **428**/Graham Hunt/ProSports; **429**, **433**/Sergey Nivens; **450 (bottom)**/© ALEXEY FILATOV; **317**/© Allexandar; **471**/© Amanda Carden; **279**/© Andrey Armyagov; **418**/© Ververidis Vasilis; **449 (bottom left)**/© Andrey Suslov; **156 (right)**/© Antonio Guillem; **37**/© Aphelleon; **159**, **207**/© Newscom; **397**/© cassiede alain; **222**/© CHEN WS; **44**/© cherezoff; **434 (bottom)**/© chinasong; **374**/© conrado; **466 (a)**/© Hodyachaya Alla; **449 (top left)**/© Constantine Pankin; **282**/© CP DC Press; **448 (bottom left)**/© Craig Walton; **25**/© D. Pimborough; **271**/© danpastia; **188 (bottom)**/© David Fowler; **451 (bottom)**/© desdemon72; **470 (top)**/© Designua; **389**/© Diego Barbieri; **43**/© dikobrazyi; **443**/© Dr Project; **155**/© Egor_Kulinich; **224**/© endeavor; **70**/© fl1photo; **456**/© Feng Yu; **489**/© Friday24; **414**/© FS Stock; **212 (left)**/© general-fmv; **326 (bottom)**/© Georgios Kollidas; **334**/© Germanskydiver; **448 (bottom right)**/© Guy J. Sagi; **275**/© hfzimages; **492**/© ilkercelek; **340**/© Ivan Smuk; **145**/© Joel_420; **11 (right)**/© kaband; **457**/© Katsiuba Volha; **449 (bottom right)**, **465 (bottom)**/© KinoMasterskaya; **434 (top)**/© Kletr; **466 (top)**/© litchima; **259**/© magnetix; **356 (top)**/© manzrussali; **463**/© marekuliasz; **361**/© MARGRIT HIRSCH; **318 (top)**/© mariolav; **356 (bottom)**/© maxpro; **34**/© Mihancea Petru; **153**/© Mike Focus; **451 (top)**/© milanzeremski; **355**/© Mitch Gunn; **3**/© mkrol0718; **469**/© Molekuul_be; **178 (top)**/© Molodec; **156 (left)**/© MPIX; **14**/© Nagy-Bagoly Arpad; **176**/© NASA images; **470 (bottom)**/© Nasky; **465 (top)**/© NatalieIme; **57 (bottom)**/© NavinTar; **393**/© Neale Cousland; **35**/© Nightman1965; **112**/© Olga Kashubin; **449 (top right)**/© oTTo-supertramp; **6**/© photastic; **326 (top)**/© Photohunter; **174**/© Phovoir; **394**/© picturepartners;

441/© pikepicture; 462/© PixieMe; 180 (bottom)/© PlanilAstro; 6/© Polryaz; 28/© praphab
louilarrprasert; 447/© Pressmaster; 318 (bottom)/© Radu Razvan; 134/© RalphHuijgen; 256/© Ramsay;
Brent, 313/© Razor527; 178 (bottom)/© Sander van Sinttruye; 448 (middle)/© science photo; 436/©
Sergey Zaykov; 209/© ShadeDesign; 277/© Skumer; 343/© Stason4ik; 450 (middle left)/© Stefan Rotter;
242/© Thorsten Schier; 453/© Tomas Ragina; 450 (top right)/© vitfoto; 149/© vldkont; 80, 450 (middle
right)/© Volodymyr Krasyuk; 180 (top)/© Wolfgang Kloehr; 436/© zsirosistvan • United States Nuclear
Regulatory Commission: 423 • Visionlearning, Inc: 38, 48

Every effort has been made to trace the ownership of copyright material. Information that will enable the
publisher to rectify any error or omission in subsequent reprints will be welcome. In such cases, please
contact the Permissions Section of John Wiley & Sons Australia, Ltd.

UNIT 1

WHAT IDEAS EXPLAIN THE PHYSICAL WORLD?

Ideas in physics are dynamic. As we continue to learn and apply experimental techniques that have been used over the centuries, our knowledge of the physical world improves and theories evolve.

In this unit, you will be introduced to the fundamental physics concepts of thermodynamics, electricity and matter, and will explore how physicists use these fundamental ideas and models in an attempt to understand and explain the world we live in, even those things that are beyond what we can see.

You will learn how physics examines and explores concepts and theories that dictate the behaviour of the smallest particles to the expanse of the universe, and uses this understanding to create a model of our universe.



AREA OF STUDY	OUTCOME	TOPICS
1. How can thermal effects be explained?	Apply thermodynamic principles to analyse, interpret and explain changes in thermal energy in selected contexts, and describe the environmental impact of human activities with reference to thermal effects and climate science concepts.	1. Thermodynamics principles 2. Thermodynamics and climate science
2. How do electric circuits work?	Investigate and apply a basic DC circuit model to simple battery-operated devices and household electrical systems, apply mathematical models to analyse circuits, and describe the safe and effective use of electricity by individuals and the community.	3. Concepts used to model electricity 4. Circuit analysis 5. Using electricity and electrical safety
3. What is matter and how is it formed?	Explain the origins of atoms, the nature of subatomic particles and how energy can be produced by atoms.	6. Origins of atoms 7. Particles in the nucleus 8. Energy from the atom

Source: VCE Physics Study Design (2016–2021) extracts © VCAA; reproduced by permission.

1 Thermodynamic principles

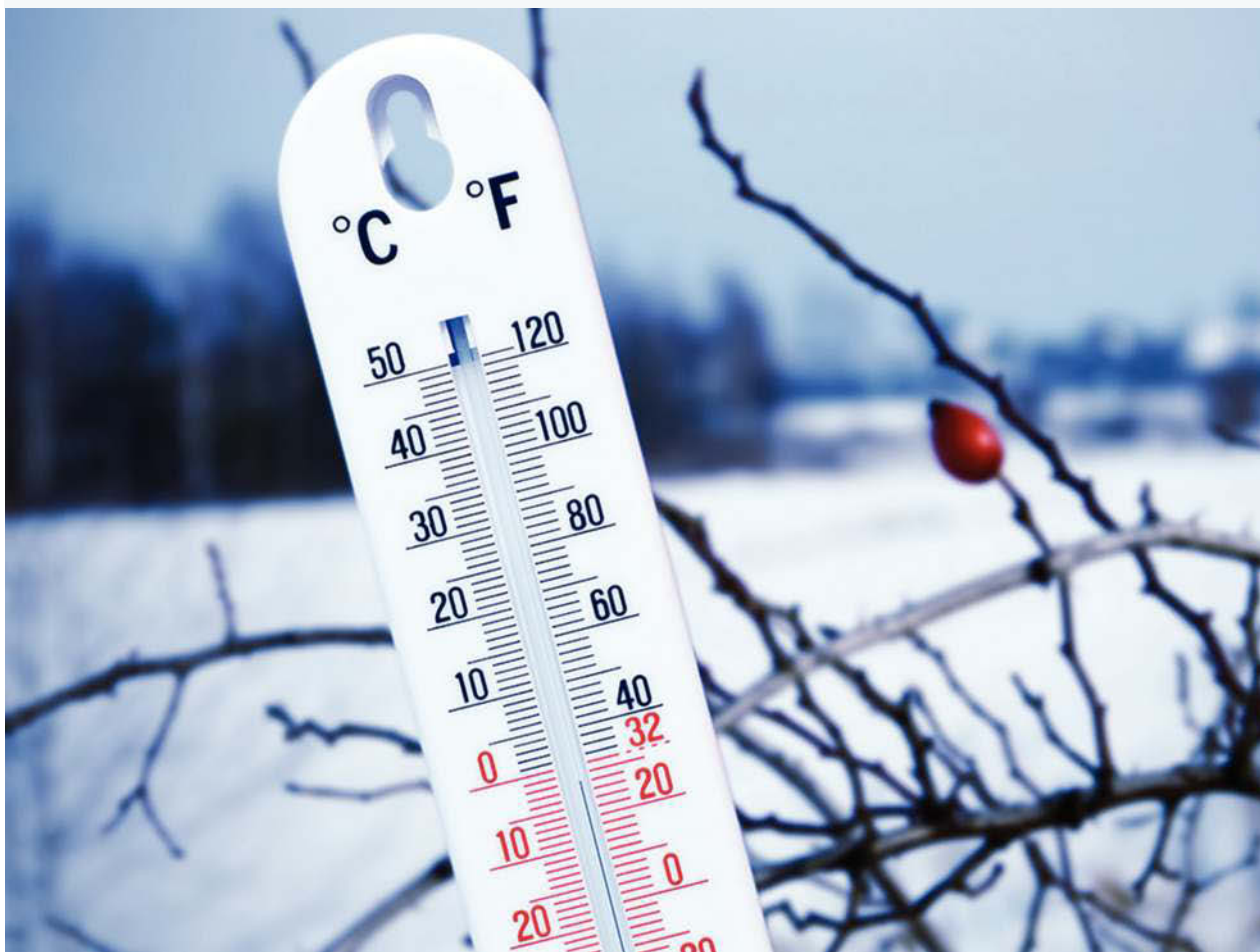
1.1 Overview

Numerous **videos** and **interactivities** are available just where you need them, at the point of learning, in your digital formats, learnON and eBookPLUS at www.jacplus.com.au.

1.1.1 Introduction

In this topic you will revisit your understanding of energy, utilise your knowledge of the particle theory and apply practical skills of measuring temperature. By the end of this topic you should be able to identify and apply the zeroth and first laws of thermodynamics to describe how the energy within a system is shared and transferred. You will be able to use the particle theory to explain internal energy, temperature and heat transfer. You will describe and explain internal energy as the random motion of particles in a substance. You will test and manipulate the relationships that dictate temperature changes in a substance (specific heat capacity) and changes of state (latent heat) and consider how these concepts are engineered to our benefit.

FIGURE 1.1 A cold day in two temperature scales. A balloon caught on a twig shrinks as the translational kinetic energy of the air inside is transferred to the surrounding air, losing the ability to stop the air pressure pushing it in.



1.1.2 What you will learn

KEY KNOWLEDGE

After completing this topic you will be able to:

- convert temperature between degrees Celsius and kelvin
- describe the Zeroth Law of Thermodynamics as two bodies in contact with each other coming to a thermal equilibrium
- describe temperature with reference to the average kinetic energy of the atoms and molecules within a system
- investigate and apply theoretically and practically the First Law of Thermodynamics to simple situations:
 $Q = \Delta U + W$
- explain internal energy as the energy associated with random disordered motion of molecules
- distinguish between conduction, convection and radiation with reference to heat transfers within and between systems
- 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: $Q = mL$
- explain why cooling results from evaporation using a simple kinetic energy model.

Source: VCE Physics Study Design (2016–2021) extracts © VCAA; reproduced by permission.

PRACTICAL WORK AND INVESTIGATIONS

Practical work is a central component of learning and assessment. Experiments and investigations, supported by a **Practical investigation logbook** and **Teacher-led videos**, are included in this topic to provide opportunities to undertake investigations and communicate findings.



Resources



Digital documents Key science skills–VCE Units 1–4 (doc-31856)
Key terms glossary (doc-31857)
Practical investigation logbook (doc-31853)



To access key concept summaries and practice exam questions download and print the **studyON: Revision and practice exam question booklet** (sonr-0026).

1.2 Explaining heat using the kinetic theory

KEY CONCEPTS

- Explain internal energy as the energy associated with random disordered motion of molecules.
- Describe temperature with reference to the average kinetic energy of the atoms and molecules within a system.

1.2.1 What is heat?

It may surprise you to consider that **heat** was not considered a form of energy until quite late in human history. Fire was one of the four elements in ancient times and it was clear that when substances combusted, heat was released. Thus, for centuries heat was considered a substance that could be transferred between objects and this was the starting point for scientific thought. In 1667 Johann Joachim Becher proposed that a substance he called *phlogiston* was released during combustion. Later, in 1789, the French scientist Antoine Lavoisier published a treatise on chemistry in which he described heat as an invisible, tasteless,

odourless, weightless fluid that he called *calorific fluid*, which flowed from hot to cold objects. Although now defunct as an explanation of heat, the measure of the calorie is still used.

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

AS A MATTER OF FACT

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

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

On return to England, his activities included:

- (i) redesigning an industrial furnace, which revolutionised the production of quicklime, a component of cement and is used for lighting ('limelight')
- (ii) redesigning the domestic fireplace to narrow the chimney at the hearth to increase the updraught, resulting in greater efficiency and no smoke coming back into the room
- (iii) inventing thermal underwear, a kitchen range and a drip coffee pot.

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

FIGURE 1.2 Count Rumford



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

Joule used different methods and compared the results.

- *Using gravity.* A falling mass spins a paddle wheel in an insulated barrel of water, raising the temperature of the water.
- *Using electricity.* Mechanical work is done turning a dynamo to produce an electric current in a wire, which heats the water.

- *Compressing a gas.* Mechanical work is used to compress a gas, which raises the gas's temperature.
- *Using a battery.* Chemical reactions at the battery terminals produce a current, which heats the water.
- *Using gravity.* Measure the temperature of water at the top and bottom of a waterfall.

Joule obtained approximately identical answers for all methods.

This confirmed heat as a form of energy. To honour his achievement, the SI unit of energy is the **joule** (J). The unit joule is used to measure the:

- kinetic energy of a runner
- light energy in a beam
- chemical energy stored in a battery
- electrical energy in a circuit
- potential energy in a lift on the top floor
- heat energy when water boils.

One joule is approximately the amount of energy needed to lift a 100 gram apple through a height of 1 metre.



The usual metric prefixes make the use of the unit joule more convenient. For example:

$$1 \text{ kJ (kilojoule)} = 10^3 \text{ J} \quad 1 \text{ MJ (megajoule)} = 10^6 \text{ J} \quad 1 \text{ GJ (gigajoule)} = 10^9 \text{ J}$$

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

Examples of 1 joule include:

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



1.2.2 Linking energy and heat: the kinetic theory of matter

Joule showed that a measure of energy was directly related to a change in temperature. But what happens to this energy within a material? The kinetic theory of matter enables us to explain the effect of energy on a material.

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

The evidence for the existence of particles includes the following.

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

FIGURE 1.3 Iodine crystals sublime (turn directly into a gas) when heated.



The kinetic theory of matter assumes that:

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

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

Gases

In a gas made up of single atoms, such as helium, the atoms move around, randomly colliding with each other and the walls of the container. So, each atom has some **translational kinetic energy** (see figures 1.4 and 1.5).

However, if the gas is made up of molecules with two or more atoms, the molecules can also stretch, contract and spin, so these molecules also have other types of kinetic energy called **vibrational kinetic energy** and **rotational kinetic energy** (see figure 1.5).

Liquids

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

Solids

In a solid, atoms jiggle rather than move around. They have kinetic energy, but they also have a lot of potential energy stored in the strong attractive force that holds the atoms together. This means that a lot of energy is required to melt a solid. This is seen in Figure 1.6.

FIGURE 1.4 Moving single atoms have translational kinetic energy.

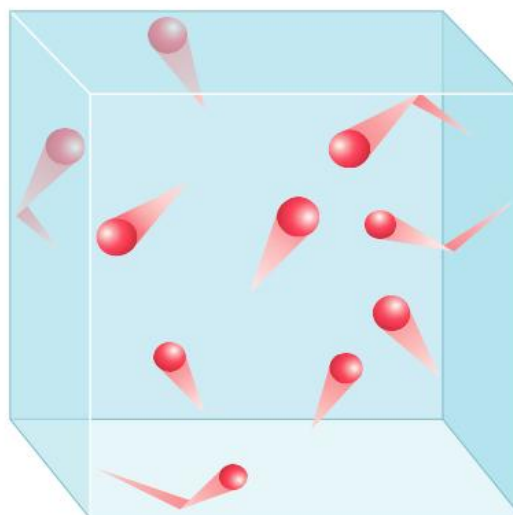


FIGURE 1.5 The movements of a molecule

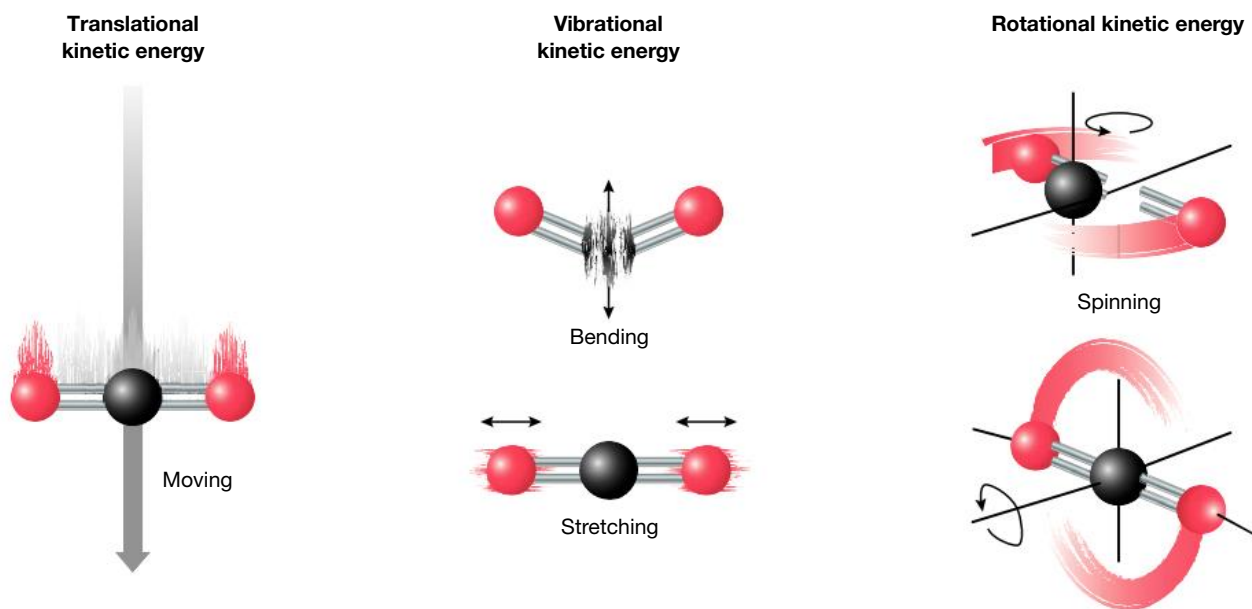
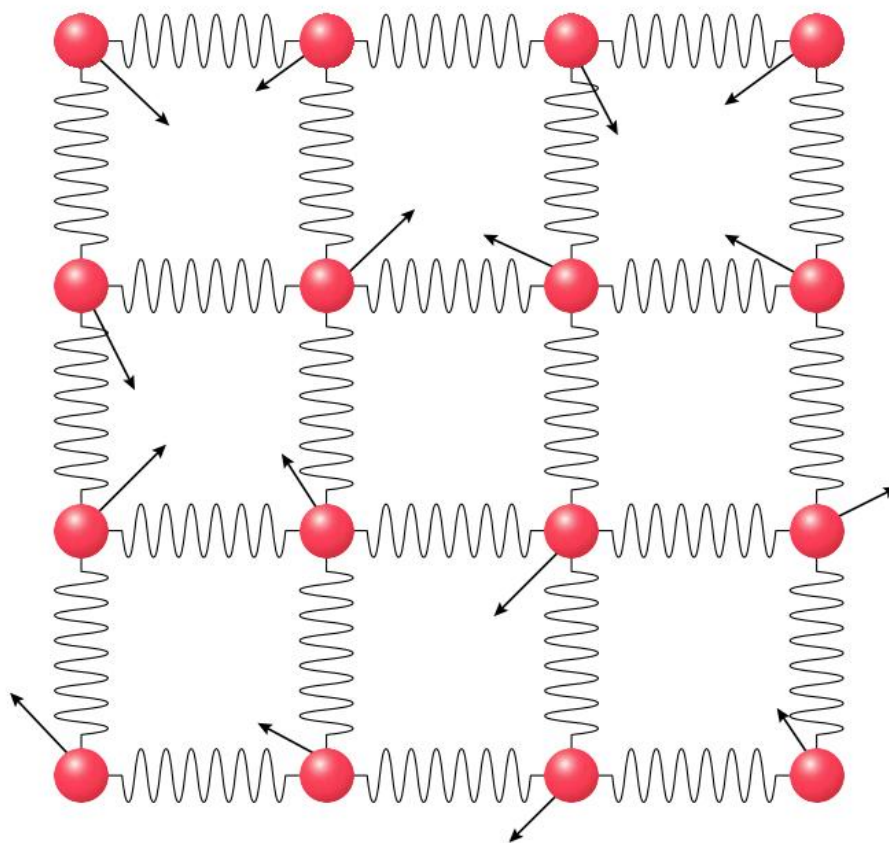


FIGURE 1.6 In a solid, atoms can jiggle around an essentially fixed location.



When the internal energy of a substance increases, this means the particle movement increases. Heating or cooling is reflected in a change in the particle movement. Heat energy will always transfer from a hotter substance to a colder substance as the collisions of the faster moving particles transfer translational kinetic energy to the slower moving particles.

TABLE 1.1 The internal energy of different objects

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

1.2 EXERCISE

To answer questions online and to receive **immediate feedback** and **sample responses** for every question go to your learnON title at www.jacplus.com.au.

1. Use the particle theory to explain why you can smell what's for dinner from the front door of your house.
2. Explain the difference between translational kinetic energy and other types of internal energy.
3. Use the particle theory to explain what happens when your cup of tea cools down over time.
4. Cling film on a warm bowl of soup placed in the fridge gets sucked down when it cools. Use the particle theory to explain this.
5. James Joule showed that mechanical energy could be transformed into the internal energy of a substance or object. The temperature of a nail, for example, can be raised by hitting it with a hammer. List as many examples as you can of the use of mechanical energy to increase the temperature of a substance or object.
6. Explain in terms of the kinetic particle model why a red-hot pin dropped into a cup of water has less effect on the water's temperature than a red-hot nail dropped into the same cup of water.
7. Explain why energy is transferred from your body into the cold sea while swimming even though you have less internal energy than the surrounding cold water.

studyon

To answer practice exam questions online and to receive immediate feedback and sample responses for every question go to your learnON title at www.jacplus.com.au.

studyON: Practice exam questions 

Fully worked solutions and sample responses are available in your digital formats.

1.3 Measuring and converting temperature

KEY CONCEPT

- Convert temperature between degrees Celsius and kelvin.

We have learnt that heat is described as energy and that energy can be measured using the joule. We also know that heating a substance causes the particles within that substance to move faster. This movement is erratic and impossible to measure individually. Instead we consider the average increase in translational kinetic energy.

1.3.1 Measuring temperature

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

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

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

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

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

A third temperature scale was proposed in 1848 by William Thomson, later to be ennobled as Lord Kelvin. He proposed the scale based on the better understanding of heat and temperature that had developed by that time (see page 9). This scale uses the symbol 'K' to stand for 'kelvin'.

Other materials, including gases and metals, also expand with temperature and are used as thermometers. A bimetallic strip is two lengths of different metals, usually steel and copper, joined together. The two metals expand at different rates, so the strip bends one way as the temperature rises, or the other as it cools. A bimetallic strip can be used as a thermometer, a thermostat or as a compensating mechanism in clocks.

THE LOWEST TEMPERATURE

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

Properties that change with temperature and can be employed in designing a thermometer are:

- electrical resistance of metals, which increases with temperature
- electrical voltage from a thermocouple, which is two lengths of different metals with their ends joined; if one end is heated, a voltage is produced (see figure 1.7)
- colour change; liquid crystals change colour with temperature (see figure 1.8)
- colour emitted by a hot object; in steel making, the temperature of hot steel is measured by its colour (see figure 1.9).

FIGURE 1.7 This thermocouple is connected to a voltmeter, which reads differing voltages as the thermocouple changes temperature.

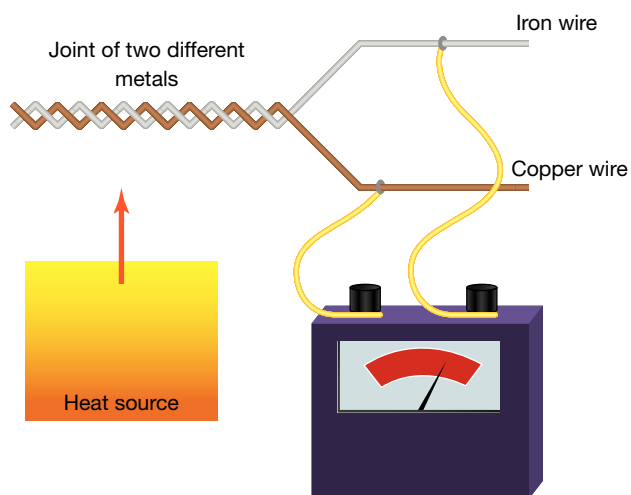


FIGURE 1.8 This liquid crystal thermometer indicates body temperature when the liquid crystals change colour. The thermometer is registering 37 °C.

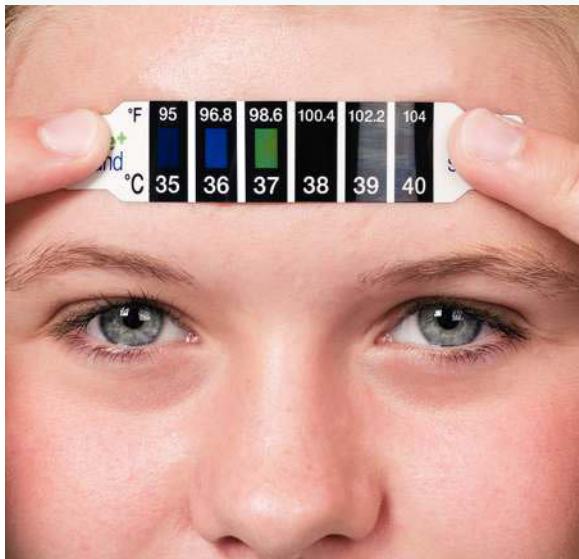


FIGURE 1.9 This steel is nearly 1000 °C and has recently been poured into a mould to shape it. The steel will continue to glow until it has cooled to about 400 °C.



1.3.2 The Kelvin scale

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

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

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

In kelvin, absolute zero is 0 K. The increments in the Kelvin temperature scale are the same size as those in the Celsius scale, so if the temperature increased by 5 °C , it also increased by 5 K.

The conversion formula between the two temperature scales is:

$$\text{kelvin} = \text{Celsius} + 273$$

$$T_{(\text{kelvin})} = T_{(\text{Celsius})} + 273$$

FIGURE 1.10 By extrapolating his trend line back, Kelvin was able to establish absolute zero at $-273\text{ }^{\circ}\text{C}$. With modern equipment absolute zero is now determined to be $-273.15\text{ }^{\circ}\text{C}$.

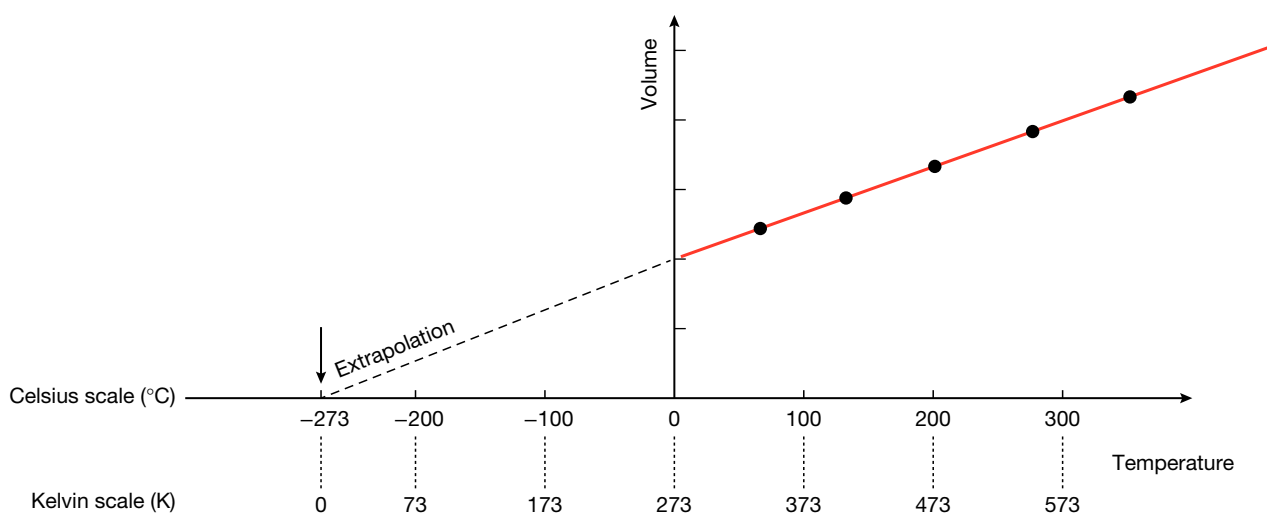


TABLE 1.2 Some temperatures on the Kelvin and Celsius scales

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

Note: In 1968, the international General Conference on Weight and Measures decided that kelvin temperatures do not use the $^{\circ}$ symbol, unlike Celsius and Fahrenheit temperatures.

SAMPLE PROBLEM 1

What is the kelvin temperature at which ice melts?

 **Teacher-led video:** SP1 (tlvd-0003)

THINK

- Recall the relationship between the two temperature scales.
- Ice melts at $0\text{ }^{\circ}\text{C}$. Substitute $0\text{ }^{\circ}\text{C}$ into the conversion formula.
- State the solution.

WRITE

$$T_{(\text{kelvin})} = T_{(\text{Celsius})} + 273$$

$$\begin{aligned} T_{(\text{kelvin})} &= T_{(\text{Celsius})} + 273 \\ &= 0 + 273 \\ &= 273\text{ K} \end{aligned}$$

Ice melts at 273 K.

PRACTICE PROBLEM 1

The temperature of the universe predicted by the cosmic microwave background is 3 K. What is this in degrees Celsius?

1.3 EXERCISE

To answer questions online and to receive **immediate feedback** and **sample responses** for every question go to your learnON title at www.jacplus.com.au.

1. Why is the Celsius scale of temperature commonly used rather than the Kelvin scale?
2. What is the main advantage of an absolute scale of temperature?
3. Estimate each of the following temperatures in kelvin:
 - (a) the maximum temperature in Melbourne on a hot summer's day
 - (b) the minimum temperature in Melbourne on a cold, frosty winter's morning
 - (c) the current room temperature
 - (d) the temperature of cold tap water
 - (e) the boiling point of water.
4. The temperature of very cold water in a small test tube is measured with a large mercury-in-glass thermometer. The temperature measured is unexpectedly high. Suggest a reason for this.
5. Carbon dioxide sublimates, that is, goes directly from solid to gas, at -78.5°C . What is this temperature in kelvin?
6. The temperature of the surface of Mars was measured by the Viking lander and ranged from 256 K to 166 K. What are the equivalent temperatures in degrees Celsius?

studyon

To answer practice exam questions online and to receive immediate feedback and sample responses for every question go to your learnON title at www.jacplus.com.au.

studyON: Practice exam questions 

Fully worked solutions and sample responses are available in your digital formats.

1.4 Transferring heat

KEY CONCEPTS

- Distinguish between conduction, convection and radiation with reference to heat transfers within and between systems.
- Identify regions of the electromagnetic spectrum as radio, microwave, infra-red, visible, ultraviolet, X-ray and gamma waves.

From our understanding of the particle theory and its relationship to heat we know that energy is always transferred from a region of higher temperature to a region of lower temperature.

There are many situations in which it is necessary to control the rate at which the energy is transferred.

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

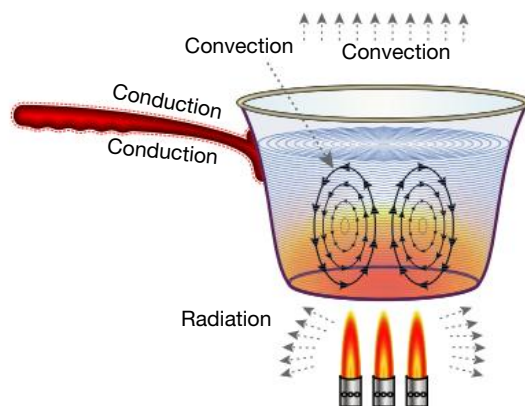
- The storage of many foods in cold temperatures is necessary to keep them from spoiling. In warm climates most beverages are enjoyed more if they are cold. The transfer of heat from the warmer surroundings needs to be kept to a minimum.

FIGURE 1.11 Reducing heat transfer to and from buildings saves precious energy resources, and reduces gas and electricity bills.



There are three different processes through which energy can be transferred during heating and cooling: **conduction**, **convection** and **radiation** (see figure 1.12).

FIGURE 1.12 Heat is transferred by conduction, convection and radiation.

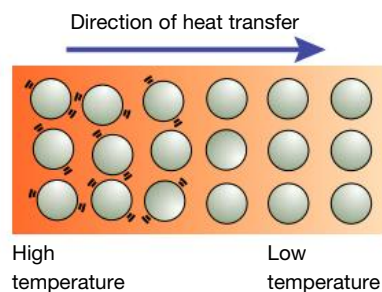


1.4.1 Conduction

Conduction is the transfer of heat through a substance as a result of collisions between neighbouring vibrating particles. The particles in the higher temperature region have more random kinetic energy than those in the lower temperature region. As shown in figure 1.13, the more energetic particles collide with the less energetic particles, giving up some of their kinetic energy. This transfer of kinetic energy from particle to particle continues until thermal equilibrium is reached. There is no net movement of particles during the process of conduction.

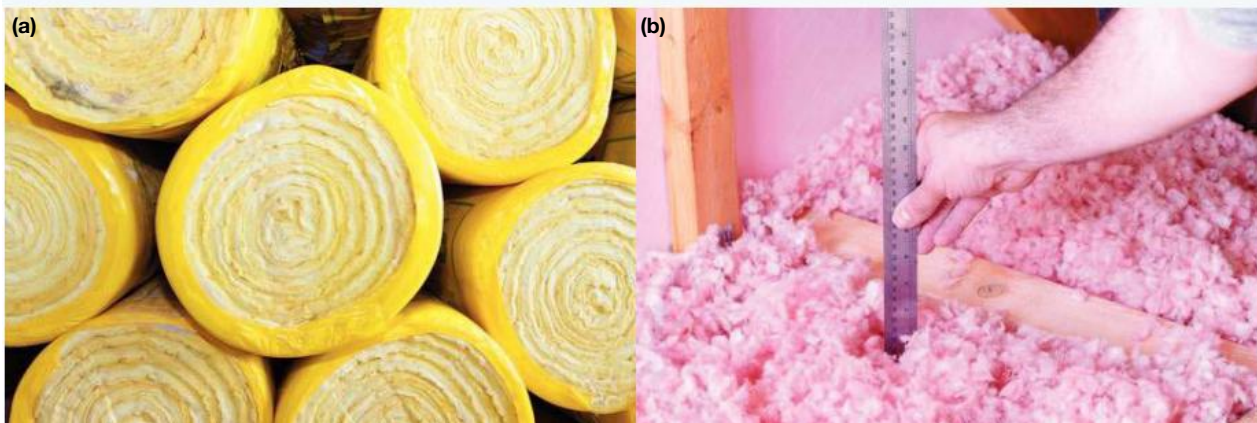
Solids are better **conductors** of heat than liquids and gases. In solids, the particles are more tightly bound and closer together than in liquids and gases. Thus, kinetic energy can be transferred more quickly. Metals are the best conductors of heat because free electrons are able to transfer kinetic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

FIGURE 1.13 Conduction is the transfer of thermal energy (heat) due to collisions between neighbouring particles.



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

FIGURE 1.14 (a) Insulators like rock mineral wool have excellent thermal and acoustic properties. (b) Fibreglass insulation is made from recycled glass bottles, sand and other materials.

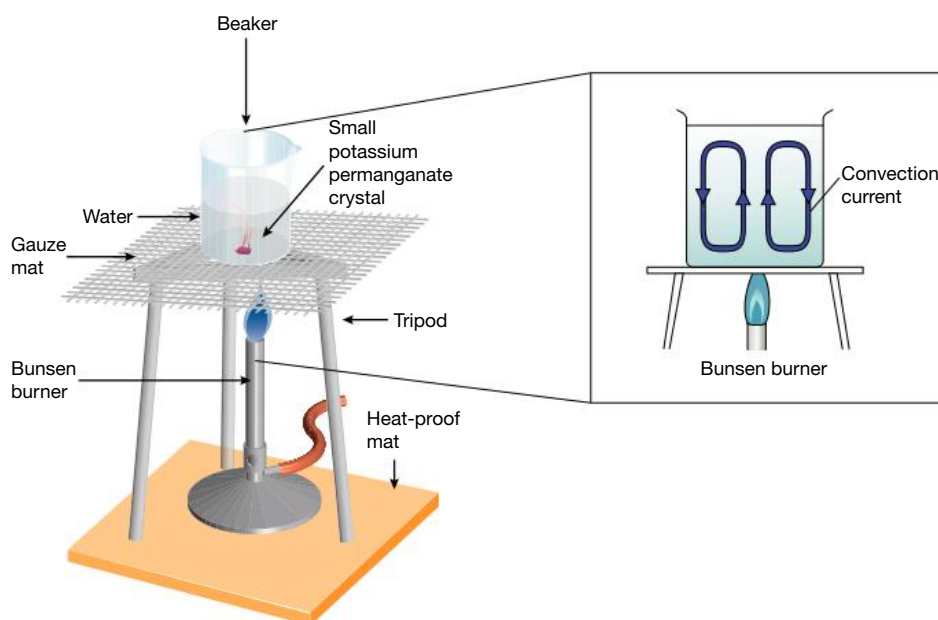


1.4.2 Convection

Convection is the transfer of heat through a substance as a result of the movement of particles between regions of different temperatures. Convection takes place in liquids and gases where particles are free to move around. In solids, the particles vibrate about a fixed position and convection does not generally occur, except under specific conditions (e.g. in the extreme temperature and pressure in the Earth's mantle).

The movement of particles during convection is called a **convection current**. Faster moving particles in hot regions rise while slower moving particles in cool regions fall. The particles in the warm water near the flame in figure 1.15 are moving faster and are further apart than those in the cooler water further from the flame. The cooler, denser water sinks, forcing the warm, less dense water upwards. This process continues as the warm water rises, gradually cools and eventually sinks again, replacing newly heated water.

FIGURE 1.15 Purple particles from a crystal of potassium permanganate carefully placed at the bottom of the beaker are forced around the beaker by convection currents in the heated water.



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

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

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

1.4.3 Radiation

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

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

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

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

FIGURE 1.16 Convection currents circulate warm air pushed out by home heating systems. The warm air rises, circulates around the room until it cools and sinks, being replaced with more warm air.

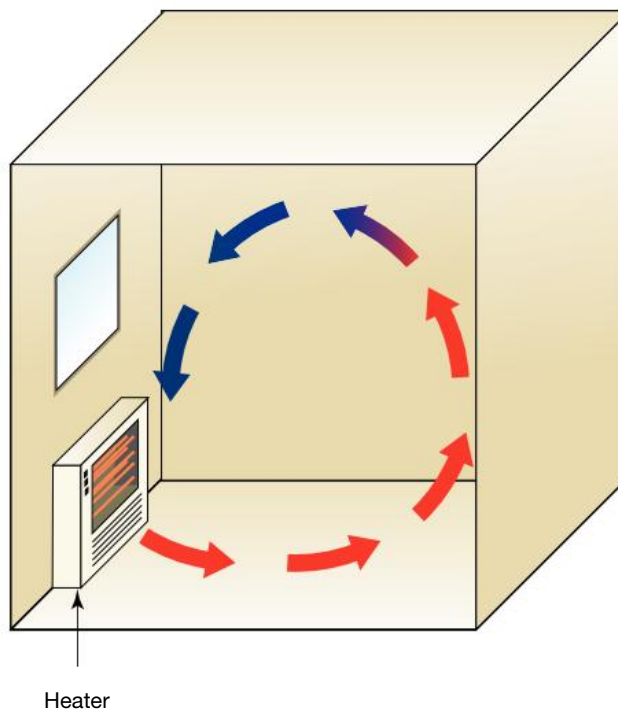
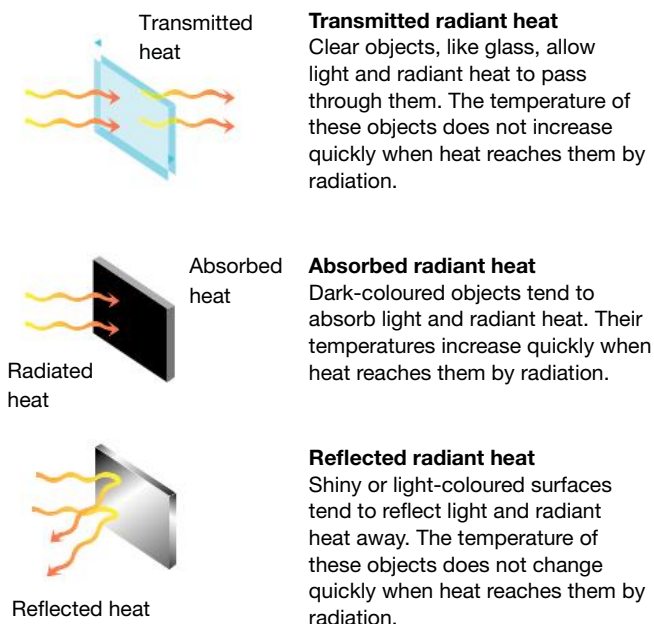


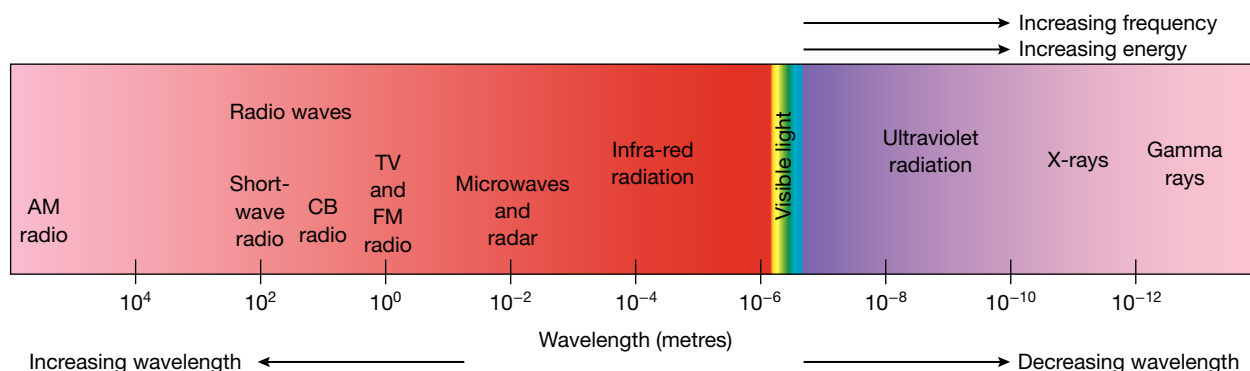
FIGURE 1.17 Radiant heat can be transmitted, absorbed or reflected



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

Figure 1.18 shows the electromagnetic spectrum and demonstrates that higher energy radiation corresponds to low wavelength.

FIGURE 1.18 The electromagnetic spectrum. All objects emit some electromagnetic radiation.

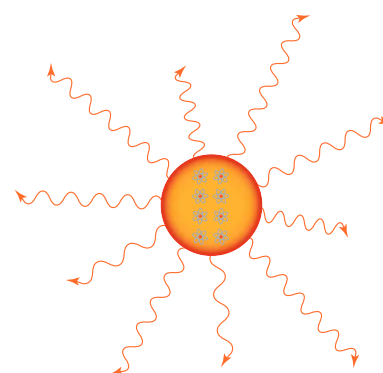


Why do hot objects emit electromagnetic radiation?

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

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

FIGURE 1.19 Electromagnetic radiation from a hot body



1.4 EXERCISE

To answer questions online and to receive **immediate feedback** and **sample responses** for every question go to your learnON title at www.jacplus.com.au.

1. Explain with the aid of a well-labelled diagram how heat is transferred through a substance by conduction.
2. Why are liquids and gases generally poorer conductors of heat than solids?
3. Explain how convection occurs in a liquid that is being heated from below.
4. Why is it not possible for heat to be transferred through solids by convection?
5. At what speed does radiant energy move through space? What is significant about this speed?
6. When you swim in a still body of water on a hot afternoon there is a noticeable temperature difference between the water at the surface and the deeper water.
 - (a) Explain why this difference occurs.
 - (b) If the water is rough, the difference is less noticeable. Why?
7. Standing near the concrete wall of a city building after a hot day you can instantly feel its warmth from a few metres away.
 - (a) How is the energy transferred to you?
 - (b) What caused the building to get hot during the day?
8. Why is it not practical to drink hot coffee in an aluminium picnic cup?
9. Why do ducts in the ceiling need more powerful fans than those in the floor?

1.5 Thermal equilibrium and the laws of thermodynamics

KEY CONCEPTS

- Describe the Zeroth Law of Thermodynamics as two bodies in contact with each other coming to a thermal equilibrium.
- Investigate and apply theoretically and practically the First Law of Thermodynamics to simple situations:
 $Q = \Delta U + W$.
- Explain why cooling results from evaporation using a simple kinetic energy model.

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

So when a hot nail is dropped into a beaker of cold water, energy will be transferred from the hot nail into the water even though the hot nail has less total internal energy than the water. When thermal equilibrium is reached, the temperature of both the water and the nail is the same. The particles of water and the particles in the nail have the same amount of random translational kinetic energy. Figure 1.20 shows how the kinetic particle model can be used to explain the direction of energy transfer in the beaker.

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

FIGURE 1.20 The particles in the nail have more kinetic energy (on average) than those that make up the water. They collide with the particles of water, losing some of their kinetic energy and increasing the kinetic energy of individual particles of water. The temperature of the surrounding water increases.

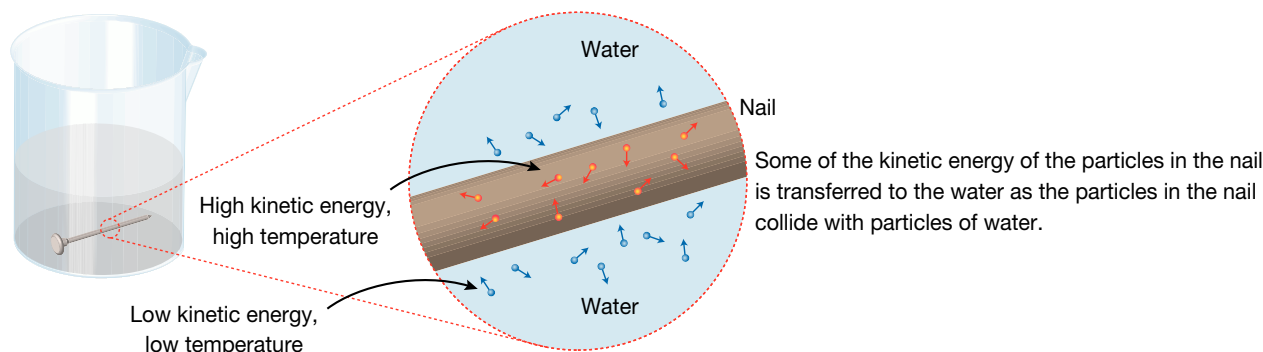
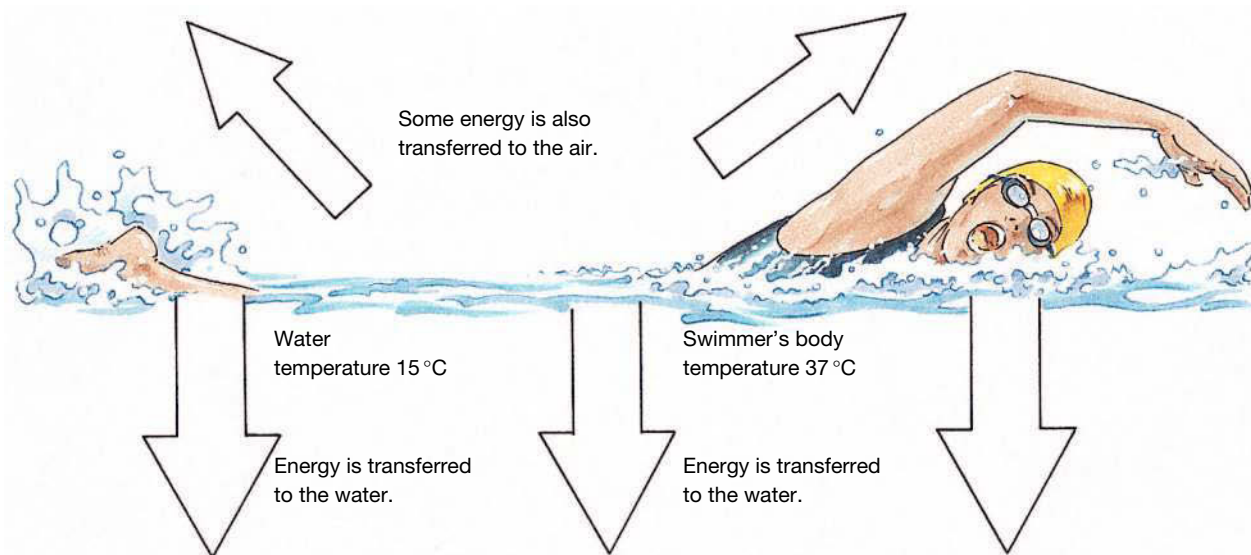


FIGURE 1.21 When you swim in a cold pool, energy is transferred from your body into the water. The water has much more total internal energy than your body because there is so much of it. However, the particles in your body have more random translational kinetic energy that can be transferred to the particles of cold water. Hopefully, you would not remain in the water long enough for thermal equilibrium to be reached.



1.5.1 Laws of thermodynamics

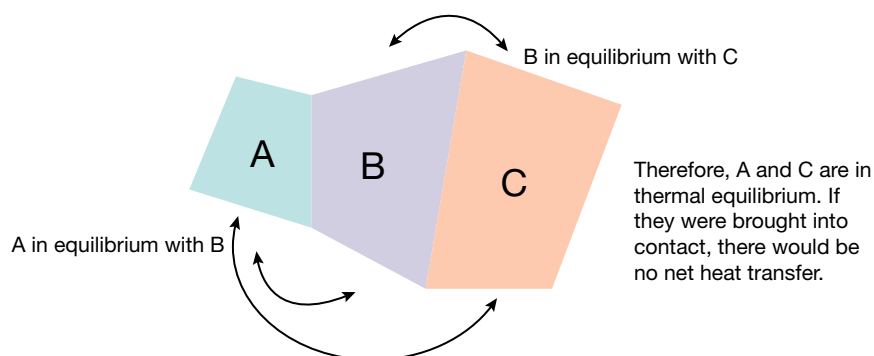
Three laws of thermodynamics were progressively developed during the nineteenth century. In the twentieth century it became apparent that the principle of thermal equilibrium could be seen as the logical underpinning of these three laws. Consequently, the Zeroth Law of Thermodynamics became accepted.

Zeroth Law of Thermodynamics

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

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

FIGURE 1.22 If objects are in contact, they will reach thermal equilibrium. The middle object is known to be in thermal equilibrium with each outer object; thus, each outer object must also be in thermal equilibrium.



First Law of Thermodynamics

The **First Law of Thermodynamics** states that energy is conserved and cannot be created or destroyed (see figure 1.23). If there is an energy change in a system, all the energy must be accounted for.

The First Law of Thermodynamics says:

$$\begin{array}{rclcl} \text{Change in the internal energy} & = & \text{Heat energy added} & - & \text{Work done} \\ \text{of the air} & & \text{to the system} & & \text{by the system} \\ \Delta U & = & Q & - & W \\ \Delta U = Q - W \text{ or } Q = \Delta U + W & & & & \end{array}$$

Where:

Q is the heat energy added to the system, in joules

W is the work done by the system, in joules

ΔU is the change in internal energy, in joules.

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

If heat is added to the system ($+Q$) or work is done on the system ($-W$), then the internal energy increases and ΔU is positive.

If heat is removed from the system ($-Q$) or work is done by the system ($+W$), then the internal energy decreases and ΔU is negative.

Consider a volume of air inside a balloon that is placed in direct sunlight. The air inside the balloon will get hotter and the balloon will expand slightly. The energy from the Sun heats the air inside the balloon, increasing the kinetic energy of the air molecules. The air molecules lose some of this energy as they repeatedly collide with the wall of the balloon, forcing it outwards.

The First Law of Thermodynamics applies to many situations: cylinders in a car engine, hot air balloons, food consumption, pumping up a tyre and the weather (see table 1.3). Consequently, the word ‘system’ is often used as a generic name when discussing thermodynamics.

FIGURE 1.23 Energy is conserved. The heat energy added to the system is equal to the energy removed from the system.

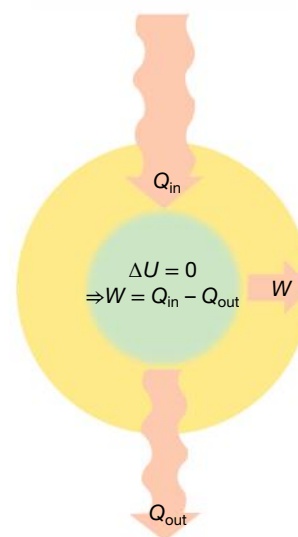


TABLE 1.3 First Law of Thermodynamics as it applies to different situations

Circumstance	Example	Result
If a system absorbs heat	Energy from sunlight	$Q > 0$
If a system releases heat	When you sweat	$Q < 0$
If a system does work on the surroundings	Hot balloon expands	$W > 0$
If the surroundings do work on the system	Pumping up a tyre	$W < 0$

SAMPLE PROBLEM 2

- a. A balloon is placed in direct sunlight. The sunlight supplies 200 joules of energy to the balloon. The air inside pushes out the balloon surface, doing 50 joules of work. By how much does the internal energy of the air inside change?
- b. A large block of ice is heated by 100 joules of energy but does not melt. What is the change in internal energy?

 Teacher-led video: SP2 (tlvd-0004)

THINK

- a. 1. Recall the relationship $\Delta U = Q - W$.
2. Identify the variables. The system is the balloon. Heat is added to the system, so Q is positive. The system does work on the surroundings, so W is positive.
3. Substitute into the relationship to find ΔU .
4. State the solution.
- b. 1. Recall the relationship $\Delta U = Q - W$.
2. Identify the variables. The system is the ice block. Heat is added to the system, so Q is positive. No work is done because the ice doesn't melt.
3. Substitute into the relationship to find ΔU .
4. State the solution.

WRITE

- a. $\Delta U = Q - W$
 $Q = 200 \text{ J}, W = 50 \text{ J}$
- $\Delta U = 200 - 50$
 $= 150 \text{ J}$
- The internal energy of the air inside the balloon has increased by 150 J.
- b. $\Delta U = Q - W$
 $Q = 100 \text{ J}, W = 0 \text{ J}$
- $\Delta U = 100 - 0$
 $= 100 \text{ J}$
- The internal energy of the ice has increased by 100 J.

PRACTICE PROBLEM 2

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



Resources



Interactivity Thermal equilibrium (int-6390)

1.5 EXERCISE

To answer questions online and to receive **immediate feedback** and **sample responses** for every question go to your learnON title at www.jacplus.com.au.

1. It is said that thermometers indirectly measure the temperature of an object by measuring their own temperature. Explain this statement by referring to the concept of thermal equilibrium.

2. For each of the following, calculate the values of Q , W and ΔU and indicate whether the temperature increases, decreases or stays the same.
 - (a) A gas in a fixed container is heated by 500 J.
 - (b) A gas in a container with a flexible lid is cooled by ice with 250 J of energy extracted.
 - (c) A gas in a container with a plunger is squashed by a heavy mass moving down, losing 150 J of gravitational potential energy.
 - (d) A stretched rubber band at room temperature with 5 J of stored energy is released.
3. A can filled with a high-pressure gas has a balloon attached over the top. What happens to the temperature of the gas inside the can as you allow the gas to expand into the balloon?
4. A barbecue uses gas from a gas bottle as its energy source. After the barbecue has been running for a while, ice is noticed around the top of the gas bottle. Explain the physics principles behind this observation.
5. Consider these three scenarios then complete the table, using either 0, – or +.
 - (a) An insulated container, such as a thermos flask, has a piston that can be moved up and down without letting the air out. The piston is pushed down.
 - (b) A metal tin with a lid is heated.
 - (c) A metal tin with a sliding lid and a mass on top is heated.

	(a)	(b)	(c)
Heat (+ is in)			
Work (+ is out)			
ΔU			

studyon

To answer practice exam questions online and to receive immediate feedback and sample responses for every question go to your learnON title at www.jacplus.com.au.

studyON: Practice exam questions 
 Fully worked solutions and sample responses are available in your digital formats.

1.6 Specific heat capacity

KEY CONCEPTS

- 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: $Q = mL$.

1.6.1 Specific heat capacity

Once the temperature of materials could be accurately measured, it became apparent that, when heated, some materials increased in temperature more quickly than others. This phenomenon is called the ‘specific heat capacity’ of materials.

The ‘specific heat capacity’ of materials is defined as the amount of energy required to increase the temperature of 1 kilogram of the substance by 1 °C (or K).

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

TABLE 1.4 Specific heat capacity of some common substances

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

Specific heat capacities differ because of two factors:

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

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

The quantity of energy, Q , transferred to or from a substance in order to change its temperature is given as:

$$Q = mc\Delta T$$

Q is directly proportional to three factors:

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

SAMPLE PROBLEM 3

- a. How much energy is needed to heat 8.0 L (about 8.0 kg) of water from a room temperature of 15 °C to 85 °C?
- b. A chef pours 200 grams of cold water with a temperature of 15 °C into a hot aluminium saucepan with a mass of 250 grams and a temperature of 120 °C. What will be the common temperature of the water and saucepan when thermal equilibrium is reached? Assume that no energy is transferred to or from the surroundings.

 Teacher-led videos: SP3 (tlvd-0005)

THINK

- Recall the relationship $Q = mc\Delta T$.
- Identify the values, using table 1.4 to determine the specific heat capacity and calculate the temperature difference in kelvin.
- Substitute values into the formula and solve.
- State the solution.

WRITE

- a. $Q = mc\Delta T$
- $$m = 8.0 \text{ kg}, c = 4200 \text{ J kg}^{-1} \text{ K}^{-1}$$
- $$\Delta T = 85^\circ \text{C} - 15^\circ \text{C}$$
- $$= 70^\circ \text{C}$$
- $$= 70 \text{ K (same change)}$$
- $$Q = 8.0 \times 4200 \times 70$$
- $$= 2\,352\,000$$
- $$= 2.4 \times 10^3 \text{ kJ}$$
- $2.4 \times 10^3 \text{ kJ}$ of energy is needed to increase the temperature of 8.0 L of water from 15 °C to 85 °C.

- b. The solution to this question relies on the following three factors.
- Energy is transferred from the saucepan into the water until both the saucepan and the water reach the same temperature (T_f °C).
 - The amount of internal energy (Q_w) gained by the water will be the same as the amount of internal energy lost by the saucepan (Q_s).
 - The internal energy gained or lost can be expressed as $mc\Delta T$. (ΔT can be expressed in K or °C since change in temperature is the same in both units.)

- Recall the relationship $Q_w = Q_s$.
- Identify the change in temperature of the water and saucepan.
- Substitute values into the formula and solve.

$$Q_w = Q_s$$

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

$$\Delta T_w = T_f - 15^\circ \text{C}$$

$$\Delta T_s = 120^\circ \text{C} - T_f$$

$$0.200 \text{ kg} \times 4200 \text{ J kg}^{-1} \text{ }^\circ\text{C}^{-1} \times (T_f - 15^\circ \text{C})$$

$$= 0.250 \text{ kg} \times 900 \text{ J kg}^{-1} \text{ }^\circ\text{C}^{-1} \times (120^\circ \text{C} - T_f)$$

$$840T_f - 12\,600 = 27\,000 - 225T_f$$

$$1065T_f = 39\,600$$

$$T_f = \frac{39\,600}{1065}$$

$$= 37.18^\circ \text{C}$$

- State the solution (to the least number of significant figures provided in the question).

The saucepan and the water have reached a common temperature of 37 °C.

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

PRACTICE PROBLEM 3

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

CAUTION! CONTENTS MAY BE HOT

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

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



1.6.2 Latent heat

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

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

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

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

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

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

Specific latent heat of fusion

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

Specific latent heat of vaporisation

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

FIGURE 1.24 Changes of state and latent heat

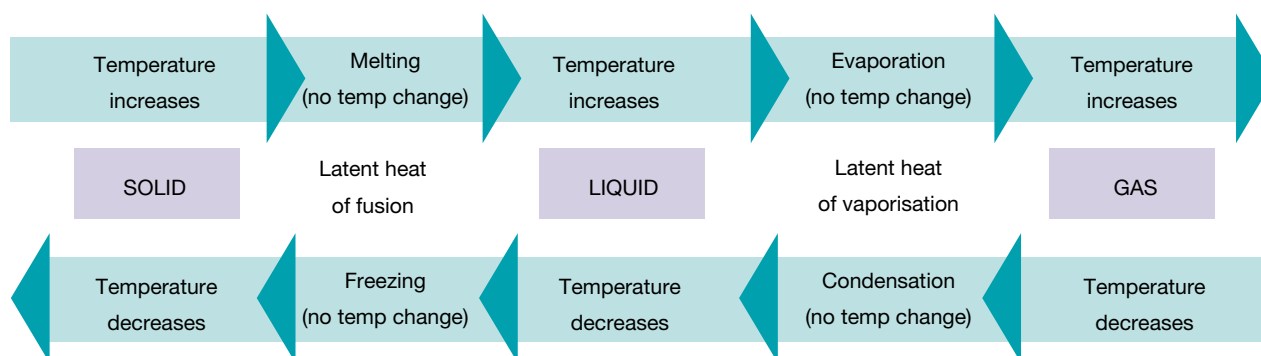


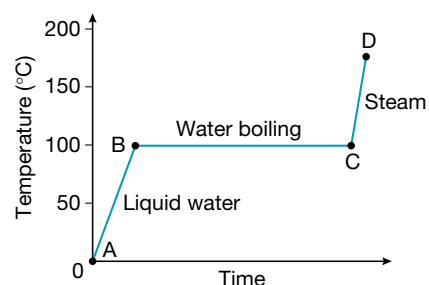
Table 1.5 details both the specific latent heat of fusion and the specific latent heat of vaporisation of a number of common substances.

TABLE 1.5 Specific latent heat of some common substances

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

The graph in figure 1.25 shows how the temperature of water increases as it is heated at a constant rate. During the interval BC, the temperature is not increasing. The water is changing state. The energy transferred to the water is not increasing the random translational kinetic energy of water particles. Note that the gradient of the section AB is considerably less than the gradient of the section CD. What difference in the properties of water and steam does this reflect?

FIGURE 1.25 A heating curve for water being heated at a constant rate



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

$$Q = mL$$

Where:

m = mass of the substance

L = specific latent heat of fusion or vaporisation.

SAMPLE PROBLEM 4

The graph in figure 1.25 might represent the melting of aluminium. The melting point of aluminium is $660.3\text{ }^{\circ}\text{C}$.

- How much energy must be transferred to completely melt 2.5 kilograms of aluminium?
- What would be the temperature of the aluminium at the instant it has all melted?

 Teacher-led video: SP4 (tlvd-0006)

THINK

1. Identify what type of change of state is occurring: fusion or vaporisation.
 2. Identify the values and calculate the temperature difference in kelvin.
 3. Substitute values into the formula and solve.
 4. State the solution.
1. All of the energy supplied is being used to change state, thus the temperature does not rise (see flat section of graph).

WRITE

- Changing from solid to liquid is fusion.
 $Q = mL$
 $L = 2.2 \times 10^3 \text{ J kg}^{-1}, m = 2.5 \text{ kg}$
 $Q = 2.2 \times 10^3 \text{ J kg}^{-1} \times 2.5 \text{ kg}$
 $= 5.5 \times 10^3 \text{ J}$
 $5.5 \times 10^3 \text{ J}$ of energy is needed to completely melt 2.5 kg of aluminium.
- The temperature just after state change is still $660.3\text{ }^{\circ}\text{C}$.

PRACTICE PROBLEM 4

Determine how much energy is absorbed to evaporate 15 grams of water.



Resources



Interactivity Changes of state (int-0222)

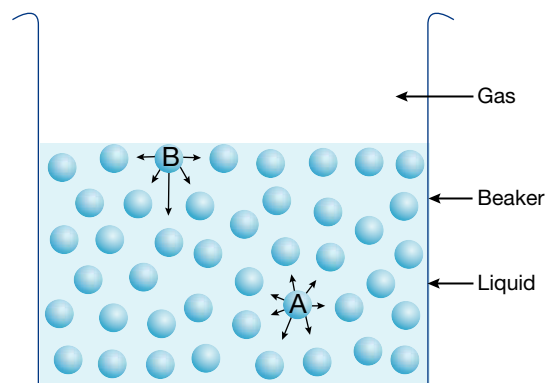
1.6.3 Evaporation

Your skin is not completely watertight, which allows water from the skin and tissues beneath it to evaporate. The latent heat of vaporisation required for the water to change state from liquid to gas is obtained from the body, reducing its temperature. Evaporation of water from the mouth and lungs

also takes place during the process of breathing. Even without sweating, the energy used to evaporate water in the body accounts for about 17 per cent of the total heat transfer from the body to the environment.

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

FIGURE 1.26 Particle A experiences forces of attraction from the surrounding particles in all directions. Particle B does not experience as many forces, so it will need less kinetic energy to escape the forces of attraction and evaporate.



STEAM BURNS

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



on Resources

 **Digital documents** Investigation 1.1 The good oil on heating (doc-31854)

Investigation 1.2 Cooling (doc-31855)

 **Teacher-led video** Investigation 1.2 Cooling (tlvd-0804)

1.6 EXERCISE

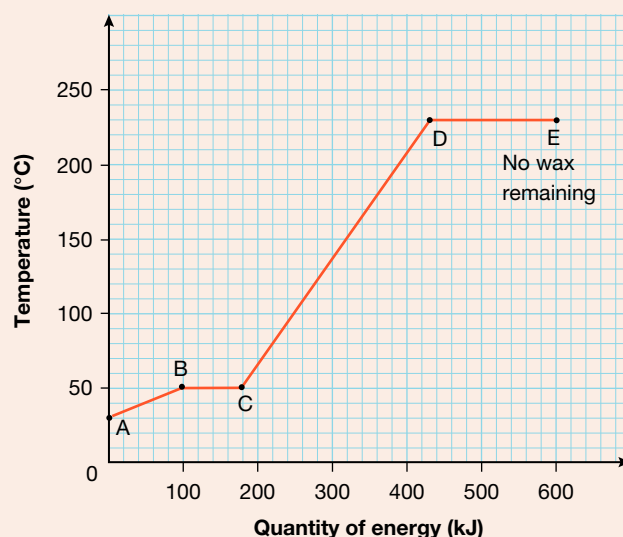
To answer questions online and to receive **immediate feedback** and **sample responses** for every question go to your learnON title at www.jacplus.com.au.

- The same hotplate is used to heat 50 grams of ethylene glycol (used in car antifreeze) and 50 grams of cooking oil. Both substances are heated for 2 minutes. Use the data in the table 1.4 to determine which liquid:
 - needs more energy to increase its temperature by 1°C
 - will experience the greater increase in temperature.
- The quantity of energy needed to increase the temperature of a substance is directly proportional to the mass, specific heat capacity and the change in temperature of the substance. If 200 kJ is used to increase the temperature of a particular quantity of a substance, how much energy would be needed to bring:
 - twice as much of the substance through the same change in temperature
 - three times as much of the substance through a temperature change twice as great?

3. Use table 1.4 to answer the following questions.
- Why is the specific heat capacity of the human body so high?
 - Why is the specific heat capacity of deserts so much lower than that of fertile topsoil?
 - When heating water to boiling point in a saucepan, some of the energy transferred from the hotplate is used to increase the temperature of the saucepan. Which would you expect to gain the most energy from the hotplate: an aluminium, copper or steel saucepan?
 - Make some general comments about the order of substances listed in table 1.4.
4. Use the following data to determine the quantity of energy needed to evaporate 500 grams of water without a change in temperature.

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

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



- What is the boiling point of the candle wax?
 - During the interval BC, there is no increase in temperature even though heating continued. What was the energy transferred to the candle wax being used for during this interval?
 - In which state of matter was the candle wax during the interval CD?
 - Use the heating curve to determine the latent heat of fusion of candle wax.
 - Which is higher: the specific heat capacity of solid candle wax or the specific heat capacity of liquid candle wax? Explain your answer.
 - Explain in terms of the kinetic particle model what is happening during the interval DE.
6. How much ice at 0°C could be melted with 1 kilogram of steam at 100°C , assuming no loss of energy to the surroundings? Use the specific latent heat values quoted in table 1.5. The specific heat capacity of water is $4200 \text{ J kg}^{-1} \text{ K}^{-1}$.
7. Explain the importance of keeping a lid on a simmering saucepan of water in terms of latent heat of vaporisation.
8. How does the evaporation of water cause a reduction in the temperature of the surrounding air?

studyon

To answer practice exam questions online and to receive immediate feedback and sample responses for every question go to your learnON title at www.jacplus.com.au.

studyON: Practice exam questions online only

Fully worked solutions and sample responses are available in your digital formats.

1.7 Review

1.7.1 Summary

- The kinetic particle model of matter explains heat phenomena.
- Internal energy is the energy associated with the random movement of molecules and it comes in many forms, including translational, rotational and vibrational kinetic energy, and potential energy.
- A thermometer measures temperature, and various properties of materials can be used to make one.
- There are different temperature scales, with Celsius and kelvin being the common ones. Temperatures in one scale can be converted to any other.
- Temperature is a measure of the average translational kinetic energy of the atoms and molecules in a substance.
- Heat energy can be transferred by conduction, convection and radiation.
- Conduction is the transfer of heat energy through a material by collisions between adjacent particles.
- Some materials conduct heat energy well and are called conductors. Others do not and are called insulators.
- Convection is the transfer of heat energy through a substance, usually a liquid or a gas, by the movement of particles between regions of different temperature. Hotter material is less dense because faster moving particles push each other further apart. If free to move, the less dense and hotter material will rise, displacing cooler material.
- Objects at different temperatures, if placed in contact, will reach a common temperature. This process is called thermal equilibrium and is described as the Zeroth Law of Thermodynamics.
- The First Law of Thermodynamics states that if energy is transferred to or from a system, then the total energy must be conserved, with any changes in the internal energy of the system given by $\Delta U = Q - W$, where ΔU is the change in internal energy, Q is the heat added to the system and W is the work done by the system.
- The specific heat capacity, c , of a substance is the amount of energy required to increase the temperature of 1 kilogram of the substance by 1 °C or 1 K.
- When substances of different specific heat capacities and different temperatures are mixed, the final temperature can be determined by using the conservation of energy and the relationship $Q = mc\Delta T$ for each substance.
- The latent heat, L , of a substance is the amount of energy required to change the state from solid to liquid or liquid to gas of 1 kilogram of the substance. For a substance of mass m kg, the energy required is given by $Q = mL$.
- Evaporation of a liquid occurs because some of the faster particles have sufficient energy and speed to break free of the surface. The removal of these particles lowers the overall average kinetic energy of the remaining particles and consequently the temperature of the liquid.

on Resources

studyon

To access key concept summaries and practice exam questions download and print the **studyON: Revision and practice exam question booklet** (sonr-0026).

1.7.2 Key terms

Absolute zero is the lowest temperature that is physically possible. At this temperature, particles cease to vibrate. It is equal to 0 K or approximately $-273\text{ }^{\circ}\text{C}$.

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

A **conductor** is a material that contains charge carriers.

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

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

An **electromagnetic radiation** is an electromagnetic wave or radiation that includes visible light, radio waves, gamma rays and X-rays.

First Law of Thermodynamics :

$$\Delta U = Q - W \text{ or } Q = U + W$$

Where:

Q is the heat energy in joules

W is the work done in joules

ΔU is the change in internal energy in joules.

Gravitational potential energy is the energy stored in an object as a result of its position relative to another object to which it is attracted by the force of gravity.

Heat is defined as the transfer of energy from one body to another due to a temperature difference.

The **internal energy** of an object is the sum of all kinetic energy of the particles that make up that object.

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

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

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

Radiation is heat transfer without the presence of particles.

Rotational kinetic energy is the energy due to the rotational motion of objects.

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

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

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

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

Translational kinetic energy is the energy due to the motion of an object from one location to another.

Vibrational kinetic energy is the energy due to the vibrational motion of objects.

Resources

 **Digital document** Key terms glossary (doc-31857)

1.7.3 Practical work and investigations

Investigation 1.1

The good oil on heating

Aim: To show that different substances require different quantities of energy to change their temperatures by the same amount and to show that the quantity of energy required to change the temperature of a given substance is directly proportional to the mass of the substance

Digital document: doc-31854

Investigation 1.2

Cooling

Aim: To show that the internal energy of a substance can change without a subsequent change in temperature and to produce a cooling curve that illustrates the concept of latent heat.

Digital document: doc-31855

Teacher-led video: tlvd-0804



1.7 Exercises

To answer questions online and to receive **immediate feedback** and **sample responses** for every question, go to your learnON title at www.jacplus.com.au.

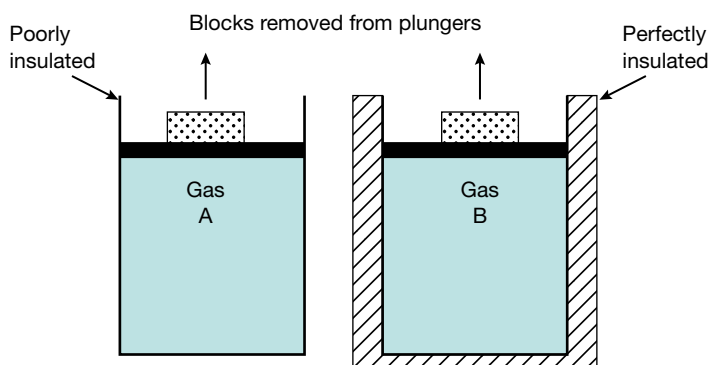
1.7 Exercise 1: Multiple choice questions

- Which of the following is correct in relation to the kinetic theory of matter?
 - States that all matter is made up of a large number of small particles
 - Can be used to explain the process of convection and conduction
 - Is needed to explain absolute zero
 - All of the above
- What is the internal energy of a substance?
 - The sum of all energy contained within the matter of that substance, including kinetic and potential energy
 - The sum of all kinetic energy in a substance
 - The sum of all the translational kinetic energy in a substance
 - The average of all the translational kinetic energy in a substance
- What is temperature a measure of?
 - The average of all energy contained within the matter of that substance, including kinetic and potential energy
 - The sum of all kinetic energy in a substance
 - The sum of all the translational kinetic energy in a substance
 - The average of all the translational kinetic energy in a substance
- The Kelvin scale is a temperature measure based on which of the following?
 - The temperature of the human body
 - The temperatures of when water boils and when it freezes
 - Absolute zero when all particle movement stops
 - The temperature of the North Pole at midday in summer
- How is heat best described?
 - When a material gets hot
 - The energy transferred as a result of temperature difference
 - The energy inside matter
 - The translational kinetic energy of an object
- What does the First Law of Thermodynamics state?
 - The change in internal energy of a system plus the heat entering a system must equal the work done to the surroundings.
 - The change in internal energy plus the work done to the surroundings must be equal to the heat entering a system.
 - The work done to the surroundings plus the heat entering the system is equal to the change in internal energy.
 - Objects at different temperatures, if placed in contact, will reach a common temperature.
- A balloon shrinks when left outside in the cold. Which of the following is true for this scenario?
 - $\Delta U > 0$, $Q < 0$ and $W > 0$
 - $\Delta U < 0$, $Q < 0$ and $W > 0$
 - $\Delta U > 0$, $Q < 0$ and $W > 0$
 - $\Delta U < 0$, $Q < 0$ and $W < 0$

8. For two substances to reach thermal equilibrium, which of the following must they have?
 - A. The same internal energy
 - B. The same kinetic energy
 - C. The same translational kinetic energy
 - D. None of the above
9. What is the specific heat capacity a measure of?
 - A. How much internal energy a substance can hold
 - B. How much energy is required to raise the temperature of 1 kilogram of a substance by 1 °C
 - C. How much energy is required to raise the temperature of 1 kilogram of a substance by 100 °C
 - D. The temperature change for 1 kilogram of a substance when its internal energy has increased by 1 J
10. When the cooling curve of wax is examined a flat section on the graph is found. This section is due to which of the following?
 - A. A pause in energy reaching the system causing no temperature change
 - B. The wax changing from a solid to a liquid and consuming extra energy without a temperature change
 - C. A fault in the measuring equipment as this type of flat section would never occur
 - D. The wax changing state from liquid to solid releasing extra energy without a temperature change

1.7 Exercise 2: Short answer questions

1. Why can't you put your hand on your own forehead to estimate your body temperature?
2. If today's maximum temperature was 14 °C and tomorrow's maximum temperature is expected to be 28 °C, will tomorrow be twice as hot? Explain your answer.
3. Explain with the aid of a well-labelled diagram how convection occurs in a liquid that is being heated from below.
4. The daytime temperature of an area can decrease for several days after a major bushfire. Why does this happen?
5. The microwave cooking instructions for frozen pies state that pies should be left to stand for two minutes after heating. What happens to the pie while it stands?
6. Why do conventional ovens without fans have heating elements at the bottom? What is the advantage of having an oven with a fan?
7. In the figure, two beakers are filled with the same gas. A plunger is fitted so that no gas escapes; friction is negligible between the plunger and the beaker walls. The block is removed from each plunger, the plunger moves upward.
 - a. In each case, does the gas do work or is work done on the gas? Explain your reasoning.
 - b. Is there a larger transfer of thermal energy as heat between gas A and the surroundings or between gas B and the surroundings? Explain your reasoning in a few sentences.
 - c. For the expansion of gas A, how do the work and heat involved in this process affect the internal energy of the gas? Explain your reasoning in a few sentences.
 - d. For the expansion of gas B, how do the work and heat involved in this process affect the internal energy of the gas? Explain your reasoning.



8. Two insulated containers are connected by a valve. The valve is closed. One container is filled with gas, the other is a vacuum. The valve is opened. Is there any change in temperature? Is there any change in the internal energy? What are the values of Q and W in this situation?
9. Explain why vegetables cook faster by being steamed than boiled.
10. In hot weather, sweat evaporates from the skin.
 - a. Where does the energy required to evaporate the sweat come from?
 - b. Why do you feel cooler if there is a breeze?
 - c. Why is the cooling effect greatly reduced if the weather is humid rather than dry?

1.7 Exercise 3: Exam practice questions

Question 1 (2 marks)

Adam says 'A thermometer measures the average temperature between itself and the object it is measuring', while Katie says 'A thermometer directly measures the temperature of the object'. Explain why each is wrong.

Question 2 (4 marks)

The image on the right is of a heat sink. These are used to cool electrical devices such as computers.

They are made from aluminium, usually painted black and have thin fins as shown.



- a. Discuss the design of the device with respect to your understanding of heat transfer. **2 marks**
- b. Discuss the material used to manufacture a heat sink by commenting on its thermodynamic properties. **2 marks**

Question 3 (3 marks)

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

Question 4 (3 marks)

How much energy does it take to completely convert 2.0 kilograms of ice at -5.0°C into steam at 100°C ? Assume no energy loss to the surroundings.

Question 5 (2 marks)

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

1.7 Exercise 4: studyON topic test

Fully worked solutions and sample responses are available in your digital formats.

teach

Test maker

Create unique tests and exams from our extensive range of questions, including practice exam questions. Access the Assignments section in learnON to begin creating and assigning assessments to students.

2 Thermodynamics and climate science

2.1 Overview

Numerous **videos** and **interactivities** are available just where you need them, at the point of learning, in your digital formats, learnON and eBookPLUS at www.jacplus.com.au.

2.1.1 Introduction

In this topic, you will apply many of the concepts you were introduced to in topic 1 to develop a more sophisticated understanding of the Earth's energy systems. You will be introduced to two relationships that enable physicists to determine the power radiated from objects given their temperature (Stefan–Boltzmann law) and the peak wavelength re-radiated from an object given its temperature (Wien's law). You will consider how these relationships are used to examine the Earth's thermal energy. By the end of this topic you will be able to explain how atmospheric gases create the greenhouse effect. You will describe and apply thermal equilibrium to the Earth's flow of thermal energy. You will analyse changes in the thermal energy of the surface of the Earth and of the Earth's atmosphere. Finally, you will analyse the evidence for the influence of human contributions to the enhanced greenhouse effect, including surface materials and the balance of gases in the atmosphere.

FIGURE 2.1 Incoming radiation is reflected off ice back into space, but is absorbed by the water. Consider how increasing air and ocean temperatures will change this scene.



2.1.2 What you will learn

KEY KNOWLEDGE

After completing this topic you will be able to:

- describe electromagnetic radiation emitted from the Sun as mainly ultraviolet, visible and infrared
- calculate the peak wavelength of the re-radiated electromagnetic radiation from Earth using Wien's law: $\lambda_{\text{max}} T = \text{constant}$
- compare the total energy across the electromagnetic spectrum emitted by objects at different temperatures such as the Sun
- describe power radiated by a body as being dependent on the temperature of the body according to the Stefan–Boltzmann law, $P \propto T^4$
- model the greenhouse effect as the flow and retention of thermal energy from the Sun, Earth's surface and Earth's atmosphere
- explain how greenhouse gases in the atmosphere (including methane, water and carbon dioxide) absorb and re-emit infrared radiation
- analyse changes in the thermal energy of the surface of Earth and of Earth's atmosphere
- analyse the evidence for the influence of human activity in creating an enhanced greenhouse effect, including affecting surface materials and the balance of gases in the atmosphere
- apply thermodynamic principles to investigate at least one issue related to the environmental impacts of human activity with reference to the enhanced greenhouse effect
- explain how concepts of reliability, validity and uncertainty relate to the collection, interpretation and communication of data related to thermodynamics and climate science.

Source: VCE Physics Study Design (2016–2021) extracts © VCAA; reproduced by permission.

PRACTICAL WORK AND INVESTIGATIONS

Practical work is a central component of learning and assessment. Experiments and investigations, supported by a **Practical investigation logbook** and **Teacher-led videos**, are included in this topic to provide opportunities to undertake investigations and communicate findings.

Resources

-  **Digital documents** Key science skills — VCE Units 1–4 (doc-31856)
 - Key terms glossary (doc-31861)
 - Practical investigation logbook (doc-31858)

study

To access key concept summaries and practice exam questions download and print the **studyON: Revision and practice exam question booklet** (sonr-0027).

2.2 Earth's energy systems

KEY CONCEPTS

- Describe electromagnetic radiation emitted from the Sun as mainly ultraviolet, visible and infrared.
- Calculate the peak wavelength of the re-radiated electromagnetic radiation from Earth using Wien's law: $\lambda_{\text{max}} T = \text{constant}$.
- Compare the total energy across the electromagnetic spectrum emitted by objects at different temperatures such as the Sun.
- Describe power radiated by a body as being dependent on the temperature of the body according to the Stefan–Boltzmann law, $P \propto T^4$.

2.2.1 Energy from our Sun

You will recall that hot objects produce electromagnetic radiation across a broad range of wavelengths. The hottest object in our environment is our sun. Nearly all of the energy available to Earth comes from the Sun, whose energy output is $3.86 \times 10^{26} \text{ J s}^{-1}$ ($3.86 \times 10^{26} \text{ W}$). This is known as its **luminosity**. A tiny portion of this energy hits the Earth, heating and lighting it. When we examine the light from the Sun, we see the characteristic spectrum of light produced by hot objects, known as **blackbody radiation**.

FIGURE 2.2 Nearly all the energy available to Earth comes from the Sun.

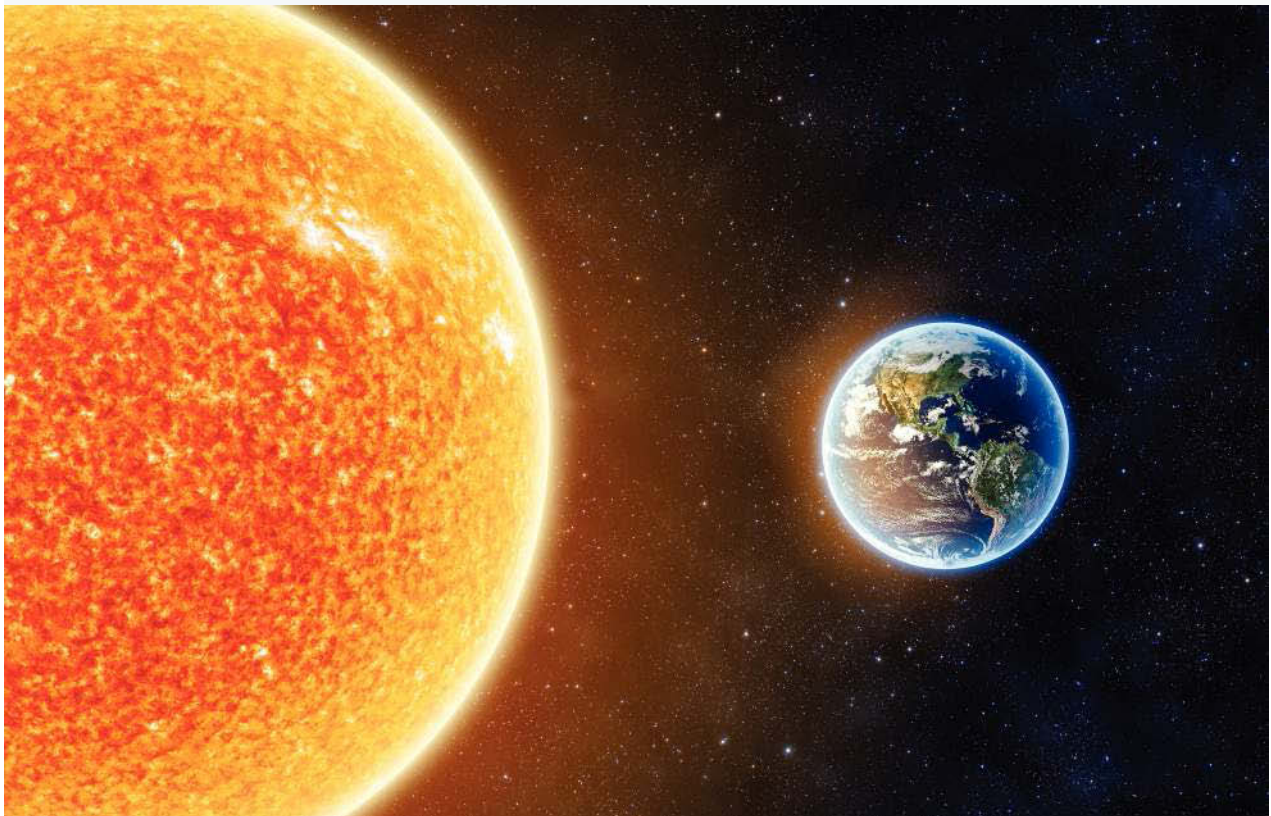
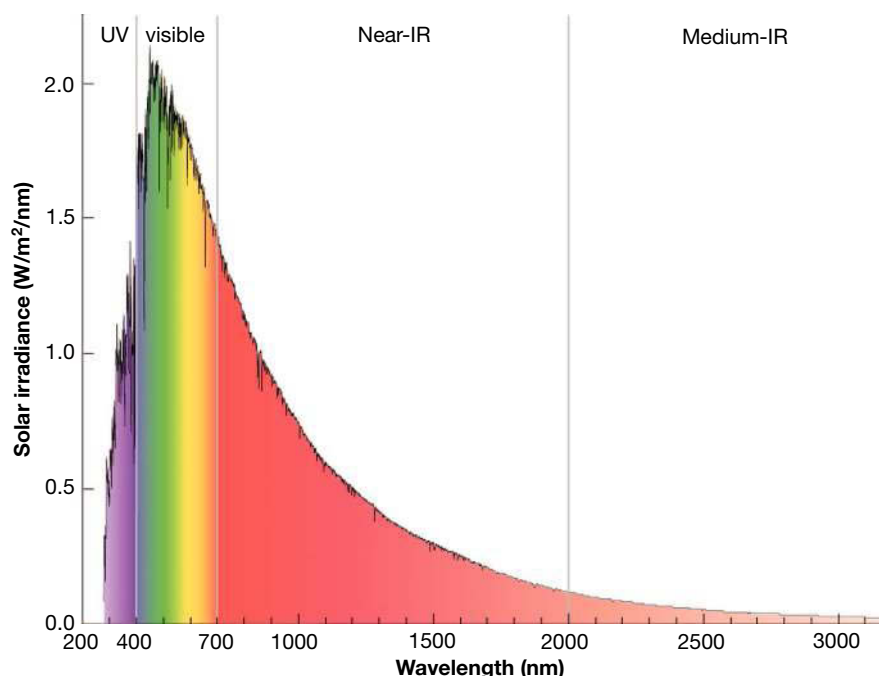


Figure 2.3 shows the characteristic shape of a **black body** plotted against its electromagnetic (EM) emission. Note that the highest section of the peak is in the visible section of the EM spectrum; however, a significant amount of heat energy (infrared) is clearly illustrated, as well as a smaller but not insignificant amount of light in the ultraviolet section.

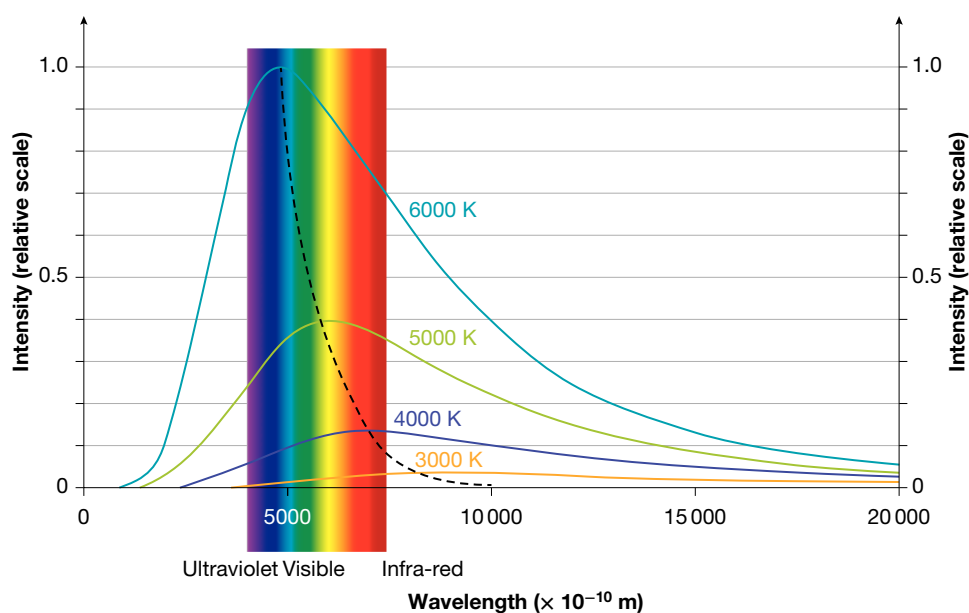
FIGURE 2.3 The characteristic blackbody shape of the solar spectrum. The electromagnetic radiation emitted from the Sun is mainly ultraviolet, visible and infrared.



What is blackbody radiation?

During the late nineteenth century, scientists conducted investigations into how much radiation was produced across the light spectrum and how this distribution changed with temperature. The results are displayed in figure 2.4.

FIGURE 2.4 The variation in intensity versus wavelength produced for different hot objects. Note that not only does the intensity peak higher as temperature increases, but the spectrum moves to the left and becomes bluer (dotted line).



In figure 2.4, the graphs for the four different temperatures are generally the same shape. Starting from the right with long wavelengths, there is very little infrared radiation emitted. As the wavelength gets shorter, the radiation produced increases to a maximum; finally, as the wavelength shortens even further the amount of radiation drops quite quickly. The graphs for higher temperatures have a peak at a shorter wavelength and a much larger area under the graph, meaning a lot more energy is emitted (intensity). This shape is typical of blackbody radiation and all heated objects exhibit these characteristics to some degree.

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

He found that the power was proportional to **absolute temperature** to the power of 4, that is, $P \propto T^4$.

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

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

Ludwig Boltzmann later proved this from a theoretical standpoint, and so the $P \propto T^4$ relationship is called the Stefan–Boltzmann law.

Stefan–Boltzmann law

$$P \propto T^4$$

This relationship applies to all objects, but the constant of proportionality depends on the size of the object and other factors. It is this property of any hot object that has enabled astronomers to determine the surface temperatures of stars.

SAMPLE PROBLEM 1

- When iron reaches about 480 °C it begins to glow with a red colour. How much more energy is emitted by the iron at this temperature, compared to when it is at a room temperature of 20 °C?
- How much hotter than 20 °C would the iron need to be to emit 10 times as much energy?

 **Teacher-led video:** SP1 (tlvd-0007)

THINK

- Convert the temperature to kelvin.

WRITE

- Temperature of hot iron:

$$\begin{aligned} T_{(\text{kelvin})} &= T_{(\text{Celsius})} + 273 \\ &= 480\text{ °C} + 273 \\ &= 753\text{ K} \end{aligned}$$

Temperature of cold iron:

$$\begin{aligned} T_{(\text{kelvin})} &= T_{(\text{Celsius})} + 273 \\ &= 20\text{ °C} + 273 \\ &= 293\text{ K} \end{aligned}$$



2. Calculate the ratio.

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

$$\begin{aligned}\frac{P_{\text{hot}}}{P_{\text{cold}}} &= \left(\frac{T_{\text{hot}}}{T_{\text{cold}}} \right)^4 \\ &= \left(\frac{753}{293} \right)^4 \\ &\approx 44\end{aligned}$$

3. State the solution.

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

- b. 1. Convert the temperature to kelvin.

- b. Temperature of cold iron:

$$\begin{aligned}T_{(\text{Kelvin})} &= T_{(\text{Celsius})} + 273 \\ &= 20^\circ\text{C} + 273 \\ &= 293\text{ K}\end{aligned}$$

2. Calculate the ratio.

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

$$\begin{aligned}\frac{P_{\text{hot}}}{P_{\text{cold}}} &= \left(\frac{T_{\text{hot}}}{T_{\text{cold}}} \right)^4 \\ 10 &= \left(\frac{T_{\text{hot}}}{293} \right)^4 \\ 10^{\frac{1}{4}} &= \frac{T_{\text{hot}}}{293} \\ T_{\text{hot}} &= 293 \times 10^{\frac{1}{4}}\end{aligned}$$

3. Use your calculator to evaluate $10^{\frac{1}{4}}$, then use that value to calculate T_{hot} .

$$10^{\frac{1}{4}} \approx 1.778$$

4. Convert the temperature to Celsius.

$$\begin{aligned}T_{\text{hot}} &= 293 \times 1.778 \approx 521\text{ K} \\ T_{(\text{Celsius})} &= 521\text{ K} - 273 \\ &= 248^\circ\text{C}\end{aligned}$$

5. State the solution.

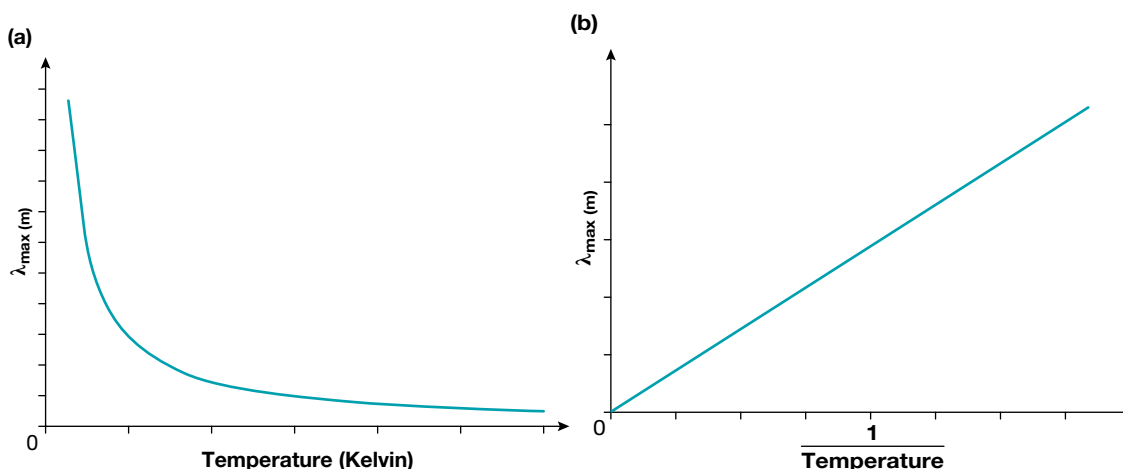
The iron would need to be at 248°C to emit 10 times the energy every second it does at 20°C .

PRACTICE PROBLEM 1

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

In 1893, Wilhelm Wien (pronounced *Veen*) was able to show that as the temperature increased, the wavelength of maximum intensity of energy emitted decreased, and indeed the two quantities were inversely proportional. That is, the wavelength is proportional to the inverse of the temperature. This can be seen in figure 2.5b.

FIGURE 2.5 The wavelength is proportional to the inverse of the temperature. These graphs illustrate that as the temperature increased, the wavelength of maximum intensity of energy emitted decreased.



Wien's law can be written as:

$$\lambda_{\max} T = \text{constant}$$

The value of this constant is $2.90 \times 10^{-3} \text{ mK}$ (metre-kelvin).

SAMPLE PROBLEM 2

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

 **Teacher-led video:** SP2 (tlvd-0008)

THINK

- State Wien's law, and rearrange the equation to make $\lambda_{\max}$ the subject.
 - Substitute the known values into the equation to find $\lambda_{\max}$.
 - State the solution.
- Refer to figure 2.4.

WRITE

$$\text{a. } \lambda_{\max} T = \text{constant}$$

$$\lambda_{\max} = \frac{\text{constant}}{T}$$

$$\text{Constant} = 2.90 \times 10^{-3} \text{ mK}, T = 11\,000 \text{ K}$$

$$\begin{aligned} \lambda_{\max} &= \frac{\text{constant}}{T} \\ &= \frac{2.90 \times 10^{-3} \text{ mK}}{11\,000 \text{ K}} \\ &= 2.64 \times 10^{-7} \text{ m} \end{aligned}$$

The light coming from a star whose surface temperature is 11 000 K has a peak intensity at a wavelength of $2.64 \times 10^{-7} \text{ m}$.

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

PRACTICE PROBLEM 2

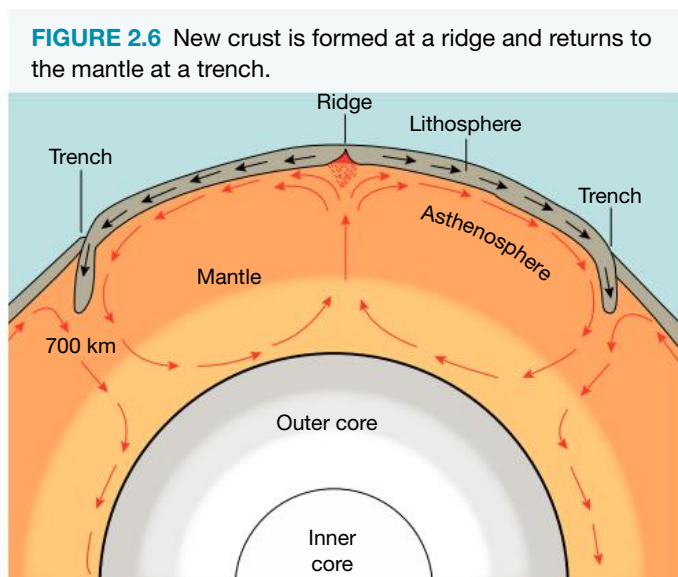
Determine the surface temperature of a star that emits light at a maximum intensity of 450 nm.

2.2.2 Heat from within

Although the sun is our primary source of energy on Earth, our secondary source of energy comes from within the Earth. The heat energy within the Earth comes from the **radioactive decay** of elements such as uranium. This heat energy is not evenly distributed and hot spots occur under the mantle.

Energy transfer by convection is common in gases and liquids, but it can also occur in solids under the right conditions. The high temperatures, about 2000 °C, and pressures in the Earth's mantle are enough to make solid rock move, only very slowly of course. The hot lighter rock at these points slowly rises, while denser rock at colder spots slowly sinks. This sets up a convection cell in the Earth's mantle with the surface crust moving horizontally across the Earth. The speed of the rock movement is a few centimetres per year.

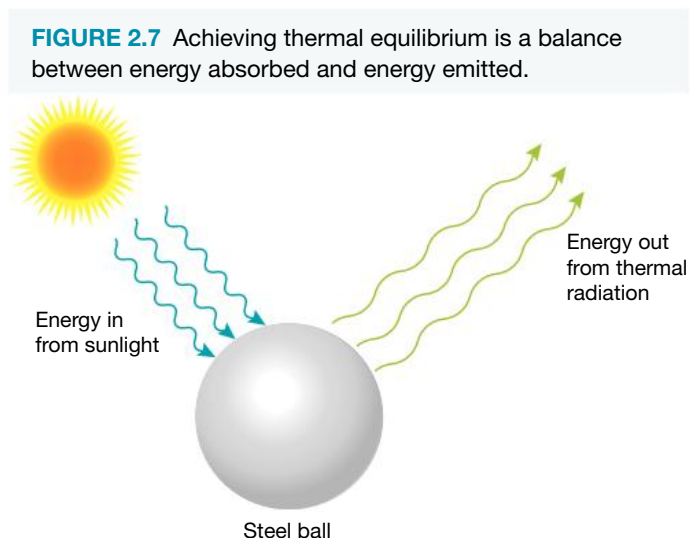
The molten rock wells up at mid-ocean ridges and moves out. The rock eventually meets the edge of a continental plate and cools further, becoming denser, then sinks back towards the mantle in a deep ocean trench.



2.2.3 Energy in balance

Every object attempts to achieve thermal equilibrium — that is, a balance between energy absorbed and energy emitted. Imagine a steel ball placed in direct sunlight as shown in figure 2.7.

When light energy heats and warms an object, like a steel ball, its particles start to get more excited and its translational kinetic energy starts to increase. As a result, the steel ball emits thermal radiant energy (usually in the infrared). The absorbed energy increases the temperature of the ball; the increased temperature means that the ball will radiate more thermal energy. If the amount of energy radiated is less than the amount absorbed, the temperature of the ball will continue to increase, leading to more energy being emitted, until a temperature is reached where energy in and energy out balance.



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

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

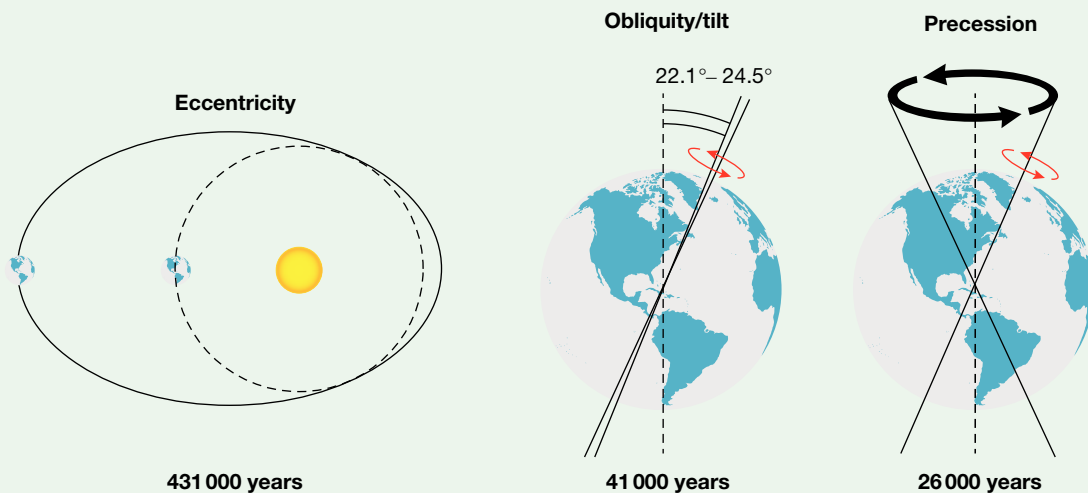
With the Stefan–Boltzmann relationship, $P \propto T^4$, it is possible to use the amount of energy the Earth radiates into space to calculate the temperature of the Earth as observed from space.

MILANKOVITCH CYCLES

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

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

FIGURE 2.8 The variation in solar radiation that the Earth is exposed to has changed the climate over tens and hundreds of thousands of years. These variations explain the ice ages the Earth has experienced in its past but do not explain the current global warming.

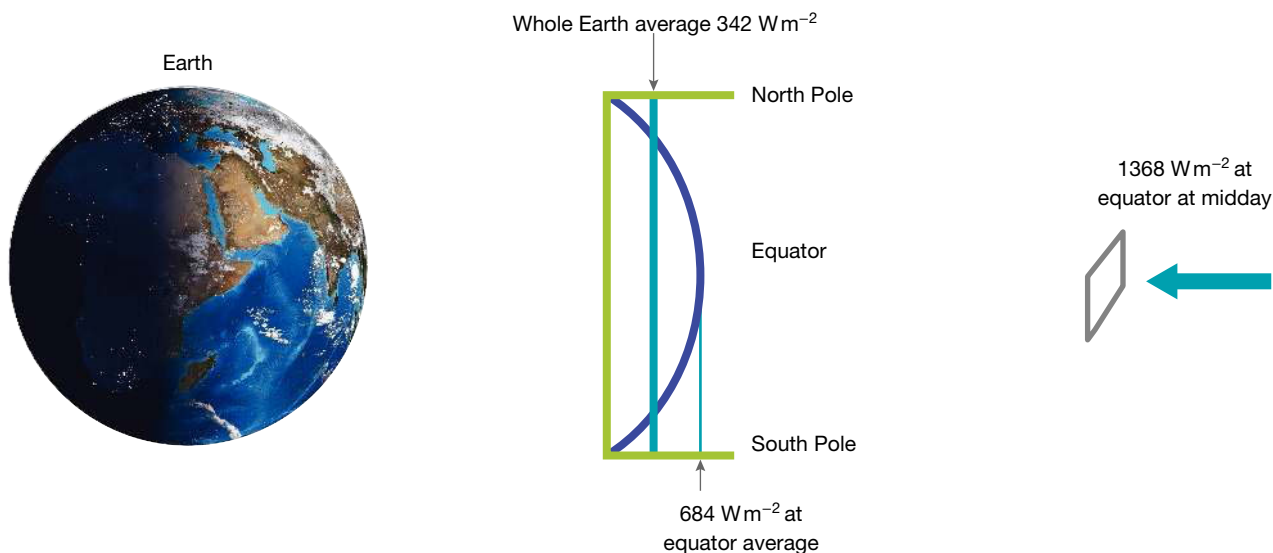


All these changes are due to gravitational interactions in the solar system between the Earth, the Sun and other planets. It is thought that these factors may explain the long-term cooling trend the Earth has been in over the last 6000 years. From the slowness with which these changes occur, none can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

2.2.4 How much energy does the Earth get from the Sun?

The Sun is directly overhead the equator at midday on the equinox. At this place and time, the solar radiation is about 1368 W m^{-2} . But because the Earth turns, producing night and day, this value has to be halved to 884 W m^{-2} . Also, the Earth is curved with the North and South Poles receiving much less light than the equator over a full year. This requires the number to be halved again. So the average solar radiation across the Earth is 342 W m^{-2} as shown in figure 2.9. About 100 W m^{-2} of this radiation is reflected straight back into space by the white surfaces of clouds and ice sheets. This leaves 242 W m^{-2} to heat up the Earth.

FIGURE 2.9 At the Earth's equator at midday, the light intensity from the Sun is 1368 W m^{-2} . The average over night and day and from pole to pole is 342 W m^{-2} .



2.2 EXERCISE

To answer questions online and to receive **immediate feedback** and **sample responses** for every question go to your learnON title at www.jacplus.com.au.

- A 100 W light globe has a tungsten filament with a temperature of 2775 K when switched on.
 - How much radiation does the filament emit at 20°C ?
 - The voltage on the light globe is reduced to increase the lifetime of the filament. The temperature of the filament is now 2000 K. What is the power saving?
 - The voltage is now increased so that the power output is 200 W. What is the new filament temperature in kelvin?
- A piece of iron has a yellow glow when it reaches 1150°C . How much more energy is emitted every second at this temperature compared to when the iron glows red at 480°C ?
 - At what temperature in degrees Celsius would the iron give off 10 times as much energy as it does at 480°C ?
- What is the wavelength of the light with the peak intensity from our solar system's closest neighbouring star, Proxima Centauri, which has an average surface temperature of 3042 K?
- Our Sun gives off most of its light in the 'yellow' portion of the electromagnetic spectrum. Its λ_{max} is 510 nm. Calculate the average surface temperature of the Sun.
- The Earth's surface has an average temperature of 288 K. What is the wavelength of maximum emission from the Earth's surface?
- The human body has a surface temperature of about 37°C .
 - What is the wavelength at which the human body emits the most radiation?
 - In what part of the spectrum is this wavelength?
- Suppose the surface temperature of the Sun was about 12 000 K, rather than about 6000 K.
 - How much more thermal radiation would the Sun emit?
 - What would happen to the Sun's wavelength of peak emission?

studyon

To answer practice exam questions online and to receive immediate feedback and sample responses for every question go to your learnON title at www.jacplus.com.au.

studyON: Practice exam questions online only

Fully worked solutions and sample responses are available in your digital formats.

2.3 The enhanced greenhouse effect

KEY CONCEPTS

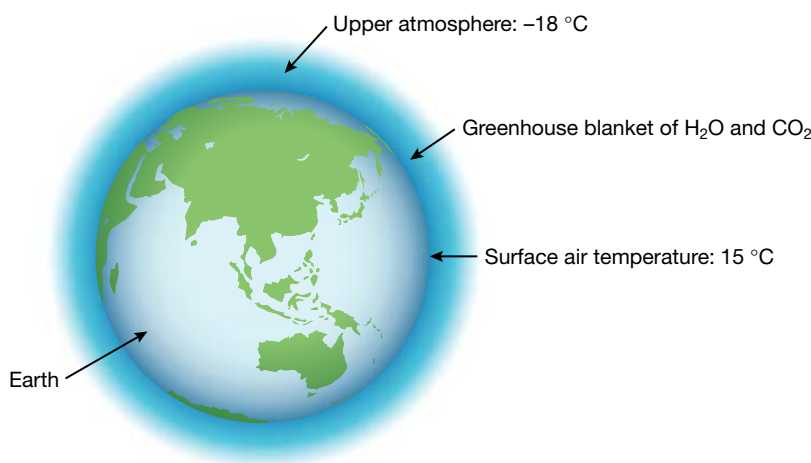
- Model the greenhouse effect as the flow and retention of thermal energy from the Sun, Earth's surface and Earth's atmosphere.
- Explain how greenhouse gases in the atmosphere (including methane, water and carbon dioxide) absorb and re-emit infrared radiation.
- Analyse changes in the thermal energy of the surface of Earth and of Earth's atmosphere.

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

2.3.1 The natural greenhouse effect

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

FIGURE 2.10 The necessary temperature (-18°C) for the Earth to radiate 242 W m^{-2} actually occurs at an altitude of about 5 kilometres above the surface. So, the Earth's surface is warmed by a 5-kilometre thick blanket!



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

If you shine a broad spectrum of light through a gas, some colours will be absorbed. The colours absorbed are specific to the substance, which means each substance produces its own unique pattern of **absorption bands**. These absorption bands are like fingerprints and can be used to identify molecules. The light in the absorption band has been absorbed by the molecule and then subsequently re-emitted, but in a random direction (see figure 2.13). This means the spectrum of light from the source will have gaps where absorption has occurred. The light from the other parts of the spectrum passes through the gas without a change in direction.

Ultraviolet light has more energy than visible light, which has more energy than infrared, but none of them are energetic enough to break up molecules. These three types of radiation have only enough energy

to stretch, twist and spin molecules. Molecules with two atoms such as nitrogen (N_2) and oxygen (O_2) have very strong bonds. When they absorb ultraviolet light, their bonds stretch. The energy of visible light and infrared radiation is too low to affect such molecules. This means the two gases are transparent to visible light and infra-red.

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

Figure 2.11 shows the different ways water vapour molecules bend and stretch and figure 2.12 shows the different ways carbon dioxide molecules bend and stretch.

FIGURE 2.11 The water molecule has three different ways of stretching or bending, as well as oscillations about three axes.

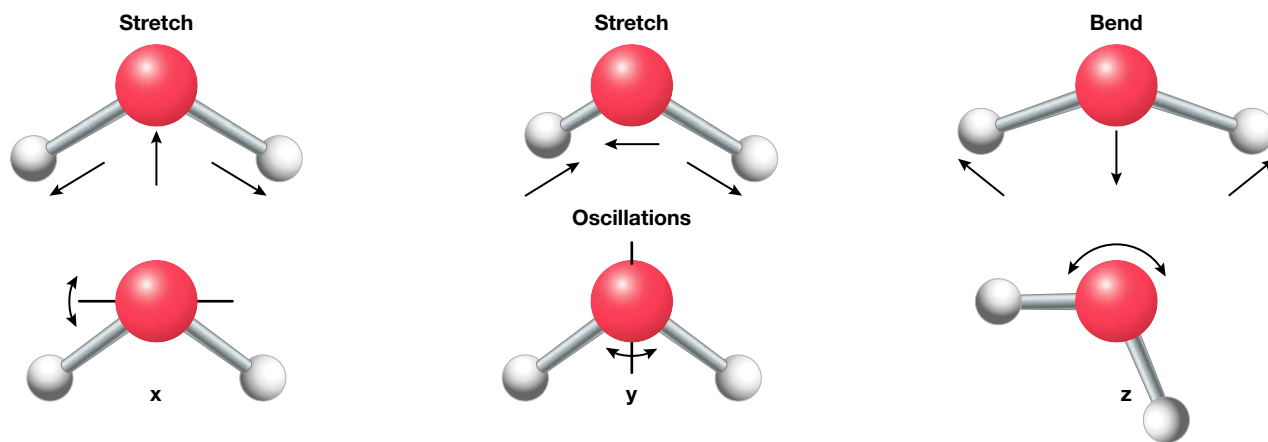
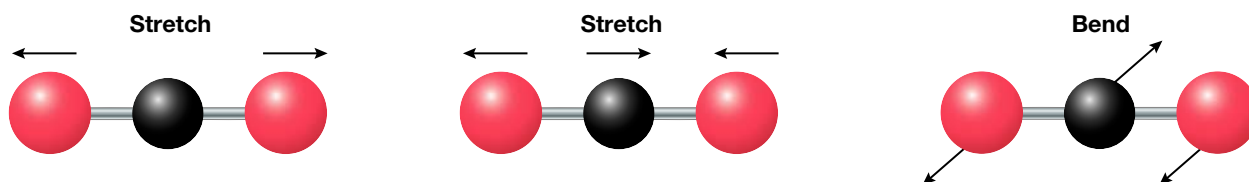


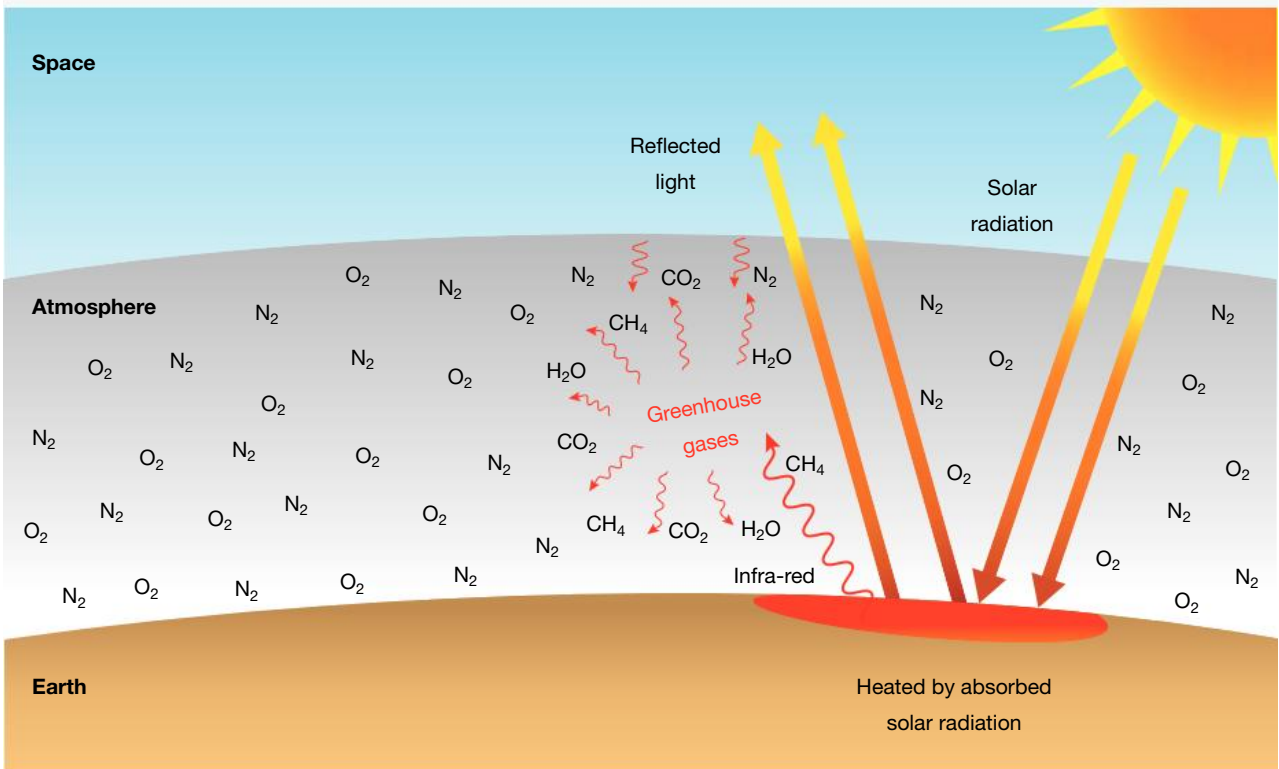
FIGURE 2.12 The carbon dioxide molecule has three different ways of stretching.



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

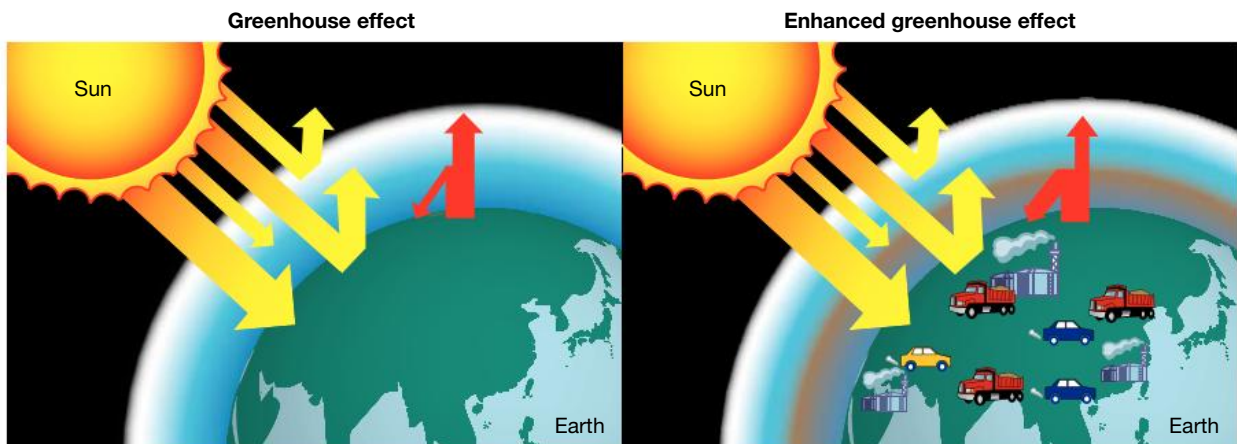
Once a gas molecule has absorbed infra-red radiation coming from the Earth's surface, it re-emits the radiation but, importantly, in a random direction (see figure 2.13). So, for the gas as a whole, some radiation goes back down to the Earth to increase its temperature and some is directed towards the top of the atmosphere and out into space. However, other molecules further up in the atmosphere can absorb this radiation and re-emit more back to the Earth. The overall effect is that more than half the radiation emitted by the gas comes back to the Earth's surface.

FIGURE 2.13 Infra-red radiation from the Earth's surface is absorbed by greenhouse gases and re-emitted in all directions.



Human activities, such as the burning of fossil fuels (coal, oil and natural gas), agriculture and land clearing, are increasing the concentrations of greenhouse gases in the atmosphere. This increase is sometimes called the **enhanced greenhouse effect** (see figure 2.14).

FIGURE 2.14 Comparison of the greenhouse effect and the enhanced greenhouse effect

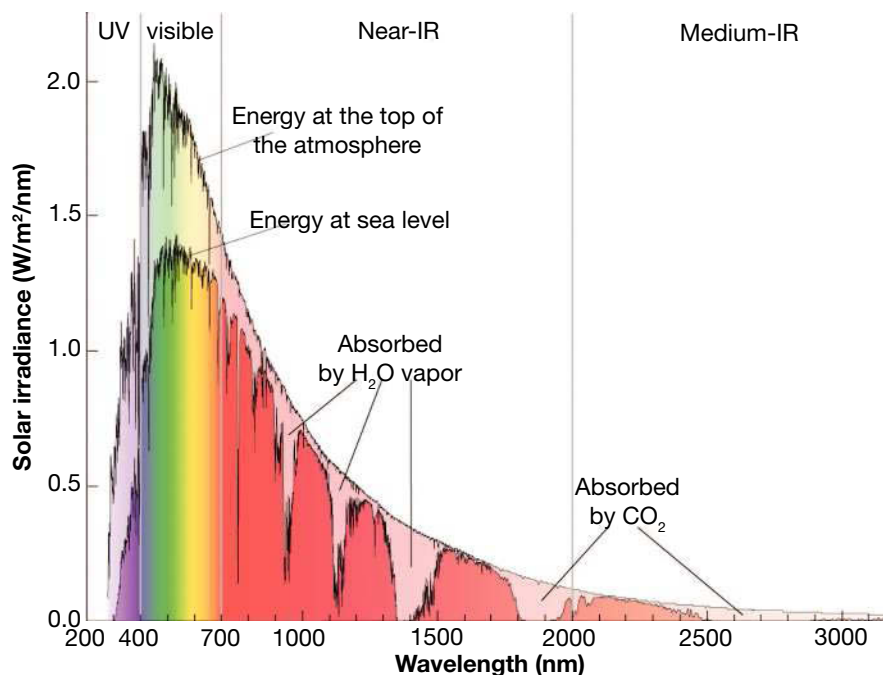


Increased carbon dioxide concentration in the atmosphere means that more of the wavelengths that carbon dioxide absorbs will be re-emitted back to Earth, increasing the temperature of the Earth.

Figure 2.15 is the same solar spectrum as figure 2.3 but also shows the:

- spread of wavelengths radiated by the Sun at 6000 K (these are the wavelengths in sunlight)
- spread of wavelengths received on the surface of the Earth, demonstrating the impact of the atmosphere on the light we receive from the Sun, and the ‘holes’ in the spectrum because of greenhouse gas absorption
- absorption spectrum for water vapour
- absorption spectrum for carbon dioxide.

FIGURE 2.15 Characteristic blackbody shape showing the irradiance at sea level and thus the effect of the atmosphere. Note the ‘holes’ at particular frequencies due to absorption from atmospheric gases.



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

2.3.2 Fossil fuels' fingerprints

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

For example, carbon has two main isotopes:

1. carbon-12 with six neutrons
2. carbon-13 with seven neutrons.

The process of **photosynthesis** in plants turns carbon dioxide and water into carbohydrates. This reaction occurs more quickly with carbon-12 than it does with carbon-13. This means the proportion of carbon-13 in the plant is less than what was in the atmosphere at the time the plant was growing.

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

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

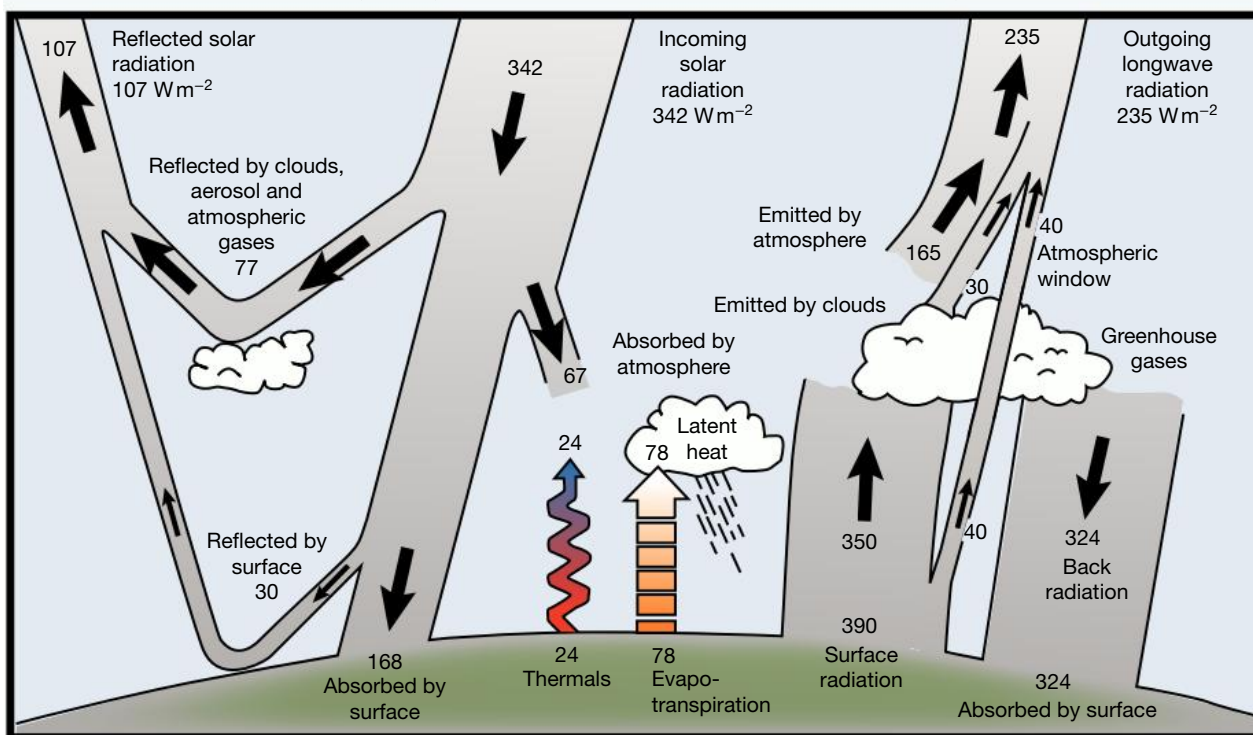
2.3.3 The Earth's energy budget

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

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

Figure 2.16 shows all the different paths energy takes from arriving at the Earth, mainly as visible light, to being emitted as longwave infrared radiation or reflected straight back into space.

FIGURE 2.16 The Earth's energy budget from the International Panel on Climate Change (IPCC)



The numbers in figure 2.16 can be used to check the energy balance between energy coming in and energy going out — not only of the whole Earth, but also of just the atmosphere or just the Earth's surface. In each case, the energy coming in should equal the energy going out (see table 2.1).

TABLE 2.1 The energy balance between energy coming in and energy going out

For the Earth as a whole	For the Earth's surface
Incoming energy = 342 W m^{-2}	Incoming energy = $168 + 324 \text{ W m}^{-2}$
Outgoing energy = $77 + 30 + 165 + 30 + 40$	$= 492 \text{ W m}^{-2}$
$= 342 \text{ W m}^{-2}$	Outgoing energy = $24 + 78 + 350 + 40$
= incoming energy	$= 492 \text{ W m}^{-2}$
	= incoming energy

Table 2.2 provides a description and the contribution to the energy budget of most of the terms in figure 2.16.

TABLE 2.2 Energy budget of the Earth by energy category

Energy category	Amount (W m^{-2})	Description
Incoming solar radiation	342	Visible light with some infra-red and ultraviolet from the Sun
Outgoing longwave radiation	235	Infra-red radiation from many sources heading out to space
Reflected solar radiation	107	Visible light from two sources heading out to space ($30 + 77 = 107$)
Reflected by clouds etc.	77	Visible light reflected by clouds, aerosol and atmospheric gases
Atmosphere window	40	Infra-red radiation passing through the atmosphere because it is in the part of the spectrum that is not absorbed by the main greenhouse gases
Emitted by clouds	30	Infra-red radiation from clouds heading out to space
Latent heat	78	Energy used or released when there is a change of state
Back radiation	324	Infra-red radiation emitted downwards by greenhouse gases in the atmosphere
Absorbed by surface	492	Visible light, infra-red and ultraviolet radiation from two sources absorbed by the Earth's surface ($168 + 324 = 492$)
Thermals	24	Rising currents of hot air
Evapotranspiration	78	Moisture in plants released as water vapour
Surface radiation	390	Infra-red radiation emitted by the Earth's surface into the atmosphere

SAMPLE PROBLEM 3

Using table 2.2, show that conservation of energy holds for the Earth system.

 **Teacher-led video:** SP3 (tlvd-0009)

THINK

1. Use table 2.2 and determine total energy in.
2. Use table 2.2 and determine total energy out.
3. Energy conservation holds if energy in = energy out.
4. State the solution.

WRITE

$$\text{Total incoming solar radiation} = 342 \text{ W m}^{-2}$$

$$\begin{aligned} \text{Total outgoing energy} &= \text{Outgoing longwave radiation} + \text{Reflected solar radiation} \\ &= 235 + 107 \\ &= 342 \text{ W m}^{-2} \end{aligned}$$

$$\text{Energy in} = 342 \text{ W m}^{-2} = \text{energy out}$$

As the energy into the Earth system is equal to the energy out, conservation of energy holds for the Earth system.

PRACTICE PROBLEM 3

Using figure 2.16, find the missing amounts in the following table.

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

2.3.4 Feedback

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

The climate has examples of both positive and negative feedback, seen in table 2.3.

TABLE 2.3 Positive and negative feedback in the climate

Positive feedback	Negative feedback
Evaporation: Increasing sea temperatures leads to more evaporation of water, a greenhouse gas, which increases the temperature of the air and sea.	Thermal radiation: Increasing surface temperature emits more infra-red radiation, which cools the Earth.

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

Another example of positive feedback in the Earth's climate is the physical quantity 'albedo'.

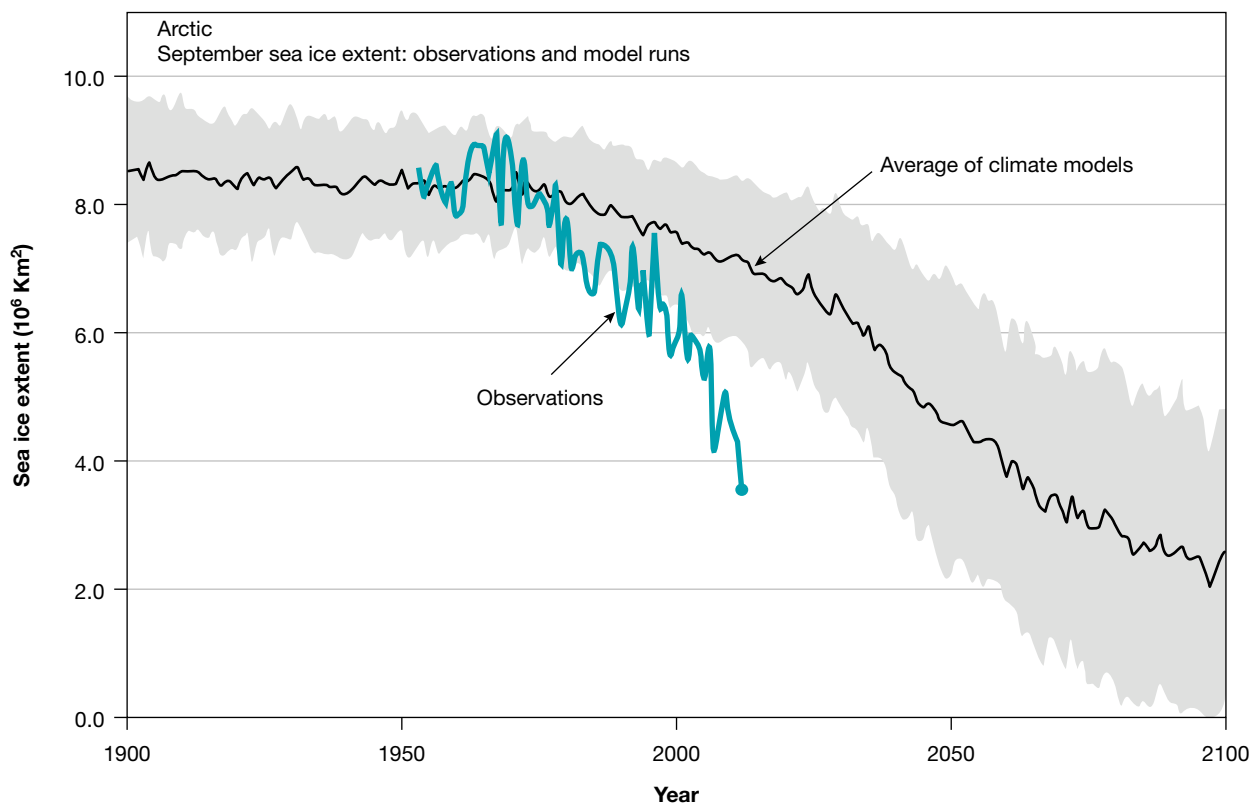
Albedo is a measure of the proportion of incoming radiation that is reflected without being absorbed. It is usually expressed as a number between 0 and 1, with 1 being a perfect reflector and 0 a perfect absorber.

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

TABLE 2.4 Albedo of different materials

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

FIGURE 2.17 The extent of Arctic sea ice in September each year. The solid line shows the average of climate model predictions, the shaded area is the spread of the predictions from the different models.



on Resources

-  **Digital documents** Investigation 2.1 Examining the sun's spectrum (doc-31859)
Investigation 2.2 The colour of temperature (doc-31860)
-  **Teacher-led video** Investigation 2.2 The colour of temperature (tlvd-0806)
-  **Video eLesson** Albedo (eles-2515)

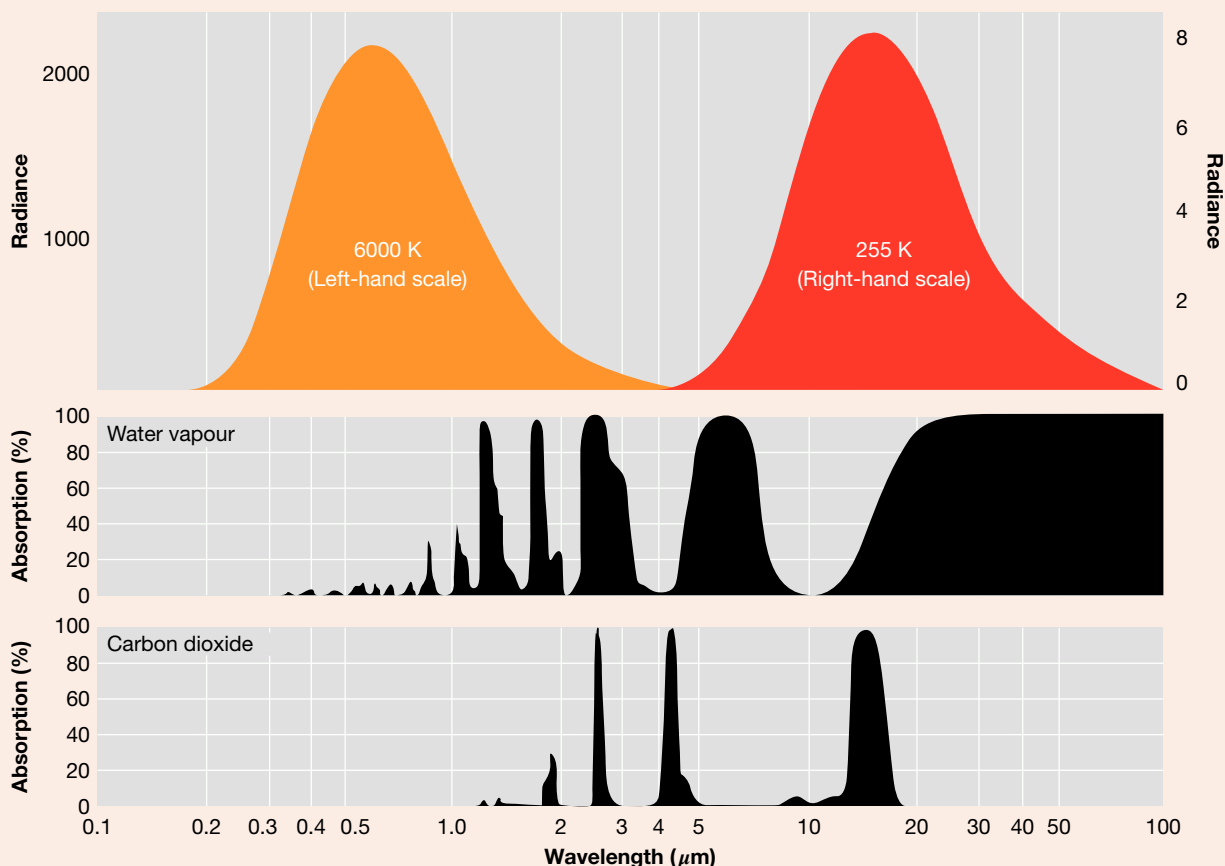
2.3 EXERCISE

To answer questions online and to receive **immediate feedback** and **sample responses** for every question go to your learnON title at www.jacplus.com.au.

- Why doesn't all of the radiation from the Sun that enters the Earth's atmosphere reach the surface?
- Why is the enhanced greenhouse effect a threat to life on Earth?
- Is the majority of the heating of the Earth's atmosphere due to the transfer of radiant energy from the Sun or from the Earth's surface?
- Identify the properties of water that cause the variation in climate over the Earth's surface.
- The following figure shows the radiance of the Sun (orange, left-hand scale) and the Earth (red, right-hand scale) and the absorption spectra for water vapour (H_2O) and carbon dioxide (CO_2).



- (a) Determine the range of wavelengths emitted by the Earth that are absorbed by:
- carbon dioxide
 - water vapour.
- (b) Which wavelengths emitted by the Earth are absorbed by carbon dioxide and not by water vapour?



6. (a) Which carbon dioxide molecule would move faster in the atmosphere: a lighter one with a carbon-12 atom or a heavier one with a carbon-13 atom?
- (b) Which molecule do you think is more likely to dissolve in the ocean? Give a reason.
7. Using figure 2.16 in section 2.3.3, calculate the total incoming energy and total outgoing energy for the atmosphere and show that each equals 519 W m^{-2} .
8. (a) Estimate the albedo of:
- the asphalt road surface
 - crops
 - the roof of your house.
- (b) Indicate whether each of the following is an example of positive or negative feedback. Explain your reasons.
- The release of methane from melting permafrost
 - Effect of clouds

studyon

To answer practice exam questions online and to receive immediate feedback and sample responses for every question go to your learnON title at www.jacplus.com.au.

studyON: Practice exam questions online only

Fully worked solutions and sample responses are available in your digital formats.

2.4 Climate models

KEY CONCEPT

- Analyse the evidence for the influence of human activity in creating an enhanced greenhouse effect, including affecting surface materials and the balance of gases in the atmosphere.

2.4.1 Scientific principles that underlie climate

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

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

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

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

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

2.4.2 How to know if a climate model is accurate?

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

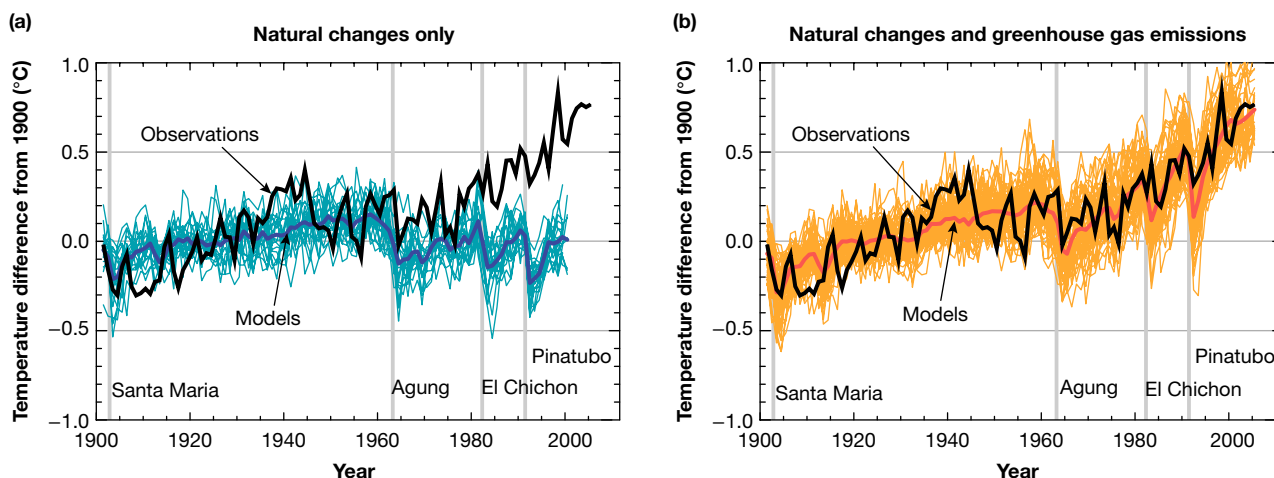
If the model is out, then it is back to the drawing board to redesign the model. If the model is accurate, it can be used to calculate the future climate. Different countries and scientific organisations each produce their own climate models. The basic scientific principles are the same, but the models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

The solid black line in each graph in figure 2.18 is the global average surface air temperature from 1900 until 2000. The models were run twice.

1. The first run assumed the carbon dioxide concentration stayed constant at its value in 1900. This produced the blue graph in figure 2.18a. The solid blue line is the average of all the different models.
2. The second run included the actual carbon dioxide concentration over the century. This produced the yellow graph in figure 2.18b. The solid red line is the average of all the different models.

The red line in figure 2.18b is a close fit to the actual observed temperature change. It is apparent from comparing the two graphs that increased carbon dioxide concentration has led to an increase in the global temperature.

FIGURE 2.18 Model comparisons against actual temperature from 1900 to 2000



Source: IPCC

The close match of figure 2.18b with the observations validates the design of the climate models and gives credence to the predictions for the decades and centuries ahead. The models can also be used to investigate how long the Earth's atmosphere would take to respond to a significant reduction in carbon dioxide emissions.

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

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

2.4.3 Investigating a simple climate model

The energy budget shown in table 2.2, in section 2.3.3, has been converted into a rudimentary spreadsheet model of the climate, which you can use to investigate the effect of future scenarios such as:

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

on Resources

 **Digital document** A simple climate change model (doc-16168)

2.4 EXERCISE

To answer questions online and to receive **immediate feedback** and **sample responses** for every question go to your learnON title at www.jacplus.com.au.

Use figure 2.18 in section 2.4.2 to answer questions 1–5.

1. Pinatubo, El Chichon, Agung and Santa Maria are all volcanic eruptions.
 - (a) What was the effect of the eruptions on the average global surface air temperature?
 - (b) Suggest a mechanism for this effect.

2. There are some stretches of a number of years where the models and the actual temperature data differ significantly.
 - (a) Identify those stretches of years.
 - (b) Thinking of the history of each of those years, is there a possibility that the collection of temperature data to obtain a global average may have been unreliable?
3. Looking at the two graphs, when do you think the increased carbon dioxide concentrations started to affect the global average surface air temperature?
4. The Earth's surface is made up of solid rock, liquid oceans and a gaseous atmosphere.
 - (a) Which do you think would be better to use to measure the temperature of the Earth's surface?
 - (b) Why do you think the air temperature is used?
5. Although the IPCC graphs show that long-term global warming is occurring, the temperature increase is not steady. What factors make the increase so erratic?

studyon

To answer practice exam questions online and to receive immediate feedback and sample responses for every question go to your learnON title at www.jacplus.com.au.

studyON: Practice exam questions online only

Fully worked solutions and sample responses are available in your digital formats.

2.5 Investigating issues related to thermodynamics

KEY CONCEPTS

- Apply thermodynamic principles to investigate at least one issue related to the environmental impacts of human activity with reference to the enhanced greenhouse effect.
- Explain how concepts of reliability, validity and uncertainty relate to the collection, interpretation and communication of data related to thermodynamics and climate science.

2.5.1 Issues related to thermodynamics

You have studied many aspects of thermodynamics in this and the previous topic that affect our lives in many ways, including:

- storing food
- designing our homes, as well as heating and cooling them
- keeping our bodies at an even temperature
- selecting energy sources for our economy
- most importantly, understanding and addressing climate change.
- It is therefore appropriate that you explore an issue in some depth, to identify the thermodynamic principles in use and to evaluate relevant public policy and social commentary for their scientific accuracy.

FIGURE 2.19 Applying thermodynamic principles is vital when designing a house.

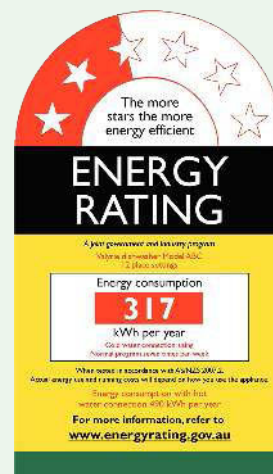


ISSUES RELATED TO THERMODYNAMICS

Some possible topics for you to research are listed here.

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

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



2.5.2 Evaluating resources

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

Some aspects worth considering are as follows.

Reliability

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

Validity

- *Accuracy*. Are physics concepts correctly used?
- *Argument*. Is the argument logically sound and strong? Are deceptive strategies used, for example, oversimplification or false selections?
- *Analysis*. Are physics relationships applied correctly?

Uncertainty

- *Graphs*. Are the graphs misleading?
- *Data*. Do the data lack precision? Are only selected data used?

2.5 EXERCISE

To answer questions online and to receive **immediate feedback** and **sample responses** for every question go to your learnON title at www.jacplus.com.au.

1. Apply thermodynamic principles to investigate at least one issue related to the environmental impacts of human activity with reference to the enhanced greenhouse effect.

studyon

To answer practice exam questions online and to receive immediate feedback and sample responses for every question go to your learnON title at www.jacplus.com.au.

studyON: Practice exam questions 

Fully worked solutions and sample responses are available in your digital formats.

2.6 Review

2.6.1 Summary

- The graph of the energy contribution of different wavelengths of emitted radiation has a characteristic shape.
- For a given temperature, there is a specific wavelength at which the most energy is emitted. Its symbol is $\lambda_{\max}$.
- The graph of the energy contribution of different wavelengths for a higher temperature has a lower $\lambda_{\max}$ and a larger area under the graph.
- $\lambda_{\max}$ is inversely proportional to the temperature measured in kelvin ($\lambda_{\max} T = \text{constant}$).
- The amount of energy emitted per second is called power.
- The area under the graph of energy contribution against wavelength is a measure of power.
- The area under the graph is proportional to the kelvin temperature raised to the power of 4. This can be expressed as $P \propto T^4$.
- The Earth on average, over the day and across the globe, receives about 342 joules of energy every second in each square metre.
- About 100 J of the energy the Earth receives is reflected back into space by ice, snow and clouds.
- Without greenhouse gases in the atmosphere, the surface temperature of the Earth would be -18°C .
- Most of the radiation emitted by the Earth is infrared radiation.
- The main greenhouse gases are water vapour (H_2O) and carbon dioxide (CO_2), with methane (CH_4) making a small contribution along with other molecules with more than two atoms.
- The relative flexibility of the greenhouse gas molecules allows them to absorb the infrared radiation emitted by the Earth's surface. After absorbing the infrared radiation, the greenhouse gases re-emit it in all directions; some upwards out into space, but most back down to the Earth to heat the surface.
- Some of the wavelengths absorbed by the greenhouse gases are common to each, but each particular gas absorbs some wavelengths that are unique to that gas.

- The energy that comes to the Earth from the Sun is balanced by the energy the Earth radiates back into space.
- The energy from the Sun is absorbed by the atmosphere, the land surface and the oceans. Some of this energy returns to the Earth's surface after being emitted by the greenhouse gases and increases the surface temperature.
- Feedback mechanisms are processes in complex systems where the output from the system can affect an input to the system. The feedback can be either positive or negative. Both types occur in the Earth's atmosphere.
- The albedo of a surface is the proportion of incoming radiation that is reflected with no change in wavelength.
- Climate models are based on the scientific principles of motion, thermodynamics and the chemistry of gases and liquids.
- Climate model calculations are very consistent with the historical record.
- Climate model calculations show that the increase in global average surface air temperature in recent decades is explained by the increased atmospheric carbon dioxide concentration.

on Resources

studyon

To access key concept summaries and practice exam questions download and print the **studyON: Revision and practice exam question booklet** (sonr-0027).

2.6.2 Key terms

Absorption bands are the range of wavelengths in the electromagnetic spectrum that are absorbed by atmospheric gases.

Absolute temperature is the temperature of an object taken in the scale using absolute zero.

Albedo is the proportion of solar radiation reflected by a surface.

A **black body** is an object that absorbs all radiation that falls on it.

Blackbody radiation is the characteristic radiation emitted by a black body when heated.

Eccentricity is a measure of how elliptical an object's orbit is.

Enhanced greenhouse effect is the greenhouse effect due to human civilization which is greater than that caused by natural forces alone.

Feedback is when a system's input is fed by its previous output.

Isotopes are atoms containing the same number of protons but different numbers of neutrons.

Negative feedback occurs when the response to the feedback is in the opposite direction to the input.

Obliquity is a measure of the angle tilt of a planet against its plane of orbit.

Photosynthesis is a chemical reaction that takes place in the chloroplasts of a plant cell consuming carbon dioxide and releasing oxygen.

Positive feedback occurs when the response to the feedback is in the same direction to the input.

Precession is a change in direction of the rotational axis of a spinning object.

on Resources

 **Digital document** Key terms glossary (doc-31861)

2.6.3 Practical work and investigations

Investigation 2.1

Examining the sun's spectrum

Aim: To show the different parts of the Sun's visible spectrum and to compare this to the other sections of the electromagnetic spectrum the Sun emits

Digital document: doc-31859

Investigation 2.2

The colour of temperature

Aim: To show that different colours have different thermal effects and to consider the implications of this for our planet

Digital document: doc-31860

Teacher-led video: tlvd-0806



on Resources

 **Digital document** Practical investigation logbook (doc-31858)

2.6 Exercises

To answer questions online and to receive **immediate feedback** and **sample responses** for every question go to your learnON title at www.jacplus.com.au.

2.6 Exercise 1: Multiple choice questions

- What would be the ratio of power $\left(\frac{P_1}{P_2}\right)$ for two stars of the same diameter if star 1 had half the surface temperature of star 2?
 - $\frac{1}{2}$
 - $\frac{1}{4}$
 - $\frac{1}{8}$
 - $\frac{1}{16}$
- In relation to figure 2.4, which statement is true?
 - The star at 3000 K would appear 'bluer' than the star at 6000 K because its peak is closer to the blue end of the visible spectrum.
 - The star at 6000 K would appear 'bluer' than the star at 3000 K because its peak is closer to the blue end of the visible spectrum.
 - The star at 6000 K would appear 'redder' than the star at 3000 K because its peak is closer to the red end of the visible spectrum.
 - Star colour cannot be determined by temperature.

3. Which of the following is *not* a feature that influences climate change on Earth?
 - A. The seasons
 - B. The properties of water
 - C. The tilt of Earth's axis
 - D. The geological features (land mass and oceans)
4. What is the major cause of the greenhouse effect?
 - A. Gases in the ozone layer absorb heat from the Earth's surface.
 - B. Gases in the ozone layer absorb heat from the Sun.
 - C. Gases in the atmosphere absorb heat from the Earth's surface.
 - D. Gases in the atmosphere absorb heat from the Sun.
5. The enhanced greenhouse effect is best described as which of the following?
 - A. The change to the natural greenhouse effect brought about by variations in solar radiation
 - B. The change to the natural greenhouse effect brought about by changing levels of gases in the atmosphere due to human activities
 - C. The change to the natural greenhouse effect brought about by changing levels of gases in the atmosphere due to variation in the plant growth
 - D. The change to the natural greenhouse effect brought about by changes in the Earth's orbit and inclination
6. Which of the following statements is true?
 - A. All bodies with temperatures higher than absolute zero emit radiation.
 - B. The higher the temperature of the object, the higher the frequency of electromagnetic radiation it emits.
 - C. The atmosphere and the surface of the Earth show a temperature range between 200 K and 300 K.
 - D. All of the above
7. What would happen if the Earth did not emit infrared radiation?
 - A. It would have no effect on the Earth's climate.
 - B. The Earth would be slightly warmer.
 - C. The Earth would be too hot to support life.
 - D. The Earth would emit visible light instead.
8. On a warm sunny day, the Sun's radiation melts very little snow on the slopes of an alpine ski resort. Why?
 - A. Snow, being a solid, is not affected by radiant heat.
 - B. The snow particles are unable to transfer the translational kinetic energy and so cannot warm up.
 - C. Snow is a type of water and due to its high latent heat capacity does not melt easily.
 - D. The white snow reflects up to 90% of the radiant energy of the Sun.
9. Electromagnetic (EM) radiation from the Sun is primarily in the visible light range on the EM spectrum. EM radiation from the Earth is primarily in which portion of the EM spectrum?
 - A. Infrared
 - B. Visible
 - C. Microwave
 - D. Ultraviolet
10. Molecules such as water (H_2O) and carbon dioxide (CO_2) absorb infrared radiation much better than oxygen (O_2) or nitrogen (O_2) molecules. Why is this?
 - A. They are more flexible.
 - B. They are less flexible.
 - C. They are cooler.
 - D. They are hotter.

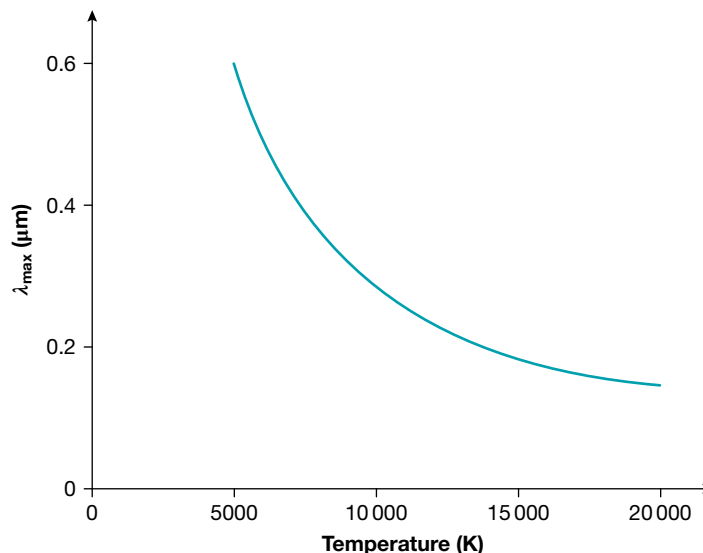
2.6 Exercise 2: Short answer questions

- The Sun gives out energy at a rate of 4.0×10^{26} W and has a surface temperature of 5778 K. Antares, a similar sized star to the Sun, has a surface temperature of 3700 K. At what rate does Antares release energy?
 - What colour would you expect Antares to be in comparison to our sun?
- Soil temperature over a small area is found to be 40.0°C during the day and is measured to lose energy at a rate of 479 W. At night the rate of energy loss is 330 W. What temperature is the soil at night?
- A violet star has a spectrum with a peak intensity at a wavelength of 4.00×10^{-7} m. Determine the temperature at the surface of this star.
 - A red star has a spectrum with a peak intensity at a wavelength of 7.00×10^{-7} m. Determine the temperature at the surface of this star.
- Two stars have identical diameters. One has a temperature of 5800 K; the other has a temperature of 2900 K. What are the colours of these stars? Which is brighter and by how much?
- Why does water take much longer to increase in temperature due to exposure to sunlight than the same mass of soil in an identical container?
- Use the Earth's energy budget illustrated in figure 2.16 to show that the total amount of energy entering the atmosphere is equal to the total amount of energy leaving it.
- It has been falsely argued that since the bulk of the greenhouse effect is caused by water, the other greenhouse gases are insignificant. Use the absorption spectra of CO_2 to show that this is not the case.
- What are the similarities and differences between the energy from the Sun that is absorbed by the Earth and the energy the Earth radiates into space?
- Estimate the quantity of radiant energy that would fall on your body (with an approximate height of 1.5 m and a width of 0.50 m) if you were to lie in the afternoon sun on the beach for 30 minutes. Assume that each square metre is receiving radiant energy at the rate of 1200 W. Explain any additional assumptions that you have made in making your estimate.

2.6 Exercise 3: Exam practice questions

Question 1 (7 marks)

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



- Use values from the graph to confirm Wien's law. **3 marks**
- Estimate the surface temperature of a star whose intensity peaks at a wavelength of:
 - $0.4 \mu\text{m}$ **1 mark**
 - $0.27 \mu\text{m}$. **1 mark**

c. Estimate the peak wavelength for a star with a surface temperature of:

- i. 15 000 K
- ii. 5550 K.

1 mark

1 mark

Question 2 (5 marks)

The specific heat capacity of water is over 4 times that of sand.

a. What effect does this have on the heating and cooling of water and sand?

1 mark

b. Explain why, on a hot day, sand is too hot to stand on in bare feet while the water in the sea can be too cold for some people.

2 marks

c. Why is the temperature of the sand of an inland desert almost always greater than that of the sand on a beach at the same latitude?

2 marks

Question 3 (3 marks)

When the Sun is directly overhead, each square metre of the Earth's surface receives 1368 J of radiant energy each second. On a typical winter's weekday, Victoria consumes about 4500 MW of electrical energy.

What area of solar collectors (of 15% efficiency) would be needed to provide energy at the same rate while the Sun is directly overhead?

Question 4 (2 marks)

In the tropical regions of the Earth, more radiant energy is received from space than is lost. At the poles, more radiant energy is lost than is received. This would suggest that average temperatures in the tropics should be continually increasing while the average temperatures at the poles should be continually decreasing.

Explain why this doesn't happen.

Question 5 (6 marks)

The following table compares the specific heat capacities as well as reflection and absorption properties of water and dry sand. The density of water is 1000 kg m^{-3} while the density of dry sand is 2400 kg m^{-3} .

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

When the Sun is directly overhead, each square metre of the Earth's surface receives radiant energy at the rate of 1368 W. Assuming all of the energy that is not reflected is absorbed, what average temperature increase would be expected during a period of 1 hour in:

a. water to a depth of 11 m

3 marks

b. sand to a depth of 1 mm?

3 marks

2.6 Exercise 4: studyON topic test

Fully worked solutions and sample responses are available in your digital formats.

teach

Test maker

Create unique tests and exams from our extensive range of questions, including practice exam questions. Access the assignments section in learnON to begin creating and assigning assessments to students.

UNIT 1 | AREA OF STUDY 1 REVIEW

AREA OF STUDY 1

How can thermal effects be explained?

OUTCOME 1

Apply thermodynamic principles to analyse, interpret and explain changes in thermal energy in selected contexts and describe the environmental impact of human activities with reference to thermal effects and climate science concepts.

PRACTICE EXAMINATION

STRUCTURE OF PRACTICE EXAMINATION		
Section	Number of questions	Number of marks
A	20	20
B	6	20
Total		40

Duration: 50 minutes

Information:

- This practice examination consists of two parts. You must answer all question sections.
- Pens, pencils, highlighters, erasers, rulers and a scientific calculator are permitted.
- You may use the VCAA Physics formula sheet for this task.



Resources



Weblink VCAA Physics formula sheet

Additional practice examination information

Specific heat capacities	Water	$4.2 \times 10^3 \text{ J kg}^{-1} \text{ K}^{-1}$
	Aluminium	$0.92 \times 10^3 \text{ J kg}^{-1} \text{ K}^{-1}$
Specific latent heat of fusion	Water	$3.3 \times 10^5 \text{ J kg}^{-1}$
Specific latent heat of vaporisation	Water	$2.3 \times 10^6 \text{ J kg}^{-1}$

SECTION A — Multiple choice questions

All correct answers are worth 1 mark each; an incorrect answer is worth 0.

1. The average kinetic energy of atoms and molecules are given by which of the following?
 - A. Their temperature
 - B. The heat input into them
 - C. Their work output
 - D. The heat output from them

2. The freezing point of water could be represented by which of the following?
 - A. 0 K
 - B. 0 °F
 - C. 273.15 °C
 - D. 273.15 K
3. A system consisting of a rubber balloon and the air inside has experienced an increase in its internal energy. Which of the following could be assumed?
 - A. Heat input into the system is less than the work done by the system.
 - B. Heat output from the system is greater than the work done on the system.
 - C. Heat input into the system is greater than the work done by the system.
 - D. Heat output from the system is greater than the work done by the system.
4. Two bodies, X and Y, are in thermal equilibrium with each other. One of the bodies, X, is brought into contact with a third body, Z, and they are found to also be in thermal equilibrium. Which of the following statements is correct?
 - A. X and Z must have the same mass as they are in thermal equilibrium with each other.
 - B. Y and Z must have the same specific heat capacity because they would be in thermal equilibrium.
 - C. Y and Z would have the same temperature because they would be in thermal equilibrium.
 - D. There is insufficient information about specific heat capacities to make any correct conclusion.
5. Which of the following is correct when comparing particles in a gas with those in a liquid?
 - A. They are closer together and more energetic in a gas.
 - B. They are further apart and less energetic in a gas.
 - C. They are closer together and less energetic in a liquid.
 - D. They are further apart and more energetic in a liquid.
6. Water and aluminium, each with a mass of 1 kilogram, are placed in their own insulated containers. Initially, they are both at the same temperature and are each heated by 1 kJ. Assuming the heat is evenly distributed across each mass, which of the following statement is correct about their final temperatures?
 - A. The final temperatures of both water and aluminium are the same.
 - B. The final temperature of the water is lower than that of the aluminium.
 - C. The final temperature of the water is higher than that of the aluminium.
 - D. There is insufficient information to conclude about their final aluminium.
7. The latent heat of fusion, denoted by the symbol L , is the amount of energy required to transform the state of 1 kilogram of substance from solid to liquid, and vice versa. Which of the following could be used as a unit for L ?
 - A. $\text{J}^{-1} \text{ kg}$
 - B. J kg
 - C. J m^{-3}
 - D. J kg^{-1}
8. Meena would like to raise the temperature of a 2.2 kilogram bar of aluminium from 22 °C to 44 °C. What is the amount of energy, in kJ, required to achieve this (assuming 100% efficiency)?
 - A. 4.45 kJ
 - B. 8.90 kJ
 - C. 44.5 kJ
 - D. 89.0 kJ
9. An electric kettle supplies 67 kJ of thermal energy to 750 mL of water at an initial temperature of 18 °C. Determine the final temperature of the water assuming that all the thermal energy is transferred into the water.
 - A. 21.3 °C
 - B. 34 °C
 - C. 37.3 °C
 - D. 39.3 °C

10. How much energy, in MJ, is liberated when 1.3 kilograms of steam condenses into water at 100 °C?
 - A. 0.43 MJ
 - B. 2.3 MJ
 - C. 3 MJ
 - D. 4.3 MJ
11. At the Mawson Antarctic Research station, an electric heater supplies 37 GJ of energy to melt ice to produce water for consumption by the scientists there. How much water, in kg, at 0 °C would be produced by this amount of energy?
 - A. 1.12×10^4 kg
 - B. 1.12×10^5 kg
 - C. 1.12×10^6 kg
 - D. 1.12×10^7 kg
12. An electric hotplate with a temperature of 750 K emits 1200 W of thermal energy. What is the expected power emitted if the filament temperature is doubled to 1500 K?
 - A. 12 000 W
 - B. 19 200 W
 - C. 24 000 W
 - D. 29 200 W
13. Thermite is a reaction between aluminium powder and iron oxide, which generates temperatures of about 2200 °C. What is the wavelength of the radiation emitted by thermite?
 - A. 1.32×10^{-5} m
 - B. 1.17×10^{-5} m
 - C. 1.32×10^{-6} m
 - D. 1.17×10^{-6} m
14. A pyrometer is a device that senses temperature from the radiation emitted from a surface. One such device detected a peak radiation of 6.5 µm from an object. What is the surface temperature of the object?
 - A. 173 °C
 - B. 273 °C
 - C. 346 °C
 - D. 446 °C
15. Which grid energy supply does *not* contribute to the enhanced greenhouse effect?
 - A. Coal powered electric generator
 - B. Natural gas powered electric generator
 - C. Nuclear powered electric generator
 - D. Diesel powered electric generator
16. Which group of atmospheric gases contain only greenhouse gases?
 - A. Carbon dioxide, water vapour, methane, argon
 - B. Oxygen, nitrogen, methane, carbon dioxide
 - C. Nitrous oxide, ozone, chlorofluorocarbon
 - D. Methane, water vapour, carbon dioxide, neon
17. Albedo, which refers to the reflection of solar radiation, plays an important role in the Earth's climatic system. Which of the following has the lowest albedo?
 - A. Clouds
 - B. Sea surface
 - C. Polar ice caps
 - D. Snow-capped mountains

18. Which of the following is an example of a positive feedback mechanism that enhances the effect of global warming on climate change?
- A. Rising ocean temperatures increase evaporation, which condenses into clouds to reflect the incoming solar radiation.
 - B. Rising ocean temperatures increase evaporation, which increases the amount of water vapour, a greenhouse gas.
 - C. Rising ocean temperatures disrupts the natural flow of ocean currents to transfer heat from the tropical regions to the polar regions, resulting in a new ice age.
 - D. Rising ocean temperatures increase evaporation, which creates a humid greenhouse-like condition, which absorbs even more solar radiation.
19. What is the mechanism for heat transfer in convection?
- A. Vibrational transfer of kinetic energy
 - B. Emission of electromagnetic radiation
 - C. More energetic particles colliding with less energetic particles
 - D. Movement of fluid due to differences in buoyancy
20. Greenhouse gases such as methane (CH_4) and carbon dioxide (CO_2) absorb infrared radiation emitted from the surface of the Earth, unlike gases such as oxygen (O_2) or nitrogen (N_2). What is this absorption of infrared radiation due to?
- A. These compounds contain a carbon atom, hence the term 'carbon pollution'.
 - B. Molecules with three or more atoms bend and stretch, and can better absorb infrared radiation.
 - C. There is a higher number of atoms in those molecules.
 - D. Compounds absorb infra-red radiation better than pure elements such as oxygen or nitrogen.

SECTION B — Short answer questions

Question 1 (5 marks)

A small piece of beef and a small piece of chicken are placed in an oven, each with a meat thermometer stuck into it to measure the temperature at its centre. After 30 minutes in the oven the thermometer in the chicken indicated the temperature to be 100°C . After a further 30 minutes, the thermometer on the beef indicated the temperature at its centre to also be 100°C . They remained in the oven to cook for a further 60 minutes. During this period, the thermometers steadily indicated 100°C .

- a. The piece of beef and the piece of chicken could be said to be at thermal equilibrium after this time. By referring to the kinetic theory of matter, explain what is meant by 'thermal equilibrium'. **2 marks**
- b. Discuss why it may be possible to estimate the temperature of the air in the oven near these two masses of meat, even if the oven does not have a thermometer. Hence, give an estimate of the temperature of the air in the oven near these two masses of meat. **3 marks**

Question 2 (3 marks)

Sue and Mel are preparing for a science fair at their school. They inflated a giant rubber balloon with air and attached it to a window where it was exposed to sunlight. After an hour, Sue noticed that the balloon was bigger. She said to Mel, 'The internal energy of the air in the balloon is lower than when we attached it to a window. This is because the air inside has done work to expand the balloon'.

- a. Mel disagreed with Sue. What explanation might Mel give to show that Sue is incorrect? **2 marks**
- b. What would be necessary for the internal energy of the air in the balloon to remain the same? **1 mark**

Question 3 (4 marks)

Anton is carrying out an experiment to determine the quantity of aluminium rivets with an initial temperature of 23°C required to cool 250 grams of boiling water at 100°C inside an insulated container. Assuming the experiment was carried out with negligible heat loss, both the aluminium rivets and the water will reach thermal equilibrium at 90°C .

- Calculate the magnitude of heat lost by the water to the aluminium as it cools from $100\text{ }^{\circ}\text{C}$ to the equilibrium temperature of $90\text{ }^{\circ}\text{C}$. **2 marks**
- The amount of heat lost by the water is the heat gained by the aluminium. Determine the mass of aluminium rivets as it warmed up from the initial temperature of $23\text{ }^{\circ}\text{C}$ to the equilibrium temperature of $90\text{ }^{\circ}\text{C}$. **2 marks**

Question 4 (2 marks)

Kym and Shan are observing light emitted from different light-emitting diodes (LED). One of the LED emitted light at twice the electromagnetic radiation frequency of another LED. Kym said 'According to Wien's Law, if the electromagnetic radiation frequency of one LED is twice that of the other, it would also be at twice the absolute temperature of the other'.

Shan disagrees. What explanation might Shan offer to show that Kym is incorrect.

2 marks

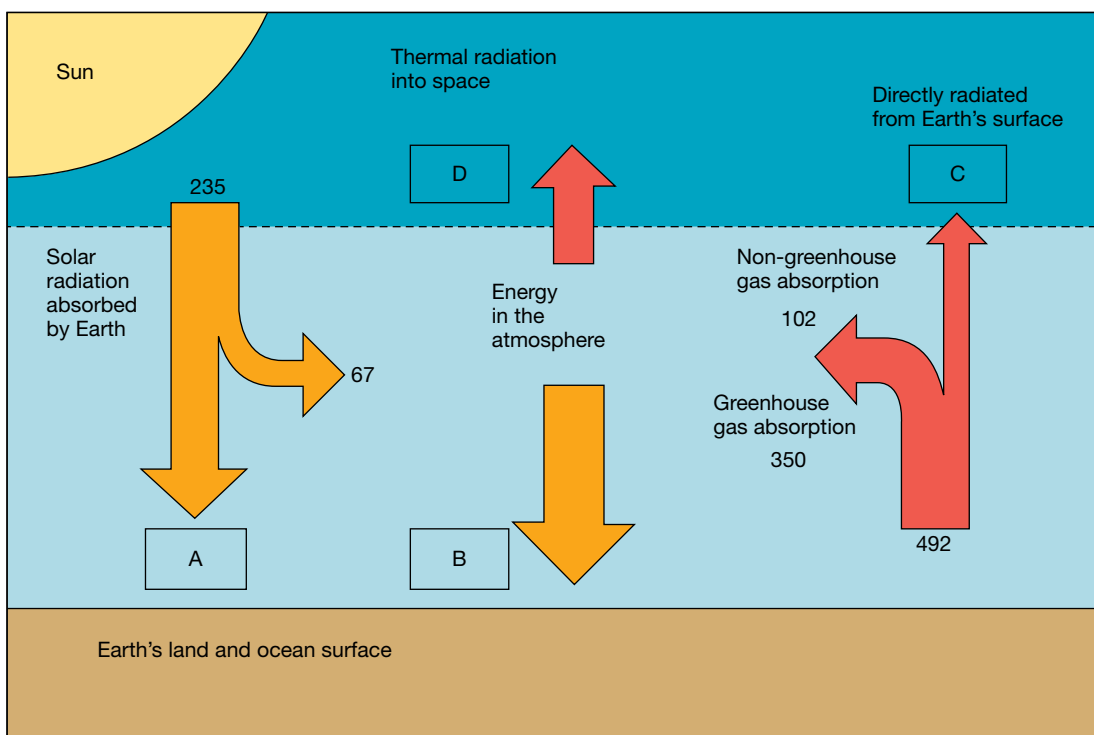
Question 5 (2 marks)

Habib's electric barbeque radiates 2250 W of energy when the heating element is at a temperature of $850\text{ }^{\circ}\text{C}$. What is the expected power output when the heating element is at a temperature of $900\text{ }^{\circ}\text{C}$?

2 marks

Question 6 (4 marks)

The following diagram shows a part of the Earth's energy budget, which is balanced. All numerical values are in W m^{-2} .



- Considering the total incoming solar radiation and the amount absorbed by the Earth's atmosphere, how much is absorbed by the Earth's land and ocean surface (box A)? **1 mark**
- Considering that the energy budget is balanced, how much energy is re-radiated downward back to the Earth's land and ocean surface from the atmosphere (box B)? **1 mark**
- How much outgoing radiation from the Earth's land and ocean surface is directly radiated into outer space (box C)? **1 mark**
- How much thermal radiation from the Earth's atmosphere goes into outer space (box D)? **1 mark**

ASSESSMENT TASK — A REPORT ON A SELECTED SCIENTIFIC PHENOMENON

In this task, you will be required to report on the phenomenon of the greenhouse effect, linking this to thermodynamic principles.

- This practice SAC requires you to write a report; a structure set of questions is supplied to assist you to write your report.
- You may use the VCAA Physics formula sheet and a scientific calculator for this task.
- You may conduct research before commencing your write-up to assist you in this task.

Total time: 50 minutes (5 minutes reading, 45 minutes writing)

Total marks: 30 marks



A WORLDWIDE CRISIS — THE IMPACT OF THE GREENHOUSE EFFECT

Humans have a dramatic impact on the environment and unfortunately it is often a detrimental one. From deforestation to pollution, the environment is being continually affected, creating huge scientific and ecological problems.

Since the Industrial Revolution, human impact on increasing greenhouse gases has been particularly evident, and has led to global warming and damage to ecosystems around the world. In Australia, the Great Barrier Reef has been significantly affected by coral bleaching caused by this global warming.

Write a report with reference to the following concepts. You should use subheadings to clearly frame your response.

1. Identify and describe the types of electromagnetic radiation emitted from the Sun.
2. Explain the roles of conduction, convection and radiation in moving heat around in Earth's mantle and surface and the Earth's atmosphere. Identify which of these is most important in contributing to the greenhouse effect.
3. Provide background information on the greenhouse effect, with a clear link to global warming using thermodynamic principles.
4. Explain how greenhouse gases absorb and re-emit infrared radiation, and describe why different greenhouse gases are involved.
5. Clearly describe the evidence of the effect of human activity in creating an enhanced greenhouse effect.
6. Describe how you would collect evidence on the enhanced greenhouse effect, explaining how you can ensure reliability and validity while minimising uncertainty.
7. Apply thermodynamic principles to investigate one of the following issues (using evidence and data) related to the impacts of human activity on the enhanced greenhouse effect. In your response, you need to show a clear link to theory and describe how it may have an impact on the greenhouse effect. You should also suggest solutions that can help minimise the enhanced greenhouse effect for your given issue.
 - Proportion of national energy use due to heating and cooling of homes
 - Comparison of the operation and efficiencies of domestic heating and cooling systems: heat pumps, resistive heaters, reverse-cycle air conditioners, evaporative coolers, solar hot water systems and/or electrical resistive hot water systems
 - Possibility of homes being built that do not require any active heating or cooling at all
 - Use of thermal imaging and infra-red thermography in locating heating losses in buildings and/or system malfunctions; cost savings implications
 - Determination of the energy ratings of home appliances and fittings: insulation, double glazing, window size, light bulbs, and/or electrical gadgets, appliances or machines
 - Cooking alternatives: appliance options (microwave, convection, induction), fuel options (gas, electricity, solar, fossil fuel)
 - Automobile efficiencies: fuel options (diesel petrol, LPG and electric), air delivery options (naturally aspirated, supercharged and turbocharged) and fuel delivery options (common rail, direct injection and fuel injection)



Resources



Digital document School-assessed coursework (doc-32273)

3 Concepts used to model electricity

3.1 Overview

Numerous **videos** and **interactivities** are available just where you need them, at the point of learning, in your digital formats, learnON and eBookPLUS at www.jacplus.com.au.

3.1.1 Introduction

What would your world be like without electricity? Would your mobile phone work or would you be able to find your way around your house on a dark night? The transfer of electrical energy into other forms of energy helps us in many ways. The electricity that is transferred to heat in order to warm us on cold nights or the electricity that is transferred to move an electric bicycle is current electricity that has been created by the movement of electric charge.

Not all electric charge moves or flows. Static electricity can be created by the removal of electrons from a material. The discharge of static electricity, as occurs during a lightning storm, can be dramatic and sometimes dangerous.

In an electric circuit, electric charges move in an organised way. A battery or other energy source separates electric charge and causes a current to flow. In a simple circuit connected to a battery, the overall movement of the electric charges is in one direction. Electric charges move in some materials better than others, particularly in metals that are used as conductors.

You should already be able to recognise and connect simple circuits such as those containing batteries and globes. At the end of this topic you should be able to describe the concepts of electric charge and the effects of current and voltage in the transformation of electrical energy into other forms of energy.

FIGURE 3.1 Electricity is an integral part of modern life. Consider how the processes of transfer and transformation of energy occur in electric circuits.



3.1.2 What you will learn

KEY KNOWLEDGE

After completing this topic you will be able to:

- apply concepts of charge (Q), electric current (I), potential difference (V), energy (E) and power (P), in electric circuits
- explore 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
- model resistance in series and parallel circuits using
 - current versus potential difference (I – V) graphs
 - resistance as the potential difference to current ratio, including $R = \text{constant}$ for ohmic devices.

Source: VCE Physics Study Design (2016–2021) extracts © VCAA; reproduced by permission.

PRACTICAL WORK AND INVESTIGATIONS

Practical work is a central component of learning and assessment. Experiments and investigations, supported by a **Practical investigation logbook** and **Teacher-led videos**, are included in this topic to provide opportunities to undertake investigations and communicate findings.

on Resources

 **Digital documents** Key science skills — VCE Units 1–4 (doc-31856)

Key terms glossary (doc-32178)

Practical investigation logbook (doc-32179)

studyon

To access key concept summaries and practice exam questions download and print the **studyON: Revision and practice exam question booklet** (sonr-0028).

3.2 Electric circuits

KEY CONCEPTS

- Apply concepts of charge (Q), electric current (I), potential difference (V), energy (E) and power (P), in electric circuits.
- Explore different analogies used to describe electric current and potential difference.

3.2.1 Fundamentals of electricity

Electric charge (in terms of the basic structure of matter)

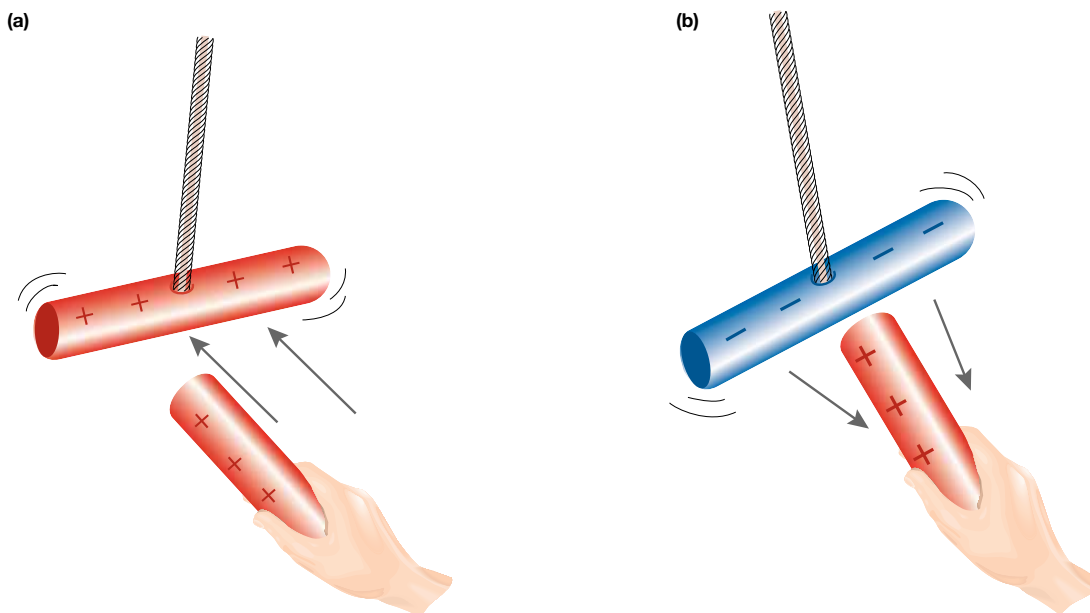
Electric charge is a basic property of matter. Matter is all the substance that surrounds us — solid, liquid and gas.

You have probably experienced that small electric shock that happens when you touch a metal rail after walking across carpet. This type of phenomenon has been observed for thousands of years. Objects such as glass, gemstones, tree resin and amber can become ‘electrified’ by friction when they are rubbed with materials such as animal fur and fabrics to produce a spark. Indeed, the words ‘electric’ and ‘electricity’ are derived from the Greek word for amber, *electron*.

Experiments in the early 1700s showed that:

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

FIGURE 3.2 (a) Two positively charged objects repel each other. (b) Oppositely charged objects attract each other.



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

The direction of the electrostatic forces between electric charges act such that:

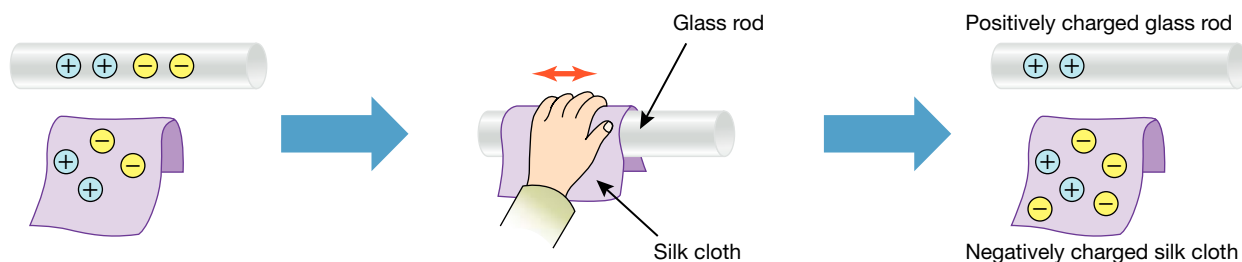
- two positive charges repel one another
- two negative charges repel one another
- a positive charge and a negative charge attract one another.

This is summarised as: *like charges repel; unlike charges attract*.

Note: **Neutral objects** carry an equal amount of positive and negative charge and do not attract or repel other neutral objects.

Electrostatic forces can be observed in the production of static electricity, in which electric charges become imbalanced. When a neutrally charged glass rod is rubbed with a neutrally charged silk cloth, electrons are transferred from the rod to the cloth. As shown in figure 3.3, the rod therefore becomes more positively charged (from losing electrons) and the cloth becomes more negatively charged. Therefore, they become attracted to one another as they have unlike charges. Experiments like these demonstrate that electric charge can be moved, while being neither created nor destroyed. Electric charge is conserved.

FIGURE 3.3 Electric charge is conserved.



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

THE RESEARCH OF BENJAMIN FRANKLIN

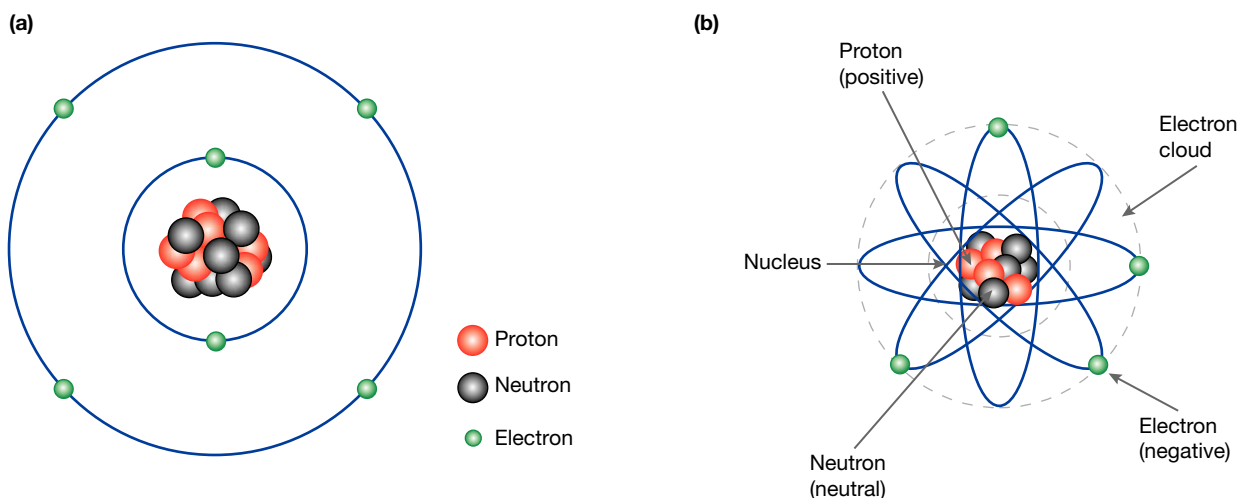
Benjamin Franklin (1706–90), a US political leader, inventor and scientist, introduced the concepts of positive and negative electricity. His research on lightning, including discharges obtained with a kite, helped to establish its electrical nature. In 1752, Benjamin Franklin conducted the kite and key electricity experiment during a lightning storm (see figure 3.4). He advocated the use of lightning rods as protective devices for buildings. Franklin was almost killed one day when he was trying to electrocute a turkey with a condenser, a device used to store charge. (Members of genteel society at the time thought it was acceptable to see how big an animal they could electrocute.)

FIGURE 3.4 Benjamin Franklin's kite and key electricity experiment



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

FIGURE 3.5 (a) The structure of an atom (electron shell) (b) An atom showing orbits and shells



Protons and electrons possess a characteristic known as electric charge; because of their electric charge, these particles exert electric force on each other. Protons carry a positive charge and electrons carry a negative charge. The positive charge on a proton is equal in magnitude to the negative charge on an electron, meaning that the negative and positive charges neutralise each other. Neutrons have no electric charge; that is, they are uncharged or neutral.

Conductors and insulators

Some materials are made up of atoms which are fixed together in such a way that all their electrons are bound tightly to the nucleus and are not free to travel through the material. Such substances are termed **electric insulators**. An insulator is a material that contains no charge carriers. If an insulator is given an electrostatic charge at a particular area on the insulator, the charge will remain at that area. Common examples of insulators include dry air, glass, plastics, rubber and ceramics.

A **conductor** is a material that contains charge carriers; that is, charged particles can move and travel freely through the material. Examples include:

- metals — materials whose outer electrons are so loosely bound to the nucleus that they are effectively free to move easily through the material. Usually this movement is random but when the free electrons are forced to flow in one direction, a current can be created
- salt solutions, whose charged particles, such as **ions**, are free to move through the solution.

Note: Pure water is not a conductor as it does not contain any ions.

Another important group of materials are *semiconductors*, which allow electrons to move freely under certain conditions. Silicon is commonly used in the construction of semiconducting photovoltaic cells. When the Sun shines on these cells in solar panels they generate electricity.



Resources



Digital document Investigation 3.1 The Van de Graaff generator (doc-31918)

3.2.2 Electric circuits

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

For a circuit to be useful, it must contain a **load**. A load is a device where electrical energy is converted into other forms of energy to perform a task such as heating something, or providing light, sound or mechanical energy from a motor. This happens in devices such as toasters, speakers, lamps and motors. A load is anything that is doing a job.

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

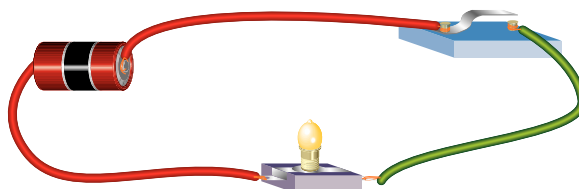
A simple circuit can be made up of:

- a source of energy, such as a battery
- conductors, such as wires
- some kind of load, where energy is transformed from electrical energy into other forms such as heat, sound, light and movement by devices
- a **switch** that stops or allows the flow of electricity in the circuit.

In figure 3.6, note:

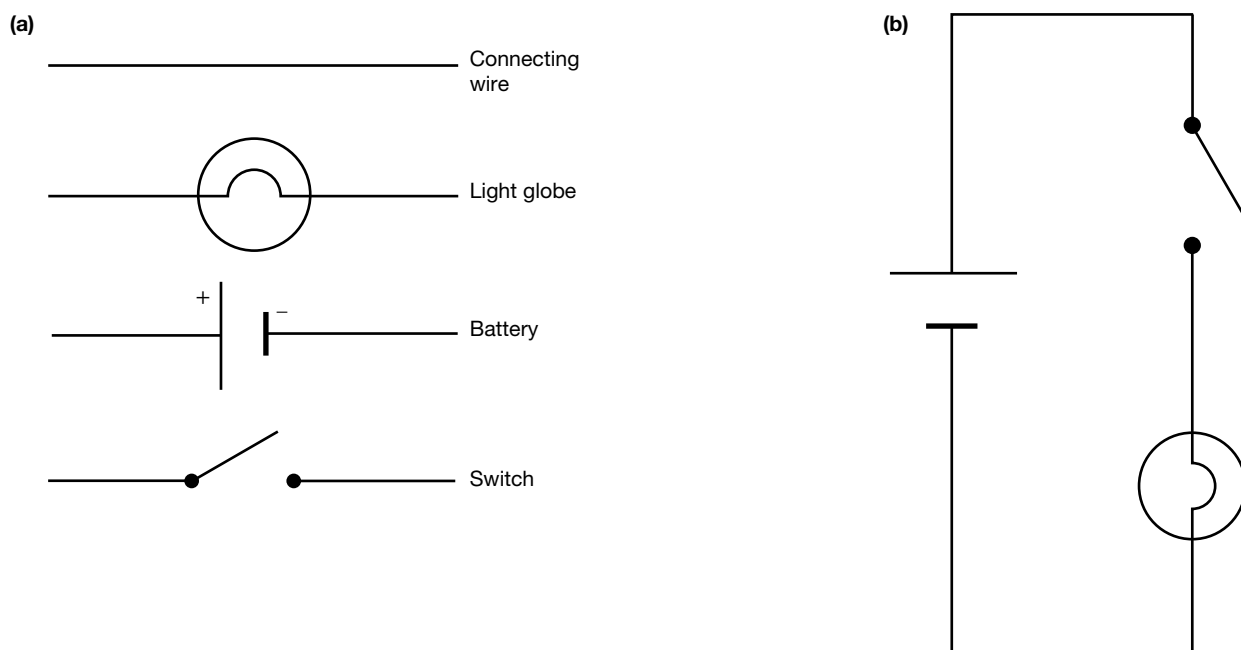
- For the globe to light up there must be a complete conducting path between the terminals of the battery. The switch must be closed.
- The battery is necessary for a current to flow around the circuit. The ability of the battery to cause a current to flow is often referred to as its voltage.
- The battery has two terminals, marked positive and negative.
- The light globe resists the flow of the current. As a result of this resistance, the current causes the light globe to heat up to such an extent that it gives off light.
- The wires connecting the light globe to the battery do not heat up.

FIGURE 3.6 A simple electric circuit



The symbols shown in figure 3.7a are used when representing electric circuits in diagrams. Therefore, the circuit shown in figure 3.6 can be represented more simply as shown in figure 3.7b.

FIGURE 3.7 (a) Symbols for circuit components (b) Diagram of the simple electric circuit



3.2 EXERCISE

To answer questions online and to receive **immediate feedback** and **sample responses** for every question go to your learnON title at www.jacplus.com.au.

1. After a plastic pen is rubbed with a piece of wool it can be used to attract small pieces of paper. Describe what has happened in terms of electric charge.
2. After rubbing a balloon on your clean dry hair, the balloon should try to stick to your hair when you try to remove it. Explain why this occurs.
3. If you separately rub two balloons on your hair and then hold them near each other what will happen? Explain why this occurs.
4. After walking across a nylon carpet in woollen socks and then touching a metal doorknob it is possible to get an electric shock. Explain why this occurs.
5. After rubbing a balloon in her hair, Chris brought it very close to an aluminium can lying on a flat table. When she slowly moved the balloon away from the can it started to roll and follow the balloon. Describe why this happened.
6. Imagine you are an electron. Describe your journey around the closed circuit of a torch, beginning at the negative terminal of a cell.
7. A doorbell connected to a battery comprises a button at the door, the bell and wires. The bell only sounds after the button is pushed. Why doesn't the bell always sound?

studyon

To answer practice exam questions online and to receive immediate feedback and sample responses for every question go to your learnON title at www.jacplus.com.au.

studyON: Practice exam questions 

Fully worked solutions and sample responses are available in your digital formats.

3.3 Current

KEY CONCEPTS

- Apply concepts of charge (Q), electric current (I), potential difference (V), energy (E) and power (P) in electric circuits.
- Justify the use of selected meters (ammeter, voltmeter, multimeter) in circuits.
- Explore different analogies used to describe electric current and potential difference.

3.3.1 Defining current

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

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

Not all moving charges constitute a current. There must be a net movement of charge in one direction for a current to exist. In a piece of metal conductor, electrons are constantly moving in random directions. Until there is a net movement of charge in one direction, as happens when a metal wire is connected in a closed circuit with a power source (such as a battery) and a load (such as a light bulb), there is no current. As water flows down a river there are millions of coulombs of charge moving with the water molecules, but there is no electrical current in this case because equal numbers of positive and negative charge are moving in the same direction.

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

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

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

Where:

I is the current, in amperes

Q is the quantity of charge flowing past a point in the circuit, in coulombs

t is the time interval, in seconds.

The unit of current is the **ampere** (A). It is named in honour of the French physicist André-Marie Ampère (1775–1836). One ampere is the current in a conductor when 1 coulomb of charge passes a point in the conductor every second.

The unit for charge is the **coulomb** (C), named after the French physicist Charles-Augustin de Coulomb (1736–1806). One coulomb of charge is equal to the amount of charge carried by 6.24×10^{18} electrons. The charge carried by a single electron is equal to -1.602×10^{-19} C.

The -1.602×10^{-19} charge possessed by an electron is the smallest free charge possible. All other charges are whole-number multiples of this value. This so-called elementary charge is equal in magnitude to the charge of a proton. The charge of an electron is negative, whereas the charge of a proton is positive.

SMALL CHARGES AND QUARKS

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

SAMPLE PROBLEM 1

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

 Teacher-led video: SP1 (tlvd-0010)

THINK

1. Current is the rate at which charge, Q flows in the circuit. Give values for Q and t .
2. Substitute values for Q and t into the formula
$$I = \frac{Q}{t}.$$
3. Current is measured in ampere (A), where:
 $1 \text{ A} = 1 \text{ C s}^{-1}.$
4. State the solution.

WRITE

$$Q = 10 \text{ C}, t = 5.0 \text{ s}$$

$$I = \frac{Q}{t}$$
$$= \frac{10 \text{ C}}{5.0 \text{ s}}$$

$$I = 2.0 \text{ C s}^{-1}$$

$$I = 2.0 \text{ A}$$

The current in the conductor is 2.0 A.

PRACTICE PROBLEM 1

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

SAMPLE PROBLEM 2

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

 Teacher-led video: SP2 (tlvd-0011)

THINK

1. To find the charge, Q , passing through the circuit transpose the formula $I = \frac{Q}{t}$ making Q the subject.
2. Give values for I and t .
Note: Be sure to convert the time to seconds.
3. Substitute values for I and t into the formula.
4. Convert to scientific notation, to 2 significant figures.
5. State the solution.

WRITE

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

$$Q = It$$

$$I = 3.0 \text{ A}, t = 5 \times 60 + 20 = 320 \text{ s}$$

$$Q = It$$
$$= 3.0 \text{ A} \times 320 \text{ s}$$

$$Q = 960 \text{ C}$$

$$Q = 9.6 \times 10^2 \text{ C}$$

$9.6 \times 10^2 \text{ C}$ charge passes through the load.

(*Note:* As the solution is quite small in magnitude, leaving the solution as 960 C instead of in scientific notation is acceptable).

PRACTICE PROBLEM 2

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

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

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

SAMPLE PROBLEM 3

Convert 450 mA to amperes.

 **Teacher-led video:** SP3 (tlvd-0012)

THINK

1. To convert mA to A divide by 1000 (or multiply by 10^{-3}).
2. State the solution.

WRITE

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

450 mA is equal to 0.450 A.

PRACTICE PROBLEM 3

Convert 280 mA to amperes.

3.3.2 Describing current direction

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

In reality, the charge carriers in a metal conductor are electrons moving from the negative terminal towards the positive terminal of the battery. The effect is essentially the same as positive charges moving in the opposite direction. When dealing with the mechanisms for the movement of electrons, the term '**electron current**' is used.

FIGURE 3.8 Conventional current direction

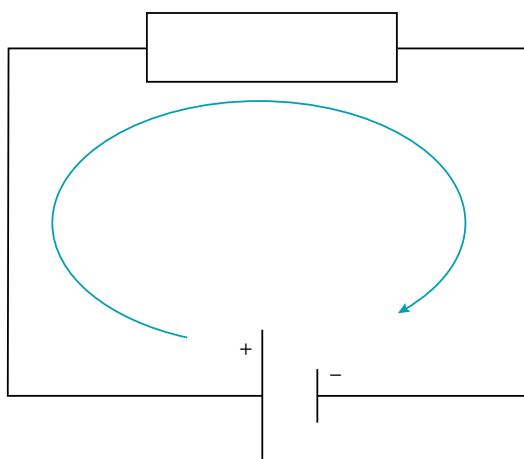
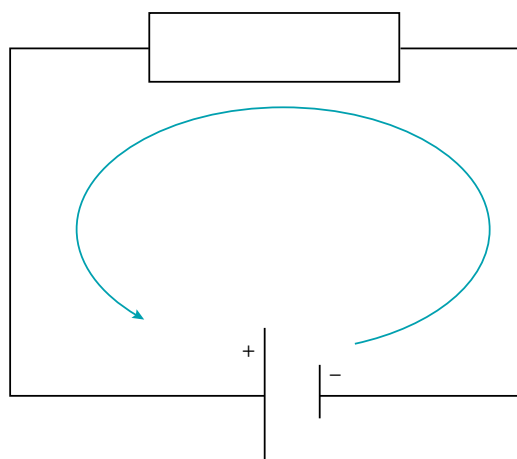


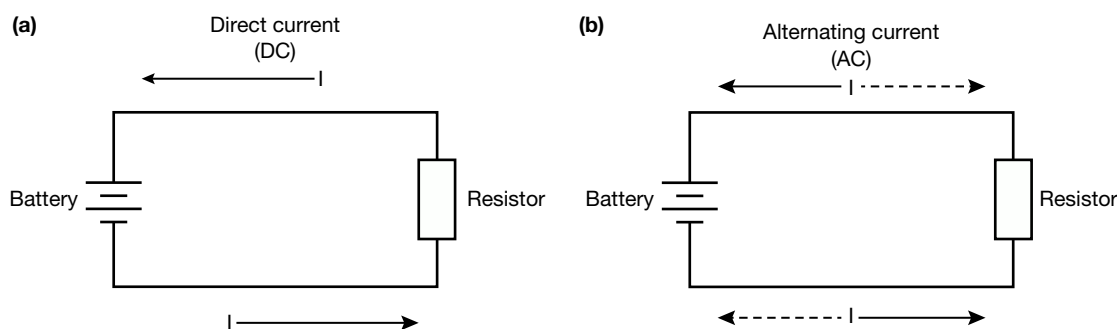
FIGURE 3.9 Electron current direction



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

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

FIGURE 3.10 Electron current direction: (a) direct current and (b) alternating current



3.3.3 Measuring electric current

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

Ammeters are designed so they do not significantly affect the size of the current in the circuit, their resistance to the flow of current being negligible.

FIGURE 3.11 The circuit diagram symbol for an ammeter

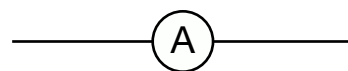
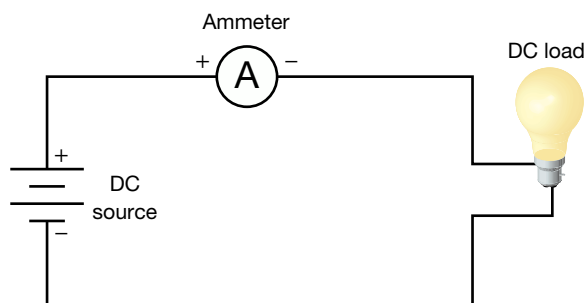


FIGURE 3.12 A needle-deflection ammeter



FIGURE 3.13 A ammeter in series

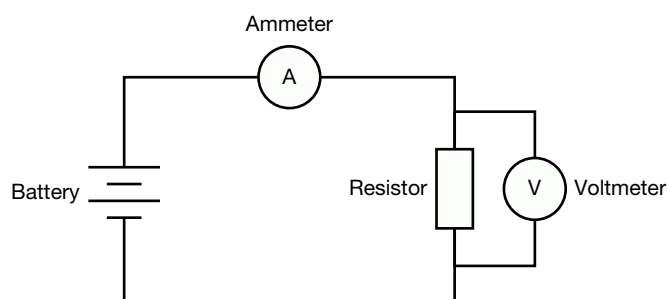


Whereas some school laboratories might use needle-deflection meters, most now use digital multimeters. Digital meters can measure voltage drop and resistance as well as current. Each quantity has a few settings to allow measurement of a large range of values. Labels on multimeters may vary but those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

FIGURE 3.14 A digital multimeter, which can measure current, voltage drop and resistance



FIGURE 3.15 Measuring current and voltage drop



If you are using digital multimeter, the following instructions generally apply.

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

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

3.3.4 Modelling an electric circuit

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

The hydraulic model of current

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

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

When the ends of a conductor are connected to a battery, the free electrons drift towards the positive terminal. The electrons are attracted by the positive terminal and indeed accelerate, but constantly bump into atoms so on average they just drift along (see figure 3.16).

The flow of electrons through a metallic conductor can also be modelled by the flow of water through a pipe (see figure 3.17).

FIGURE 3.16 The motion of free electrons through a metal. **Note:** Only two of the free electrons have been shown.

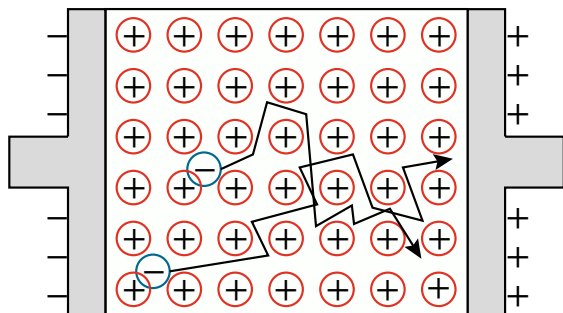
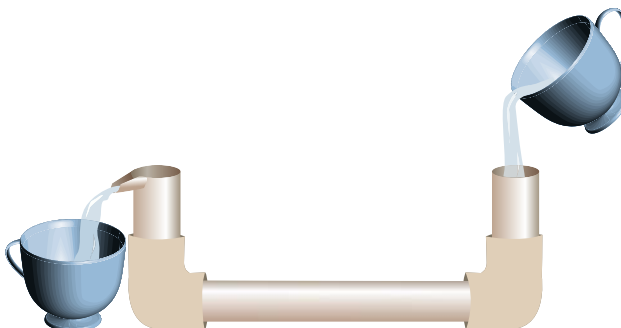


FIGURE 3.17 The hydraulic model for current flow. One cupful of water in one end of the pipe means one cupful out the other end.



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

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

Other models are sometimes used. For example, the bicycle chain model. In this model the chain represents the circuit and the links in the chain represent electrons. When the pedals are turned the chain moves and energy is transferred to the rear of the bicycle to move the rear wheel. The moving chain represents the movement of electrons around the circuit. Note that the transformation of energy from the pedals to the rear wheel is virtually instantaneous. The energy transfer from the pedals does not depend on particular chain links travelling from the pedals to the wheel. Similarly, the energy transfer in an electric circuit does not depend on particular electrons travelling to the load. Overall the transfer of electrical energy is faster than the movement of electrons in the conducting wires.

on Resources

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

3.3.5 How rapidly do electrons travel through a conductor?

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

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

SAMPLE PROBLEM 4

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

 **Teacher-led video:** SP4 (tlvd-0013)

THINK

1. The drift velocity, v , equals the distance travelled, d , divided by the time taken to travel the distance, t .
2. Transpose $v = \frac{d}{t}$ to make t the subject.
3. Substitute the known values into the formula and solve for t .
4. State the solution.

WRITE

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

$$vt = d$$

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

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

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

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

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

It would take 25 000 seconds, which is more than 7 hours.

PRACTICE PROBLEM 4

How long will it take an electron to travel to a headset from a console if it has a drift velocity of $7.4 \times 10^{-5} \text{ m s}^{-1}$ and there is 1.2 metres of copper wire to pass through?

3.3 EXERCISE

To answer questions online and to receive **immediate feedback** and **sample responses** for every question go to your learnON title at www.jacplus.com.au.

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

studyon

To answer practice exam questions online and to receive immediate feedback and sample responses for every question go to your learnON title at www.jacplus.com.au.

studyON: Practice exam questions 

Fully worked solutions and sample responses are available in your digital formats.

3.4 Voltage

KEY CONCEPTS

- Apply concepts of charge (Q), electric current (I), potential difference (V), energy (E) and power (P), in electric circuits.
- Justify the use of selected meters (ammeter, voltmeter, multimeter) in circuits.

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

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

Voltage is the energy provided to each coulomb of charge:

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

SAMPLE PROBLEM 5

- a. How much energy does a 1.5 V battery give to 0.50 coulombs of charge?
b. The charge on an electron is 1.6×10^{-19} coulombs. How much energy does each electron have as it leaves a 1.5 V battery?

 **Teacher-led video:** SP5 (tlvd-0014)

THINK

- a. 1. The energy is given by $E = VQ$.
2. Substitute the known values into the formula and solve for E .
3. State the solution.
- b. 1. The energy is given by $E = VQ$.
2. Substitute the known values into the formula and solve for E .
3. State the solution.

WRITE

- a. $E = VQ$
 $V = 1.5 \text{ V}, Q = 0.50 \text{ C}$
 $E = 1.5 \times 0.50$
 $= 0.75 \text{ J}$
The battery would give 0.75 joules of energy to 0.50 coulombs of charge.
- b. $E = VQ$
 $V = 1.5 \text{ V}, Q = 1.6 \times 10^{-19}$
 $E = 1.5 \times 1.6 \times 10^{-19}$
 $= 2.4 \times 10^{-19} \text{ J}$
Each electron would have 2.4×10^{-19} joules of energy.

PRACTICE PROBLEM 5

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

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

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

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

3.4.1 The conventional point of view

Looking from the perspective of conventional current — that is, positive charge carriers — the current would go in the opposite direction, as seen in figure 3.18.

In the circuit in figure 3.19a, positive charges at A, the positive terminal, would leave with energy, travel anticlockwise and arrive at F with no energy.

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

The graph in figure 3.19b shows the energy held by 1 C of charge — that is, the voltage — as the charge moves around the circuit from A to F.

FIGURE 3.18 The circuit symbol for a battery showing direction of conventional current

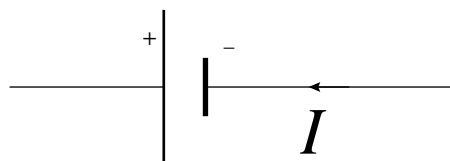
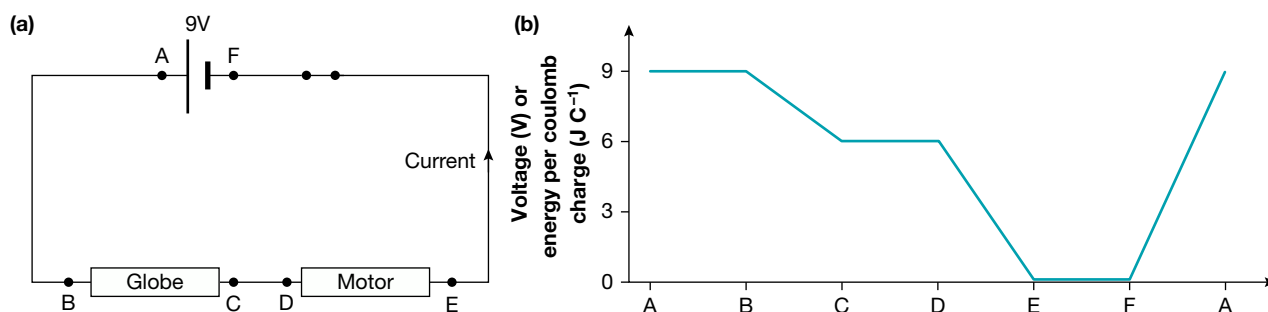


FIGURE 3.19 Voltage around a simple circuit



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

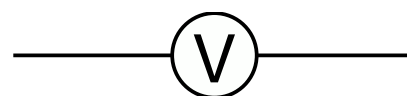
3.4.2 Measuring potential difference or voltage drop

The difference in voltage between any two points in the circuit can be measured with a **voltmeter**. This is called the **potential difference**, or **voltage drop**. The voltmeter must be connected across a part of the circuit in parallel. If the voltmeter was connected to points A and B in the circuit in figure 3.19, it would display zero, as there is no difference in the potential or voltage between those two points because charges do not use any energy moving between A and B. If instead it was connected across the globe at BC, it

would show a voltage drop of 3 V ($9 - 6 = 3$ V). This means that in the globe 3 joules of electrical energy are given up by each coulomb of charge and transformed by the globe into light and heat.

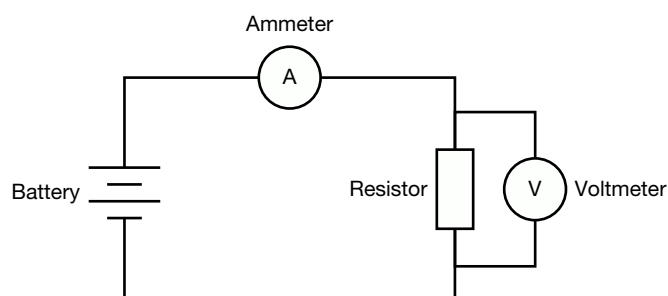
Voltmeters are designed so that they do not significantly affect the size of the current passing through the circuit element. For this reason, the resistance of the circuit elements involved. Resistance will be discussed later in this topic. The circuit diagram symbol for a voltmeter is shown in figure 3.20.

FIGURE 3.20 The circuit diagram symbol for a voltmeter



As discussed in section 3.3.3, most school laboratories now use digital multimeters, which can generally measure both AC and DC voltages (see figure 3.21). To measure DC voltages, use one of the settings near the 'V' with a bar beside it.

FIGURE 3.21 To measure the current through the resistor, an ammeter is connected in series. To measure the voltage drop across the resistor, the voltmeter is connected in parallel.



- The black or common socket, labelled 'COM', is connected to the part of the circuit that is closer to the black or negative terminal of the power supply.
- The red socket, labelled 'VΩmA', is used for measuring voltages and is connected to the part of the circuit closer to the red or positive terminal of the power supply.
- The other red socket, labelled '10A MAX' is for large currents only.
- The dial has a range of settings; when first connecting the multimeter, choose the setting with the largest value. If you want more accuracy in your measurement, turn the dial to a smaller setting.
- If the display shows only the digit '1', the voltage you are trying to measure exceeds the range of that setting and you need to go to a higher setting.

3.4 EXERCISE

To answer questions online and to receive **immediate feedback** and **sample responses** for every question go to your learnON title at www.jacplus.com.au.

1. What is the voltage supplied by a battery that gives 1.05 J of energy to 0.70 C of charge which passes through it?
2. Complete the following table by filling in the missing values.

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

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

3.5 Energy and power in an electric circuit

KEY CONCEPTS

- 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: $I = \frac{Q}{t}$, $V = \frac{E}{Q}$,

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

3.5.1 Energy transformed by a circuit

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

$$E = QV$$

since $V = \frac{E}{Q}$, where V is the potential difference across the load.

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

$$Q = It$$

$$E = VIt$$

Where:

E is the energy transferred, in joules

V is the potential difference, in volts

I is the current, in amperes

t is the time, in seconds.

SAMPLE PROBLEM 6

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

 Teacher-led video: SP6 (tlvd-0015)

THINK

1. Recall the formula that calculates the amount of energy produced.
2. Transpose the formula to make the potential difference, V , the subject.
3. Substitute the known values into the formula and solve.
4. State the solution.

WRITE

$$E = VIt$$

$$V = \frac{E}{It}$$

$$E = 3.6 \times 10^4 \text{ J}, I = 5.0 \text{ A}, t = 30 \text{ s}$$

$$\begin{aligned} V &= \frac{3.6 \times 10^4 \text{ J}}{5.0 \text{ A} \times 30 \text{ s}} \\ &= \frac{36\,000}{150} \\ &= 240 \text{ V} \end{aligned}$$

The potential difference is 240 V.

PRACTICE PROBLEM 6

What is the potential difference across a light globe if 1.44×10^3 J of heat is produced when a current of 2.0 A flows for 1 minute?

3.5.2 Power delivered by a circuit

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

Power is the rate of doing work, or the rate at which energy is transformed from one form to another. Power is equal to the amount of energy transformed per second, or the amount of energy transformed divided by the time it took to do it.

Power can be expressed as:

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

Where:

P is the power delivered, in watts (W)

E is the amount of energy transformed, in joules

t is the time interval, in seconds.

1 watt = 1 joule per second = 1 J s^{-1}

By substituting the formula for energy, $E = VIt$, into the formula for power, $P = \frac{E}{t}$, we find that:

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

$$\Rightarrow P = VI$$

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

In real circuits, large power measurements are common. It is sometimes useful to use the unit kilowatt, where 1 kilowatt = 1×10^3 watts.

When converting from watts to kilowatts, divide by 1000.

When converting from kilowatts to watts, multiply by 1000.

SAMPLE PROBLEM 7

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

 **Teacher-led video:** SP7 (tlvd-0016)

THINK

1. Use the formula for power, $P = VI$.
2. Substitute the known values into the formula and solve for P .
3. Remembering that 1 kW = 1000 watts, convert to kW by dividing the number of watts by 1000.
4. State the solution.

WRITE

$$\begin{aligned}P &= VI \\V &= 240 \text{ V}, I = 5.0 \text{ A} \\P &= VI \\P &= 240 \text{ V} \times 5.0 \text{ A} \\&= 1200 \text{ W} \\P &= 1.2 \text{ kW}\end{aligned}$$

The power rating is 1.2 kW.

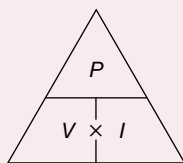
PRACTICE PROBLEM 7

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

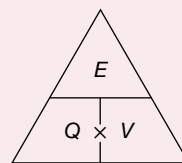
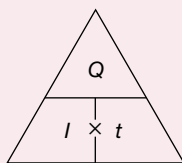
Transposing formulae

You can use the following triangles to assist transposing formulae $P = VI$, $Q = It$ and $E = QV$.

Power formula triangle



Variants of the power formula triangle



For example, if you wish to transpose the formula $P = VI$ to make I the subject, cover the pronumeral you want to be the subject, in this case I . What is visible in the triangle shows what that pronumeral equals. In this example:

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

This method can also be used for any formula of the form $x = yz$.

SAMPLE PROBLEM 8

How much energy is supplied by a mobile phone battery rated 3.7 V and 1200 mAh?

Note: 'mAh' stands for milliamp hours, which means that the battery would last for one hour supplying a current of 1200 mA or two hours at 600 mA.

 **Teacher-led video:** SP8 (tlvd-0017)

THINK

1. Recall the formula, $E = VIt$, and state the known values.
2. Convert the current from mA to amperes by dividing by 1000. Convert the time to seconds.
3. Substitute the known values and solve for E .
4. Convert the number of joules to kJ by dividing by 1000.
5. State the solution.

WRITE

$$\begin{aligned} E &= VIt \\ V &= 3.7 \text{ V}, I = 1200 \text{ mA}, t = 1 \text{ hour} \\ I &= 1200 \text{ mA} = \frac{1200}{1000} \text{ A} = 1.2 \text{ A} \\ t &= 60 \times 60 = 3600 \text{ s} \\ E &= 3.7 \text{ V} \times 1.2 \text{ A} \times 3600 \text{ s} \\ &= 16\,000 \text{ J} \\ E &= 16 \text{ kJ} \end{aligned}$$

There are 16 kJ of energy supplied.

PRACTICE PROBLEM 8

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

ELECTRON VOLT

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

 **Digital document** Investigation 3.2 Energy transferred by an electric current (doc-31862)

 **Teacher-led video** Investigation 3.2 Energy transferred by an electric current (tlvd-0807)

3.5.3 Providing energy for the circuit

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

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

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

$$E = \mathcal{E}Q$$

This can be rewritten as:

$$E = \mathcal{E}It$$

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

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

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

$$\Rightarrow P = \mathcal{E}I$$

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

SAMPLE PROBLEM 9

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

 **Teacher-led video:** SP9 (tlvd-0018)

THINK

1. Recall the formula, $P = VI$, and state the known values.
2. As the energy supplied to the circuit equals the emf of the battery, substitute the known values for V and I into the formula $P = VI$ and solve.
3. State the solution.

WRITE

$$P = VI$$

$$V = 12 \text{ V}, I = 2.5 \text{ A}$$

$$P = VI$$

$$= 12 \times 2.5$$

$$= 30 \text{ W}$$

The battery is supplying 30 W.

PRACTICE PROBLEM 9

At what rate is energy being supplied to a 3.0 V light when it is drawing a current of 4.0 A?

3.5 EXERCISE

To answer questions online and to receive **immediate feedback** and **sample responses** for every question go to your learnON title at www.jacplus.com.au.

- Calculate the current drawn by:
 - a 60 W light globe connected to a 240 V source
 - a 40 W globe with a voltage drop of 12 V across it
 - a 6.0 V, 6.3 W globe when operating normally
 - a 1200 W, 240 V toaster when operating normally.
- The element of a heater has a voltage drop of 240 V across it.
 - In terms of energy what does this mean?
 - How much energy is transformed into thermal energy in the element if 25 C of charge flow through it?
- A rear window demister circuit draws 2.0 A of current from a 12 V battery for 30 minutes.
 - How much energy is transformed by the rear window?
 - What is the power rating of the car demister?
- How long will it take a 600 W microwave oven to transform 5.4×10^4 J of energy?
- What is the power rating of an electric radiator if it draws a current of 10 A when connected to a 240 V AC household circuit?
- An electric jug is connected to a 240 V supply and draws a current of 3.3 A. How long would it take to transfer 3.2×10^4 J of energy to its contents?
- What is the emf of a battery that provides 9.0 J of energy to 6.0 C of charge?

studyon

To answer practice exam questions online and to receive immediate feedback and sample responses for every question go to your learnON title at www.jacplus.com.au.

studyON: Practice exam questions 

Fully worked solutions and sample responses are available in your digital formats.

3.6 Resistance

KEY CONCEPT

- Model resistance in series and parallel circuits using
 - current versus potential difference (I - V) graphs
 - resistance as the potential difference to current ratio, including $R = \text{constant}$ for ohmic devices.

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

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

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

The SI unit of resistance is the ohm (symbol Ω). One ohm is the resistance of a conductor in which a current of 1 ampere results from the application of a constant voltage drop of 1 volt across its ends.

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

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

Resistance is a material property and it is temperature dependent. In general, the resistance of a metal conductor increases with temperature. Usually, the increases will not be significant over small temperature ranges and most problems in this text ignore any temperature and resistance changes that might occur.

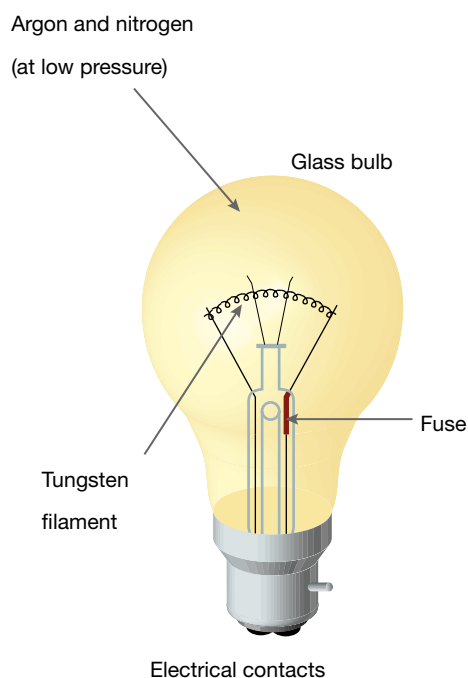
One example of the effect of a change in temperature on resistance can be seen in the tungsten filament of an ordinary light globe.

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

FIGURE 3.22 Georg Simon Ohm



FIGURE 3.23 A 240-volt, 60-watt globe



THE LIE DETECTOR

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

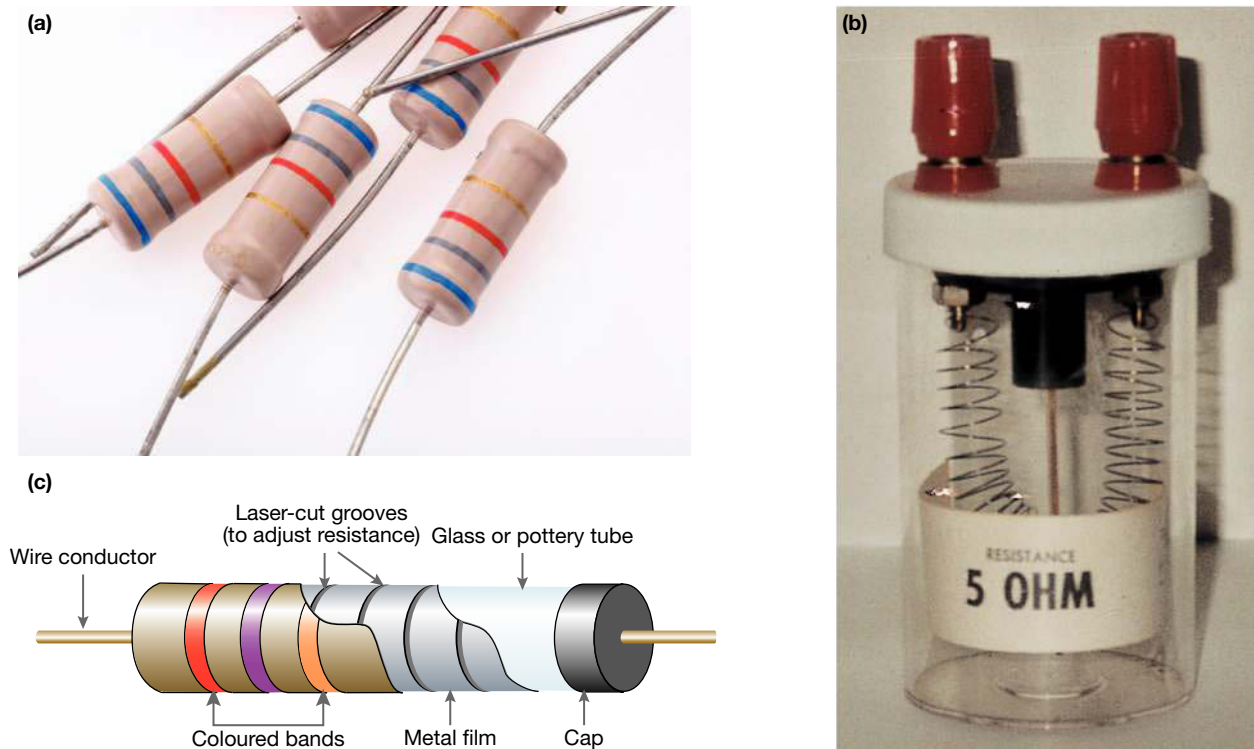
on Resources

-  **Digital documents** Investigation 3.3 The current-versus-voltage characteristics of a light globe (doc-31863)
Investigation 3.4 Dependence of resistance on length of resistance wire (doc-31864)

3.6.1 Resistors

In many electrical devices, **resistors** are used to control the current flowing through, and the voltage drop across, parts of the circuits. Resistors have constant resistances ranging from less than 1 ohm to millions of ohms. There are three main types of resistors. 'Composition' resistors are usually made of the semiconductor carbon. Wire-wound resistors consist of a coil of fine wire made of a resistance alloy such as nichrome. The third type is the metal film resistor, which consists of a glass or pottery tube coated with a thin film of metal. A laser trims the resistor to its correct value.

FIGURE 3.24 (a) Carbon or 'composition' resistors (b) Wire-wound resistor (c) Metal film resistor



Some large resistors have their resistance printed on them. Others have a colour code to indicate their resistance, as shown in figure 3.25 and table 3.1. The resistor has four coloured bands on it. The first two bands represent the first two digits in the value of resistance. The third band represents the power of ten by which the two digits are multiplied. The fourth band is the manufacturing tolerance.

FIGURE 3.25 A resistor, showing the coloured bands

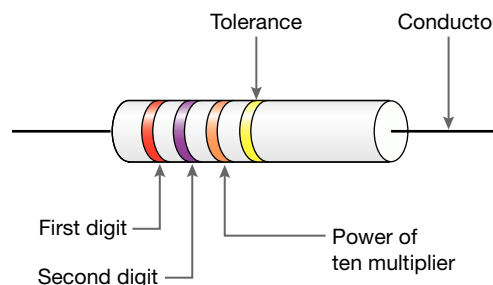


TABLE 3.1 The resistor colour code

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

SAMPLE PROBLEM 10

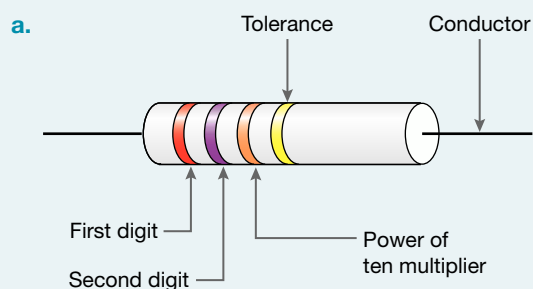
What is the resistance of the following resistors if their coloured bands are:

- red, violet, orange and gold
- brown, black, red and silver?

 **Teacher-led video:** SP10 (tlvd-0019)

THINK

- Remember when holding a resistor to read its value, keep the gold or silver band on the right and read the colours from the left.
- Using table 3.1, establish the first two digits.
- Using table 3.1, establish the multiplier.
- Using table 3.1, establish the tolerance.
- State the solution.

WRITE

Red = 2

Violet = 7

Hence, the first two digits are 27.

The third band is orange, which means multiply the first two digits by 10^3 .

The resistance is: $27 \times 10^3 = 27\,000\,\Omega = 27\,\text{k}\Omega$.

The fourth band is gold, which means there is a tolerance of 5%.

$5\% \times 27\,000\,\Omega = 1350\,\Omega$

The true value is $27 \times 10^3\,\text{k}\Omega \pm 1350\,\Omega$.

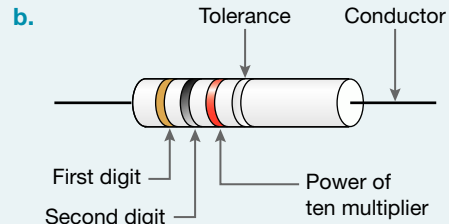
b. 1. Remember when holding a resistor to read its value, keep the gold or silver band on the right and read the colours from the left.

2. Using table 3.1, establish the first two digits.

3. Using table 3.1, establish the multiplier.

4. Using table 3.1, establish the tolerance.

5. State the solution.



Brown = 1

Black = 0

Hence, the first two digits are 10.

The third band is red, which means multiply the first two digits by 10^2 . The resistance is: $10 \times 10^2 = 1000 \Omega$
 $= 1 \text{ k}\Omega$

The fourth band is silver, which means there is a tolerance of 10%.

$10\% \times 1000 \Omega = 100 \Omega$

The true value is $1.0 \times 10^3 \Omega \pm 100 \Omega$.

PRACTICE PROBLEM 10

What are the resistances and tolerances of resistors with the colour codes:

a. orange, white, black, gold

b. green, blue, orange, silver

c. violet, green, yellow, gold?

Resources



eLesson

Resistance (eles-2516)



Interactivity

Picking the right resistor (int-6391)

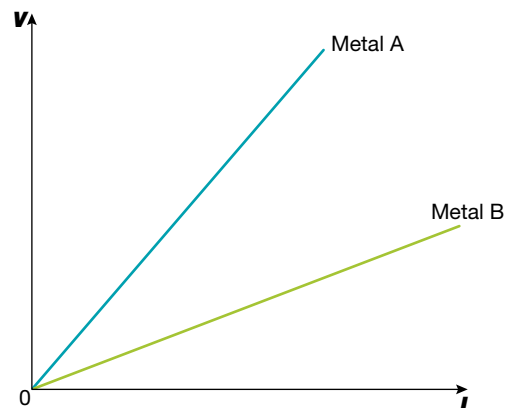
3.6.2 Ohm's Law

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

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

$$I \propto V$$

FIGURE 3.26 Graphs of voltage versus current for two different metal wires

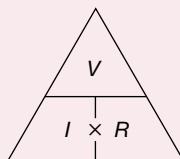


The equation of the line shown in figure 3.26 is known as Ohm's Law and can be written:

$$V = IR$$

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

You can use the triangle method for Ohm's Law.



Convert the quantity/pronumeral you want to be the subject, for example, R . What is visible in the triangle shows what the pronumeral equals.

The resistance, R , can also be expressed as:

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

SAMPLE PROBLEM 11

A transistor radio uses a 6.0 V battery and draws a current of 300 mA. What is the resistance of the radio?

 Teacher-led video: SP11 (tlvd-0020)

THINK

1. From Ohm's Law the resistance, R , can be found.
2. State the known values and convert the current into amperes by dividing by 1000.
3. Substitute the values for V and I and solve to find R .
4. State the solution.

WRITE

$$V = IR$$

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

$$V = 6.0 \text{ V}, I = \frac{300 \text{ mA}}{1000} = 0.300 \text{ A}$$

$$R = \frac{6.0 \text{ V}}{0.300 \text{ A}} \\ = 20 \Omega$$

The resistance of the radio is 20 Ω .

PRACTICE PROBLEM 11

A 240 V kitchen appliance draws a current of 6.0 A. What is its resistance?

 Resources

 Weblink Ohm's Law app

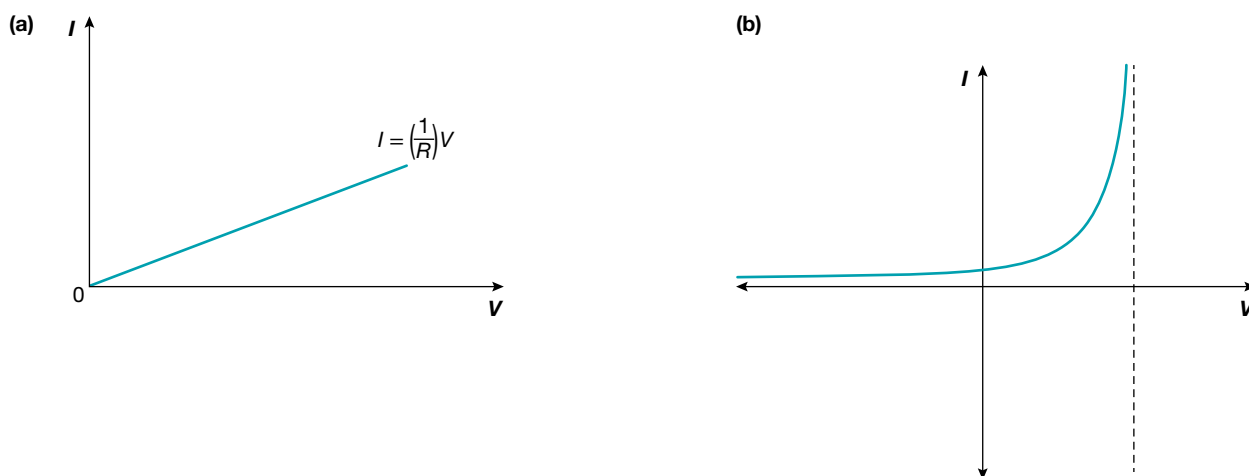
3.6.3 Ohmic and non-ohmic devices

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

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

The graph in figure 3.26 has voltage on the y-axis and current on the x-axis. The graph is drawn this way so that the gradient of lines for the metals A and B gave the resistance of each. However, accepted convention graphs the independent variable on the x-axis and the dependent variable on the y-axis. So in the graph in figure 3.27a the gradient equals $\frac{1}{R}$.

FIGURE 3.27 The current-versus-voltage graphs for (a) an ohmic resistor and (b) a diode, which is a non-ohmic device



Resources



Digital document Investigation 3.5 Ohmic and non-ohmic devices (doc-31865)



Teacher-led video Investigation 3.5 Ohmic and non-ohmic devices (tlvd-0810)

Non-ohmic devices

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

A **diode** is formed by joining two differently doped materials together. A diode allows current to flow through it in only one direction. This effect can be seen in the current–voltage graph for a diode in figure 3.29b, where a small positive voltage produces a current, while a large negative or reverse voltage produces negligible current.

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

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

FIGURE 3.28
Circuit symbol
for a diode

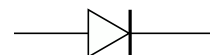
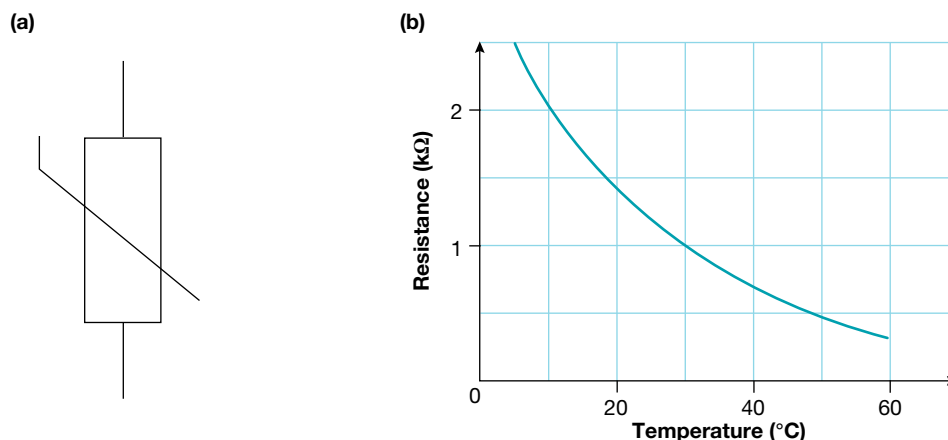
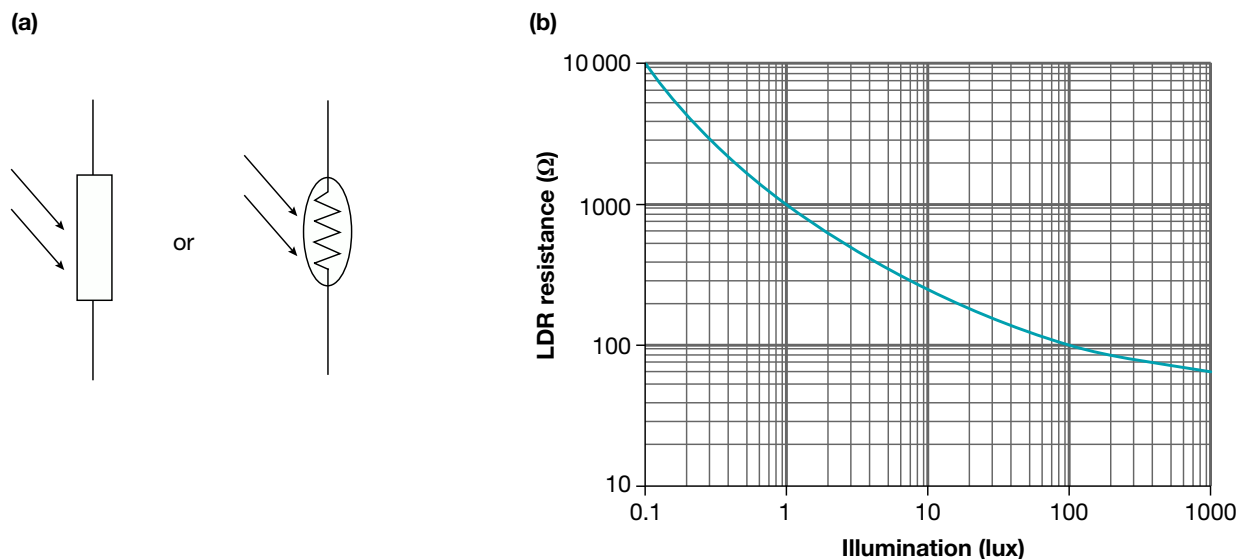


FIGURE 3.29 (a) Circuit symbol for a thermistor (b) Resistance-versus-temperature graph for a thermistor



Light-dependent resistors (LDRs) are like thermistors, except they respond to light. The resistance of an LDR decreases as the intensity of light shining on it increases. The axes in the graph for an LDR in figure 3.30 have different scales to the other graphs. As you move from the origin, each number is 10 times the previous one. This enables more data to fit in a small space.

FIGURE 3.30 (a) Circuit symbols for an LDR (b) Graph of resistance-versus-light intensity for an LDR, on a logarithmic scale



Note: A logarithmic scale is a non-linear scale and is commonly used as an effective way of displaying data that cover a large range of values on one graph. By plotting the log of resistance and the log of illumination, we are able to graphically plot two parameters.

3.6.4 Heating effects of currents

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

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

NICHROME

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

3.6.5 Power and resistance

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

$$P = VI$$

Where:

P is the power

I is the current

V is the voltage drop.

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

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

Substituting $V = IR$ into the formula $P = VI$:

$$\begin{aligned} P &= VI \\ &= (IR)I \end{aligned}$$

Thus:

$$P = I^2 R \quad [1]$$

Substituting $I = \frac{V}{R}$ into the formula $P = VI$:

$$\begin{aligned} P &= VI \\ P &= V \left(\frac{V}{R} \right) \end{aligned}$$

Thus:

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

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

$$P = VI$$

$$P = I^2 R$$

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

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

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

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

SAMPLE PROBLEM 12

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

 Teacher-led video: SP12 (tlvd-0021)

THINK

1. Recall that power is the rate of energy use and use the formula containing the variables P , V and R .
2. Substitute the known values into the formula and solve for P .

3. State the solution.

WRITE

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

$$V = 6.0\ \text{V}, R = 18\ \Omega$$

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

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

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

The radio transforms energy at $2.0\ \text{W}$.

PRACTICE PROBLEM 12

What is the power rating of an electric jug if it has a resistance of $48\ \Omega$ when hot and is connected to a $240\ \text{V}$ supply?

SAMPLE PROBLEM 13

A pop-up toaster is labelled ' $240\ \text{V}$, $800\ \text{W}$ '.

- a. What is the normal operating current of the toaster?
- b. What is the total resistance of the toaster while it is operating?

 Teacher-led video: SP13 (tlvd-0022)

THINK

1. The three variables P , V and I are given in the formula for power.
 2. Transpose the formula to make I the subject.
 3. Substitute the known values into the formula and solve for I .
 4. State the solution.
1. The three variables P , V and R are given in the formula for power.
 2. Transpose the formula to make R the subject.

WRITE

$$\text{a. } P = VI$$

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

$$V = 240\ \text{V}, P = 800\ \text{W}$$

$$I = \frac{800\ \text{W}}{240\ \text{V}}$$
$$= 3.33\ \text{A}$$

The normal operating current $3.33\ \text{A}$.

$$\text{b. } P = \frac{V^2}{R}$$

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

3. Substitute the known values into the formula and solve for R .

$$\begin{aligned} V &= 240 \text{ V}, P = 800 \text{ W} \\ R &= \frac{(240 \text{ V})^2}{800 \text{ W}} \\ &= 72 \Omega \end{aligned}$$

4. State the solution.

The resistance is 72Ω .

PRACTICE PROBLEM 13

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

- What is the normal operating current of the microwave oven?
- What is the total resistance of the microwave oven when it is operating?

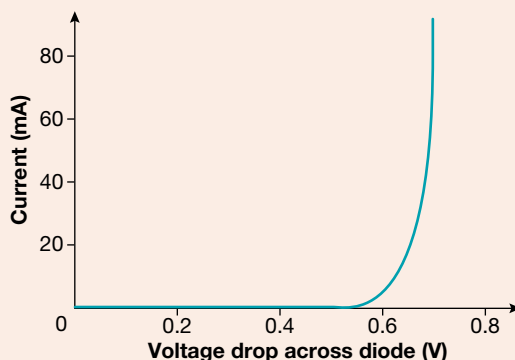
3.6 EXERCISE

To answer questions online and to receive **immediate feedback** and **sample responses** for every question go to your learnON title at www.jacplus.com.au.

- How much energy is provided by a 6 V battery if a current of 3 A passes through it for 1 minute?
- Complete the following table by filling in the missing values.

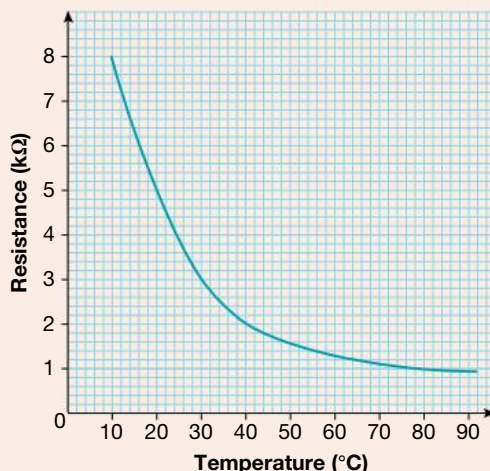
Potential difference	Current	Resistance
	8.0 A	4.0 Ω
	22 mA	2.2 k Ω
12 V		6.0 Ω
240 V		$8.0 \times 10^4 \Omega$
9.0 V	6.0 A	
1.5 V	45 mA	

- What are the resistances and tolerances of resistors with the colour codes:
 - blue, brown, orange, gold
 - yellow, white, green, silver
 - brown, red, red, gold?
- The following graph shows the current-versus-voltage characteristic for an electronic device.

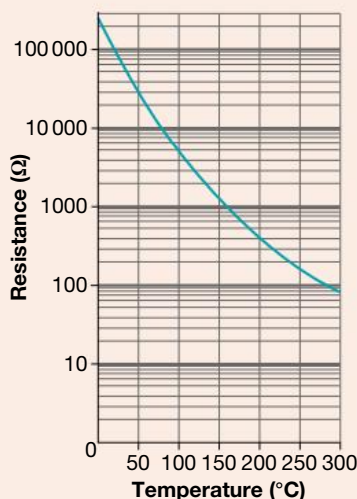


- Is this device ohmic or non-ohmic? Justify your answer.
- What is the current through the device when the voltage drop across it is 0.5 V?
- What is the resistance of the device when the voltage drop across it is 0.5 V?
- Estimate the voltage drop across the device and its resistance, when it draws a current of 20 mA.

5. At what rate is thermal energy being transferred to a wire if it has a resistance of $5\ \Omega$ and carries a current of $0.30\ \text{A}$?
6. Calculate the resistance of the following globes if their ratings are:
 (a) $240\ \text{V}$, $60\ \text{W}$ (b) $6.0\ \text{V}$, $6.3\ \text{W}$ (c) $12\ \text{V}$, $40\ \text{W}$.
7. What is the power rating of an electric jug if it has a resistance of $48\ \Omega$ when hot and is connected to a $240\ \text{V}$ supply?
8. A thermistor has the characteristic curve shown in the following graph.



- (a) What is the resistance of the thermistor at the following temperatures?
 i. $20\ ^\circ\text{C}$ ii. $80\ ^\circ\text{C}$
- (b) What is the temperature when the thermistor has the following resistances?
 i. $4\ \text{k}\Omega$ ii. $1.5\ \text{k}\Omega$
9. A temperature sensing system in an oven uses a thermistor with the characteristics shown in the following graph, on a logarithmic scale.



- (a) What is the resistance of the thermistor when the temperature in the oven is $100\ ^\circ\text{C}$?
- (b) What is the temperature in the oven when the resistance of the thermistor is $400\ \Omega$?

studyon

To answer practice exam questions online and to receive immediate feedback and sample responses for every question go to your learnON title at www.jacplus.com.au.

studyON: Practice exam questions 

Fully worked solutions and sample responses are available in your digital formats.

3.7 Review

3.7.1 Summary

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

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

- Potential difference is measured using a voltmeter.
- The electromotive force (emf) of a power supply is a measure of the amount of energy supplied to the circuit for each coulomb of charge passing through that supply.
- Resistance is the opposition provided by a substance to the flow of current through it.
- Ohm's Law states the current flowing in a metal wire varies directly with the voltage drop across the conductor and inversely with the resistance of the conductor. The graph of voltage drop versus current at a constant temperature is a straight line for an ohmic device.
- The amount of energy transformed in a device during a given time interval can be calculated using the equation $E = VIt$.
- Power is the rate at which work is done, or at which energy is transformed from one form into another.
- The power delivered to a device in an electric circuit can be calculated using the equation:

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

- Non-ohmic devices such as LDRs, LEDs, diodes and thermistors do not obey Ohm's Law; their resistance is not constant.

Resources

study

To access key concept summaries and practice exam questions download and print the **studyON: Revision and practice exam question booklet** (sonr-0028).

3.7.2 Key terms

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

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

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

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

A **conductor** is a material that contains charge carriers; that is, charged particles can move and travel freely through the material.

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

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

A **diode** is a device that allows current to pass through it in one direction only.

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

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

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

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

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

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

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

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

An **ion** is a charged particle.

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

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

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

A **model** is a representation of ideas, phenomena or scientific processes; can be a physical model, mathematical model or conceptual model.

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

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

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

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

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

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

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

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

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

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



Resources



Digital document Key terms glossary (doc-32178)

3.7.3 Practical work and investigations

Investigation 3.1

The Van de Graaff generator

Aim: To investigate electrostatic charge

Digital document: [doc-31918](#)

Investigation 3.2

Energy transferred by an electric current

Aim: To calculate how much energy is transformed from electrical potential energy into the internal energy of a load

Digital document: [doc-31862](#)

Teacher-led video [tlvd-0807](#)



Investigation 3.3

The current-versus-voltage characteristics of a light globe

Aim: To design and construct a circuit that will enable you to find the current through the globe for a suitable range of voltages

Digital document: [doc-31863](#)

Investigation 3.4

Dependence of resistance on length of resistance wire

Aim: To investigate how the resistance of a resistance wire varies with length

Digital document: [doc-31864](#)

Investigation 3.5

Ohmic and non-ohmic devices

Aim: To explore the resistance properties of a resistor and a light globe

Digital document: [doc-31865](#)

Teacher-led video [tlvd-0810](#)



Resources



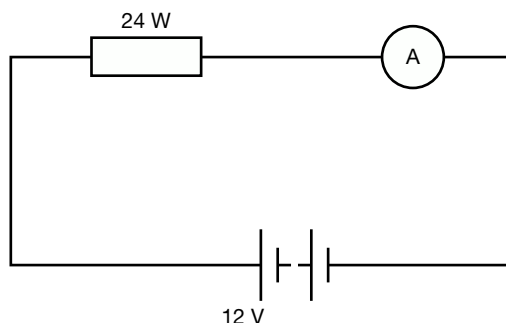
Digital document Practical investigation logbook (doc-32179)

3.7 Exercises

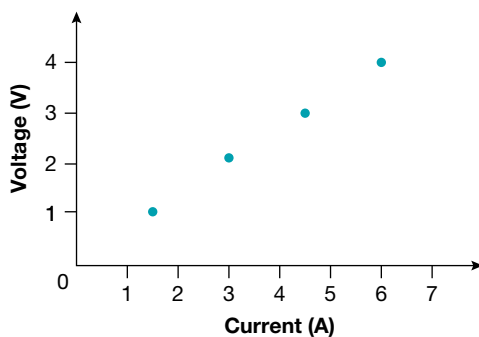
To answer questions online and to receive **immediate feedback** and **sample responses** for every question go to your learnON title at www.jacplus.com.au.

3.7 Exercise 1: Multiple choice questions

- Which best describes the transfer of electrical energy in a circuit?
 - Electric charge is moved in the direction of the current.
 - Free electrons pass all the way through the circuit to the load.
 - Free electrons dissipate their energy.
 - The battery pushes positive charges through the circuit.
- Electron charge was removed from an object. Which of the following could represent the amount of charge removed?
 - $1.5 \times 10^{-19} \text{ C}$
 - $3.0 \times 10^{-19} \text{ C}$
 - $4.8 \times 10^{-19} \text{ C}$
 - $5.4 \times 10^{-19} \text{ C}$
- For 25 seconds a battery supplies a constant current of 5.0 A to a circuit. What best represents the amount of charge leaving the battery?
 - 0 C
 - 0.20 C
 - 5.0 C
 - 125 C
- In the circuit shown which best describes the current passing through the ammeter?



- Zero, the current is used up in the 24 W load.
 - The current is 2 A.
 - Zero, the switch is open.
 - The current is non-constant.
5. The current and voltage for an object in a circuit was collected and plotted on a graph.



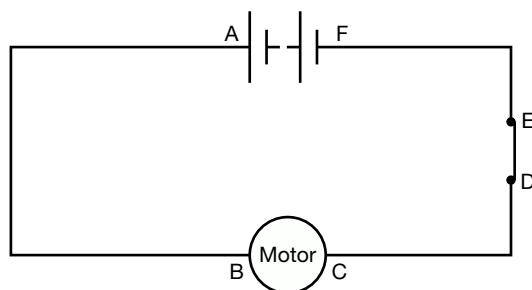
What is the resistance of this object?

- A. $0.60\ \Omega$
 - B. $0.67\ \Omega$
 - C. $1.50\ \Omega$
 - D. $1.70\ \Omega$
6. Each electron is given 1.44×10^{-18} joules of energy by a battery. What is the electromotive force provided by the battery?
- A. 1.5 V
 - B. 3.0 V
 - C. 9.0 V
 - D. 11 V
7. A 240 V rice cooker draws a current of 1.25 A. How much energy is provided to the cooker in 1 minute?
- A. 19.2 J
 - B. 300 J
 - C. 3.6 kJ
 - D. 18 kJ
8. At what rate is a 7.2 V battery supplying energy to a tablet device when it is drawing a current of 1200 mA?
- A. 6.0 J
 - B. 6.0 W
 - C. 8.6 J
 - D. 8.6 W
9. When a 240 V microwave rated at 1200 W is operating what is the current?
- A. 5.0 mA
 - B. 6.0 mA
 - C. 5.0 A
 - D. 48.0 A
10. For the microwave described in question 9 what is the total resistance when operating?
- A. $5\ \Omega$
 - B. $6\ \Omega$
 - C. $20\ \Omega$
 - D. $48\ \Omega$

3.7 Exercise 2: Short answer questions

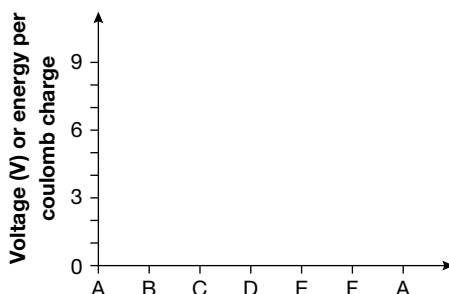
1. During a storm a lightning bolt discharges 3 million kJ of energy to Earth in 0.75 ms. The discharge involves the movement of 15 C of charge. What is the potential difference between the lightning source and Earth?
2. Consider a 3.0 V battery.
 - a. How much energy does it supply to:
 - i. one electron
 - ii. one coulomb of charge?
 - b. The battery is used in a mobile telephone. A 1-minute conversation uses the energy transferred by 0.04 C of charge. At what rate is energy being transferred to the telephone?
3. An electric kettle operating off a 240 V power supply uses 2.7 kW when boiling water.
 - a. What is the current in the kettle?
 - b. When the kettle is on for 2.5 minutes how much energy does it use?
4.
 - a. What is the voltage drop across a $44\ \Omega$ resistor carrying a current of 2.5 A?
 - b. What would be the effect of connecting the same resistor to a larger power supply?

5. A children's toy comprises a 9 V battery, a switch and an electric motor in a simple circuit as shown in the following figure. The motor is labelled '9 V, 25 mA'.

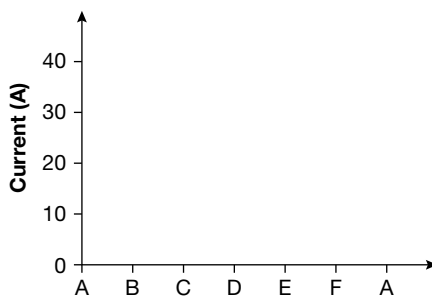


When the switch is closed:

- What is the maximum rate at which the battery can supply energy to the motor?
- By copying the axes shown, sketch a graph showing the energy held by a coulomb of charge as it moves around the circuit from A to F, then returning to A.

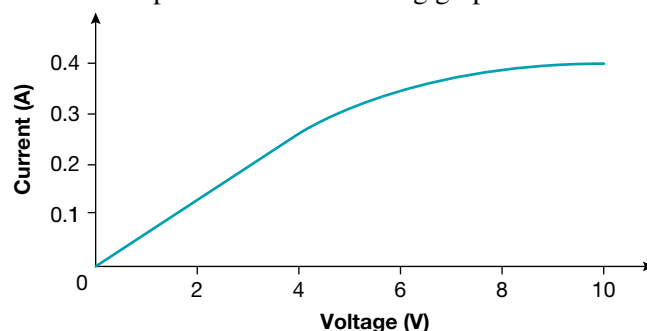


- By copying the axes shown, complete the graph for current around the circuit.

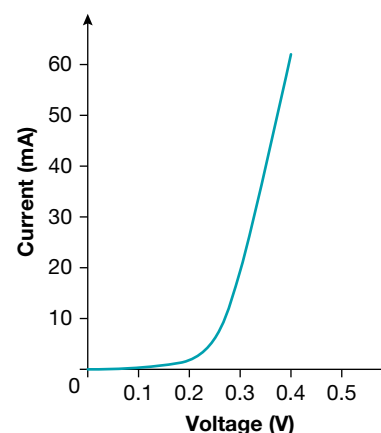


- What is the resistance of the motor when operating at its maximum capacity?
6. A handheld fan is powered by two 1.5 V batteries. When tested at room temperature 15 C of charge flowed through it every minute.
- What was the current in the device?
 - What is the resistance of the device?
 - At what rate is the device using energy?
7. A circuit comprises a 1.2 kW heating element, a switch and a voltage source.
- Draw a circuit diagram demonstrating how to measure both the voltage across the heater and the current flowing through it?
 - If the voltage supplied is 240 V, what is the current passing through the heater?

8. The voltage supplied to a tungsten globe is varied. The current and the potential difference across the lamp are measured and the results plotted in the following graph.



- a. Calculate the resistance of the globe when the current is 0.2 A.
 - b. Would you describe the globe as ohmic or non-ohmic? Justify your answer.
9. The following graph shows the current versus voltage relationship for a non-ohmic device.
- a. What is a non-ohmic device?
 - b. What is the current through the device when the voltage drop across it is 0.3 V?
 - c. What is the resistance of this device when the voltage drop across it is 0.3 V?
10. a. What is the resistance of an 800 W toaster when a current of 3.3 A is flowing?
- b. If it takes 40 seconds to brown the toast, how much energy is used?



3.7 Exercise 3: Exam practice questions

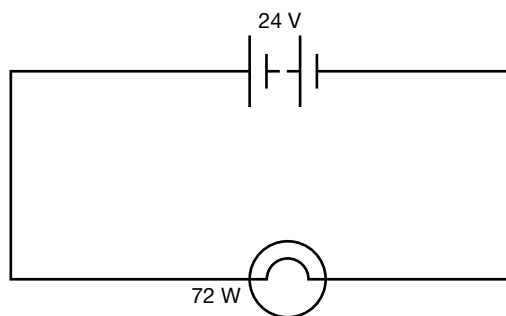
Question 1 (2 marks)

To model the energy supply, current and load in an electrical circuit a teacher and students stand in a circle loosely holding a loop of rope. The teacher models the energy supply by pulling the rope around while the students act as conductors by allowing the rope to readily move through their hands. One student, Luke, is asked to represent a globe in the circuit by making it more difficult for the rope to slide through his hands.

An observer suggests that in an electric circuit the electrons must make their way to the globe before it lights up and that Luke must wait until the rope has travelled all the way from the teacher before he feels the pull on the rope. In terms of both the model and how electricity behaves in a circuit explain whether you agree or disagree with the observer.

Question 2 (6 marks)

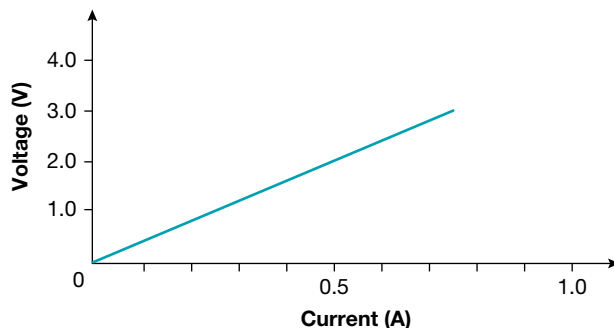
Use the following circuit diagram to answer the questions.



- a. Draw an arrow to show the direction of the electron current. **1 mark**
- b. Show where you would connect an ammeter to measure the current flowing through the globe. **1 mark**
- c. Calculate the current flowing in the circuit. **1 mark**
- d. When the switch is closed what is the voltage drop across it? **1 mark**
- e. Show where you would connect a voltmeter to confirm your prediction of the voltage drop across the switch. **1 mark**
- f. Explain what happens when the switch is opened. **1 mark**

Question 3 (3 marks)

An unknown electrical component is labelled '3.0 V, 2.4 W DC ONLY'.



- a. Describe what DC ONLY means. **1 mark**
- b. What is the maximum current that the component can safely tolerate? **1 mark**
- c. A student places another component in a simple circuit to measure its voltage current characteristics, recording the results as shown in the following graph. Calculate the resistance when the current is 600 mA. **1 mark**

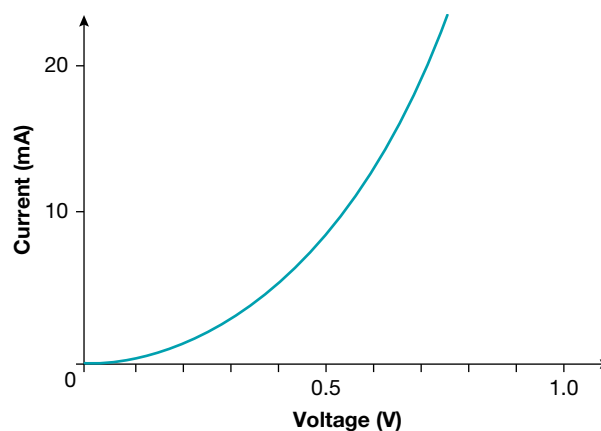
Question 4 (2 marks)

An electric drill has a rechargeable 18 V battery that can store up to 6 MJ. When fully discharged it takes the battery 8 hours to fully recharge.

- a. Calculate the total charge needed to fully charge the battery. **1 mark**
- b. Calculate the average current drawn when charging the battery. **1 mark**

Question 5 (4 marks)

The following graph shows the current-versus-voltage characteristic for an electronic device.



- a. Is this device ohmic or non-ohmic? Justify your answer. **1 mark**
- b. What is the current through the device when the voltage drop across it is 0.5 V? **1 mark**
- c. What is the resistance of the device when the voltage drop across it is 0.5 V? **1 mark**
- d. Estimate the rate at which energy is being used when the voltage drop across it is 0.5 V. **1 mark**

3.7 Exercise 4: studyON topic test online only

Fully worked solutions and sample responses are available in your digital formats.

teachon

Test maker

Create unique tests and exams from our extensive range of questions, including practice exam questions.
Access the assignments section in learnON to begin creating and assigning assessments to students.

4 Circuit analysis

4.1 Overview

Numerous **videos** and **interactivities** are available just where you need them, at the point of learning, in your digital formats, learnON and eBookPLUS at www.jacplus.com.au.

4.1.1 Introduction

In topic 3, an electric circuit was described as a number of electrical conductors connected to form a conducting path. A circuit can contain one or more sources of emf (**electromotive force**) to provide energy to the circuit.

If the conductors form a continuous closed path through which a current can circulate, the circuit is said to be a closed circuit, as shown in figure 4.1. If there is a break in the path so that charge cannot flow, for example at a switch, the circuit is said to be an open circuit.

In many simple electric circuits, electrical energy is used for heating one or more loads. The temperature increase in a **load** occurs because the **charge carriers** make repeated collisions with the atoms in the load. This increases the internal energy of the load and its temperature rises. The electrical energy transformed in the load originally came from some source of emf, for example a battery, laboratory power pack or power point in the home. Examples of this type of circuit include a torch (where the **conductor** in the filament gets so hot that it emits light), a toaster plugged into a power point and a car demister circuit. The current flowing in these circuits depends on the **resistance** of the loads. The torch globe, the heating element in the toaster and other loads make it difficult for a current to flow. In this topic you will look at what happens in different types of electric circuits and in the devices within these circuits.

FIGURE 4.1 Decorative lights that are connected in series, such as those on the Melbourne Star Observation Wheel, can contain shunts which allow the circuit to remain closed if the filament breaks.



4.1.2 What you will learn

KEY KNOWLEDGE

After completing this topic you will be able to:

- model resistance in series and parallel circuits using
 - resistance as the potential difference to current ratio, including $R = \text{constant}$ for ohmic devices
 - equivalent effective resistance in arrangements in
 - series: $R_T = R_1 + R_2 + \dots + R_n$
 - parallel: $\frac{1}{R_T} = \frac{1}{R_1} + \frac{1}{R_2} + \dots + \frac{1}{R_n}$
- calculate and analyse the effective resistance of circuits comprising parallel and series resistance and voltage dividers
- compare power transfers in series and parallel circuits.
- 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 transducers.

Source: VCE Physics Study Design (2016–2021) extracts © VCAA; reproduced by permission.

PRACTICAL WORK AND INVESTIGATIONS

Practical work is a central component of learning and assessment. Experiments and investigations, supported by a **Practical investigation logbook** and **Teacher-led videos**, are included in this topic to provide opportunities to undertake investigations and communicate findings.

on Resources

 **Digital documents** Key science skills — VCE Units 1–4 (doc-31856)

Key terms glossary (doc-32180)

Practical investigation logbook (doc-32181)

studyon

To access key concept summaries and practice exam questions download and print the **studyON: Revision and practice exam question booklet** (sonr-0029).

4.2 BACKGROUND KNOWLEDGE Electric circuit rules

BACKGROUND KNOWLEDGE

- The sum of the currents flowing into a junction is equal in magnitude to the sum of the currents flowing out of that junction: $I_{\text{in}} = I_{\text{out}}$
- In any closed loop of an electrical circuit, the sum of the voltage drops must equal the sum of the emfs in that loop.

4.2.1 Circuit diagrams

A circuit diagram shows schematically the devices used in constructing an electrical circuit. Table 4.1 shows the symbols commonly used in drawing circuits. Figure 4.2 is a diagram of a circuit comprising a battery, **switch** and **resistor**.

FIGURE 4.2 A circuit diagram

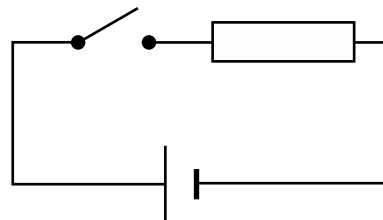


TABLE 4.1 Symbols used in circuit diagrams

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

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

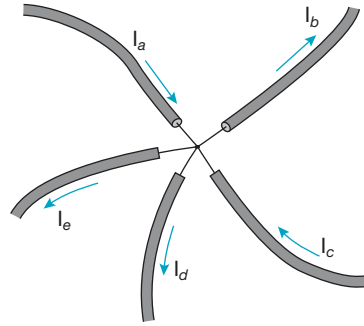
4.2.2 Circuit rules

Accounting for electrons

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

In figure 4.3, $I_a + I_c = I_b + I_d + I_e$.

FIGURE 4.3 Five wires soldered at a junction

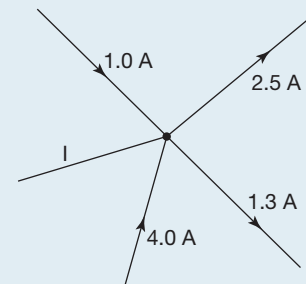


The sum of the currents flowing into a junction is equal in magnitude to the sum of the currents flowing out of that junction:

$$I_{\text{in}} = I_{\text{out}}$$

SAMPLE PROBLEM 1

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



 **Teacher-led video:** SP1 (tlvd-0023)

THINK

1. From the diagram, calculate the total currents flowing into the junction.
2. From the diagram, calculate the total currents flowing out of the junction.
3. Recall that $I_{\text{in}} = I_{\text{out}}$. The unknown values must be a flow out of the junction. Solve for the unknown current out of the junction.
4. State the solution.

WRITE

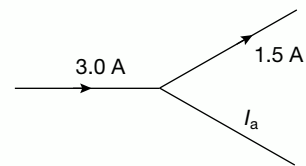
$$1.0 \text{ A} + 4.0 \text{ A} = 5.0 \text{ A}$$

$$2.5 \text{ A} + 1.3 \text{ A} = 3.8 \text{ A}$$

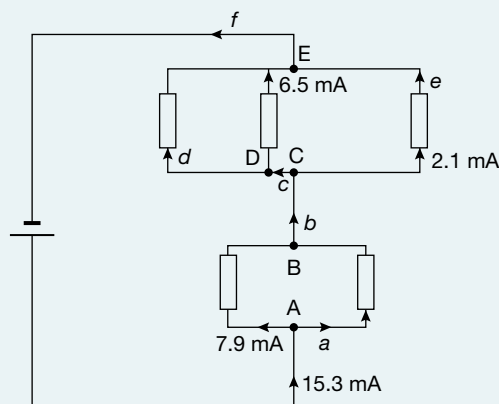
$$\begin{aligned} I_{\text{in}} &= I_{\text{out}} \\ 5.0 \text{ A} &= 3.8 \text{ A} + x \\ x &= 5.0 \text{ A} - 3.8 \text{ A} \\ &= 1.2 \text{ A} \end{aligned}$$

The unknown current flowing out of the junction is 1.2 A.

Find the unknown current at the junction in the following figure. State the direction of the current in each case.



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



THINK

1. Recall the formula $I_{\text{in}} = I_{\text{out}}$.
2. Determine the current at each junction.

WRITE

$$I_{\text{in}} = I_{\text{out}}$$

$$15.3 \text{ mA} = 7.9 \text{ mA} + a$$

$$q = 15.3 \text{ mA} - 7.9 \text{ mA}$$

$a = 7.4 \text{ mA}$

$$7.9 \text{ mA} + 7.4 \text{ mA} = b$$

$$b = 15.3 \text{ mA}$$

$$15.3 \text{ mA} = c + 2.1 \text{ mA}$$

$$c = 15.3 \text{ mA} - 2.1 \text{ mA}$$

$c = 13.2 \text{ mA}$

$$13.2 \text{ mA} = d + 6.5 \text{ mA}$$

$$d = 13.2 \text{ mA} - 6.5 \text{ mA}$$

$$d = 6.7 \text{ mA}$$

$$2.1 \text{ mA} = e$$

$$e = 2.1 \text{ mA}$$

$$d + 6.5 \text{ mA} + e = f$$

$$f = 6.7 \text{ mA} + 6.5 \text{ mA} + 2.1 \text{ mA}$$

$f = 15.3 \text{ mA}$

- 3. State the solution.**

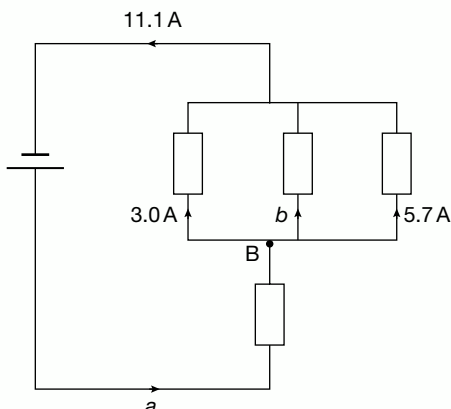
The values of the currents are:

$$a = 7.4 \text{ mA}, b = 15.3 \text{ mA}, c = 13.2 \text{ mA}.$$

$$d = 6.7 \text{ mA}, e = 2.1 \text{ mA}, f = 15.3 \text{ mA}.$$

PRACTICE PROBLEM 2

Find the values of currents a and b as marked in the following figure.



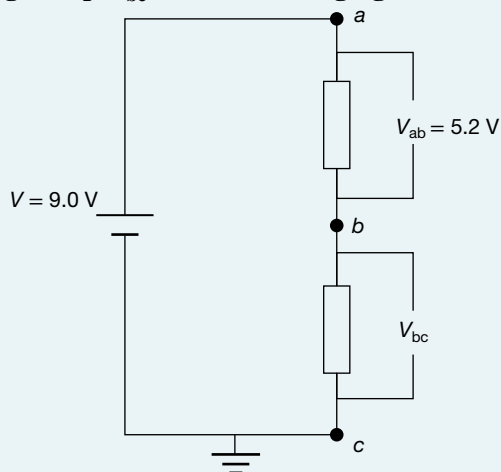
4.2.3 Conservation of electrical energy

Around a circuit electrical energy must be conserved.

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

SAMPLE PROBLEM 3

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



 **Teacher-led video:** SP3 (tlvd-0025)

THINK

1. This circuit is a closed loop and the sum of the voltage drops within it must equal the voltage supplied by the battery.

2. State the solution.

WRITE

V = the sum of the voltage drops

$$V = 9.0 \text{ V}$$

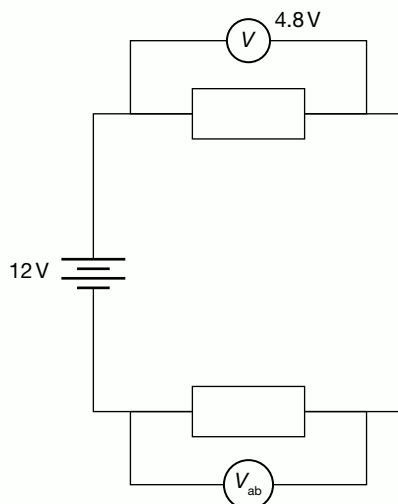
$$\begin{aligned} 9.0 \text{ V} &= V_{ab} + V_{bc} \\ &= 5.2 \text{ V} + V_{bc} \end{aligned}$$

$$V_{bc} = 3.8 \text{ V}$$

The unknown voltage drop is 3.8 V.

PRACTICE PROBLEM 3

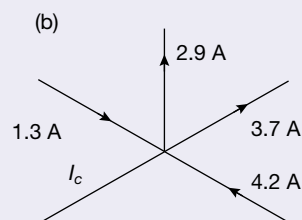
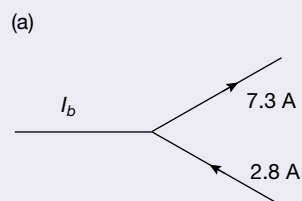
Calculate the unknown voltage drop V_{ab} in the following figure.



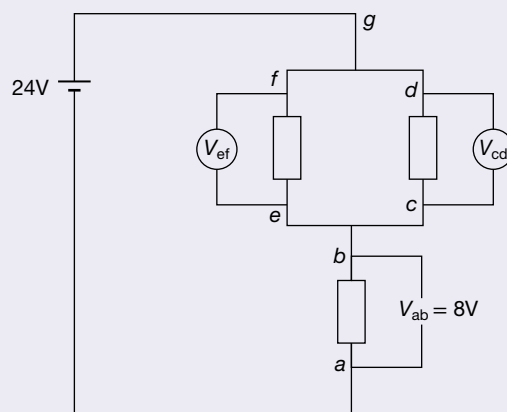
4.2 EXERCISE

To answer questions online and to receive **immediate feedback** and **sample responses** for every question go to your learnON title at www.jacplus.com.au.

1. Explain what is meant by the following terms, as they relate to electric circuits.
 - (a) Junction
 - (b) Current
 - (c) Voltage drop
 - (d) Conductor
2. Find the missing currents in the following figures. State the direction of the current in each case.



3. Calculate the voltages V_{cd} and V_{ef} in the following figure.



Fully worked solutions and sample responses are available in your digital formats.

4.3 Series and parallel circuits

KEY CONCEPTS

- Model resistance in series and parallel circuits using:
 - resistance as the potential difference to current ratio, including $R = \text{constant}$ for ohmic devices
 - equivalent effective resistance in arrangements in
 - series: $R_T = R_1 + R_2 + \dots + R_n$
 - parallel: $\frac{1}{R_T} = \frac{1}{R_1} + \frac{1}{R_2} + \dots + \frac{1}{R_n}$
- calculate and analyse the effective resistance of circuits comprising parallel and series resistance and voltage dividers.

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

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

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

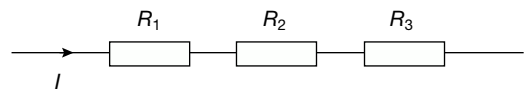
Many devices can be connected in series and parallel. These include resistors and cells.

4.3.1 Resistors in series

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

There is only one path for the current to flow through. Therefore, in figure 4.4, the current in R_1 equals the current in R_2 and in R_3 . I_1 refers to the current in R_1 ; I_2 to the current in R_2 , and so on. Similarly, V_1 is the voltage drop across R_1 ; V_2 is the voltage drop across R_2 , and so on.

FIGURE 4.4 Resistors connected in series



$$I = I_1 = I_2 = I_3$$

Since $V = IR$:

$$V_1 = IR_1$$

$$V_2 = IR_2$$

$$V_3 = IR_3$$

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

$$\begin{aligned} V_T &= V_1 + V_2 + V_3 \\ \Rightarrow V_T &= IR_1 + IR_2 + IR_3 \\ \Rightarrow V_T &= I(R_1 + R_2 + R_3) \end{aligned}$$

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

$$R_T = R_1 + R_2 + R_3$$

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

SAMPLE PROBLEM 4

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

 **Teacher-led video:** SP4 (tlvd-0026)

THINK

1. When connected in series the effective resistance of the circuit is equal to the sum of the individual resistors.
2. Substitute the resistance values.
3. Calculate the effective resistance.
4. State the solution.

WRITE

$$R_T = \sum_1^i R_i$$

$$R_T = 15\ \Omega + 25\ \Omega + 34\ \Omega$$

$$R_T = 74\ \Omega$$

The effective resistance of circuit is $74\ \Omega$.

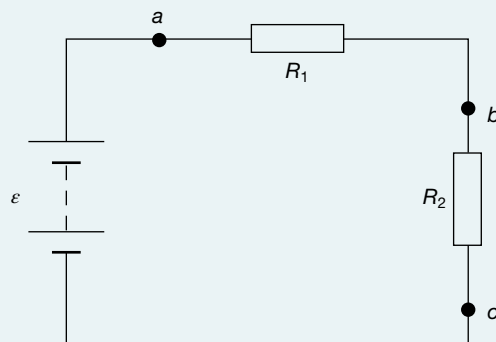
PRACTICE PROBLEM 4

Find the effective resistance of a circuit comprising three resistors, having resistance values of $1.2\ \text{k}\Omega$, $5.6\ \text{k}\Omega$ and $7.1\ \text{k}\Omega$.

SAMPLE PROBLEM 5

In the series circuit in the figure on the right, the emf of the power supply is $100\ \text{V}$; the current at point a , I_a , equals $1\ \text{A}$; and the value of R_2 is $60\ \Omega$. Find the:

- a. current at point b
- b. voltage drop across R_2
- c. voltage drop across R_1
- d. value of R_1 .



 **Teacher-led video:** SP5 (tlvd-0027)

THINK

- a. The current is the same at all points along the series circuit. Therefore, the current at point b , I_b , is $1\ \text{A}$.
- b. Substitute known values in the equation for the voltage drop across the resistor, $V_2 = IR_2$.
- c. This is a series circuit so the voltage of the battery equals the sum of the voltage drops around the circuit. So $\varepsilon = V_1 + V_2$.
- d. The resistance can be found using the relationship $V_1 = IR_1$ and making R the subject.

WRITE

$$\text{a. } I_b = 1\ \text{A}$$

$$\begin{aligned} \text{b. } V_2 &= IR_2 \\ &= 1\ \text{A} \times 60\ \Omega \\ &= 60\ \text{V} \end{aligned}$$

$$\begin{aligned} \text{c. } \varepsilon &= V_1 + V_2 \\ 100\ \text{V} &= V_1 + 60\ \text{V} \\ V_1 &= 40\ \text{V} \end{aligned}$$

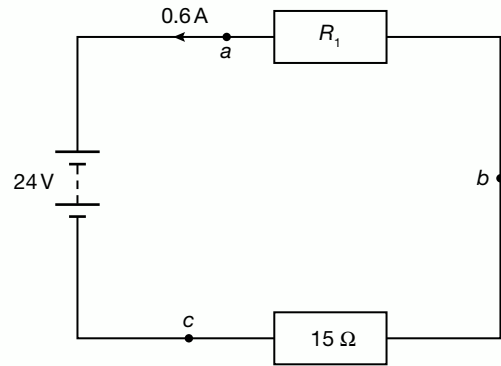
$$\begin{aligned} \text{d. } V_1 &= IR_1 \\ 40\ \text{V} &= 1\ \text{A} \times R_1 \\ R_1 &= 40\ \Omega \end{aligned}$$

PRACTICE PROBLEM 5

A 24 V battery supplies the energy to two objects connected in a series circuit as shown in the figure on the right.

The current at point a , I_a , is 0.6 A and the value of the known resistor is $15\ \Omega$. Find the:

- current at point b
- voltage drop across the known resistor
- voltage drop across the unknown resistor, R_1
- value of R_1 .



4.3.2 Resistors in parallel

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

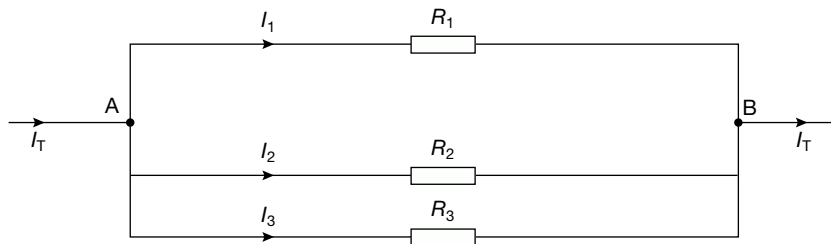
The total current flowing into the parallel section of a circuit equals the sum of the individual currents flowing through each resistor.

$$I_T = I_1 + I_2 + I_3$$

As can be seen in figure 4.5, the left-hand sides of all the resistors are connected to point A, so they are all at the same voltage. This means that all charges on that side of the resistors have the same amount of electrical potential energy. Similarly, the right-hand sides of the resistors are connected to point B, therefore, they also are at the same voltage. This means that each resistor in a parallel section of a circuit has the same voltage drop across it.

$$V_T = V_1 = V_2 = V_3$$

FIGURE 4.5 A parallel branch of a circuit



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

$$\begin{aligned} I_T &= I_1 + I_2 + I_3 \\ \Rightarrow \frac{V}{R_T} &= \frac{V}{R_1} + \frac{V}{R_2} + \frac{V}{R_3} \end{aligned}$$

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

Dividing both sides of the expression for the effective resistance by V gives:

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

This means that the reciprocal of the effective resistance is equal to the sum of the reciprocals of the individual resistances.

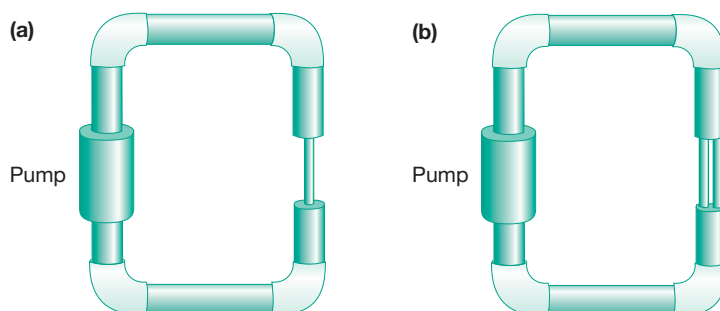
The effective resistance is less than the smallest individual resistance. The more resistors there are added in parallel, the more paths there are for the current to flow through, and the easier it is for the current to flow through the parallel section.

Modelling resistors in parallel

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

If there is only one thin pipe, as in figure 4.6a, it limits the flow of water. Adding another thin pipe beside the first, as in figure 4.6b, allows more water to flow. The total resistance offered by the two thin pipes in parallel is less than that offered by an individual thin pipe.

FIGURE 4.6 The hydraulic model for resistors in parallel showing (a) a circuit with one ‘resistor’ and (b) a second ‘resistor’ added in parallel, which allows more current to flow and reduces the effective resistance



on Resources

Digital document eModelling: Exploring resistors in parallel with a spreadsheet (doc-0047)

Weblinks
DC circuit water analogy
Simple electric circuits

SAMPLE PROBLEM 6

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

Teacher-led video: SP6 (tlvd-0028)

THINK

1. The three resistors are connected in parallel, so substitute the known values in:

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

WRITE

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

2. Solve for R_T .

$$\begin{aligned}\Rightarrow \frac{1}{R_T} &= \frac{4}{20\ \Omega} + \frac{2}{20\ \Omega} + \frac{1}{20\ \Omega} \\ \Rightarrow \frac{1}{R_T} &= \frac{7}{20\ \Omega} \\ \Rightarrow R_T &= \frac{20\ \Omega}{7} = 2.9\ \Omega\end{aligned}$$

3. State the solution.

The effective resistance of the three resistors connected in parallel is $2.9\ \Omega$.

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

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

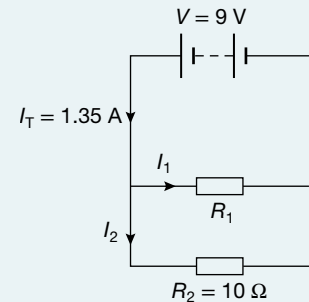
PRACTICE PROBLEM 6

Four resistors having values of $5\ \Omega$, $5\ \Omega$, $15\ \Omega$ and $20\ \Omega$ are connected in parallel. Calculate their effective resistance.

SAMPLE PROBLEM 7

Consider the parallel circuit shown in the following figure. The emf of the power supply is $9.0\ \text{V}$, R_2 has a resistance of $10\ \Omega$ and the current flowing through the power supply is $1.35\ \text{A}$. Find:

- the voltage drop across R_1 and R_2
- I_2 , the current flowing through R_2
- I_1 , the current flowing through R_1
- the resistance of R_1
- the effective resistance of the circuit.



 **Teacher-led video:** SP7 (tlvd-0029)

THINK

- For a parallel circuit, $V_1 = V_2$.
 - State the solution.
- Find the current in the resistor using the relationship $V = IR$ and making I the subject.
 - State the solution.
- Recall the formula for the current leaving the battery.
 - Make I_1 the subject and substitute the known values.

WRITE

- $V_1 = V_2 = 9\ \text{V}$
The voltage drop across R_1 and R_2 is $9\ \text{V}$.
- $I_2 = \frac{V}{R_2}$
 $\Rightarrow I_2 = \frac{9\ \text{V}}{10\ \Omega} = 0.90\ \text{A}$
 I_2 , the current flowing through R_2 , is $0.90\ \text{A}$.
- $I_T = I_1 + I_2$
 $I_1 = I_T - I_2$
 $= 1.35\ \text{A} - 0.90\ \text{A}$
 $= 0.45\ \text{A}$

3. State the solution.
- d. 1. Find the resistance by transposing the formula $V = IR$ to make R the subject.

2. State the solution.

- e. 1. The resistors are in parallel.

2. Substitute the known values.

3. R_T is the reciprocal.

4. State the solution.

I_1 , the current flowing through R_1 , is 0.45 A.

$$d. \quad R_1 = \frac{V}{I_1}$$

$$\Rightarrow R_1 = \frac{9 \text{ V}}{0.45 \text{ A}}$$

$$R_1 = 20 \Omega$$

The resistance of R_1 is 20Ω .

$$e. \quad \frac{1}{R_T} = \frac{1}{R_1} + \frac{1}{R_2}$$

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

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

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

$$= 6.7 \Omega$$

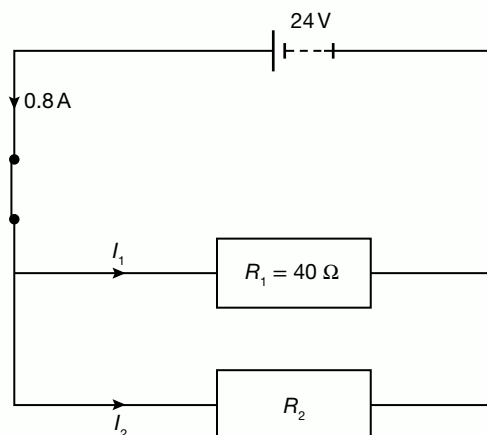
The effective resistance of the circuit is 6.7Ω .

PRACTICE PROBLEM 7

Consider the parallel circuit shown in the figure on the right.

The emf of the power supply is 24 V and the heater R_1 has a resistance of 40Ω . When the switch is closed the current flowing is 0.8 A. Find:

- the voltage drop across R_1 and R_2
- I_1 , the current flowing through R_1
- I_2 , the current flowing through R_2
- the resistance of R_2
- the effective resistance of the circuit.



SAMPLE PROBLEM 8

Find the effective resistance when a 10.0Ω resistor is placed in parallel with a $10.0 \text{ k}\Omega$ resistor.

Teacher-led video: SP8 (tlvd-0030)

THINK

1. The two resistors are connected in parallel, so substitute the known values in:

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

WRITE

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

$$= \frac{1}{10.0 \Omega} + \frac{1}{10\,000 \Omega}$$

2. The reciprocal gives the value of the resistance.

$$\begin{aligned} &= \frac{1000}{10\,000\,\Omega} + \frac{1}{10\,000\,\Omega} \\ &= \frac{1001}{10\,000\,\Omega} \end{aligned}$$

3. State the solution.

$$\begin{aligned} R_T &= \frac{10\,000\,\Omega}{1001} \\ &= 9.99\,\Omega \end{aligned}$$

The effective resistance is 9.99 Ω .

PRACTICE PROBLEM 8

Find the effective resistance when a 1.2 k Ω resistor is placed in parallel with a 4.8 k Ω resistor.

Note: Adding a large resistance in parallel with a small resistance slightly reduces the effective resistance of that part of a circuit.

Parallel circuits are used extensively. Australian households are wired in parallel with an AC voltage of 230 V. This is equivalent to a DC voltage of 230 V, and all the formulae that have been presented so far can be used for analysing AC circuits.

The advantage of having parallel circuits is that all appliances have the same voltage across them and the appliances can be switched on independently. If appliances were connected in series, they would all be on or off at the same time; and they would share the voltage between them, so no appliance would receive the full voltage. This would present problems when designing the devices, as it would not be known what voltage to allow for.

Car lights, front and rear, are wired in parallel for the same reason. If one lamp ‘blows’, the other lamps will continue functioning normally.



Resources



Digital documents Investigation 4.1 Series circuits (doc-31866)

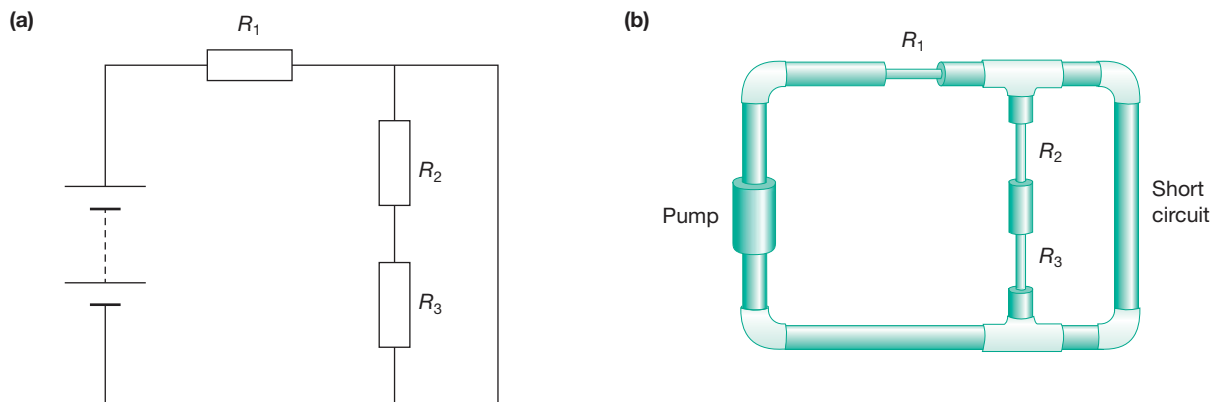
Investigation 4.2 Parallel circuits (doc-31867)

4.3.3 Short circuits

A short circuit occurs in a circuit when a conductor of negligible resistance is placed in parallel with a circuit element. This element may be a resistor or a globe. The result of a short circuit is that virtually all the current flows through the conductor and practically none flows through the circuit element. Because there is effectively no voltage drop across the wire, there is also no voltage drop across the circuit element and no current flows through it. Think of what would happen in the hydraulic model if a conducting pipe were placed beside a thin pipe. This situation is represented in both ways in figure 4.7.

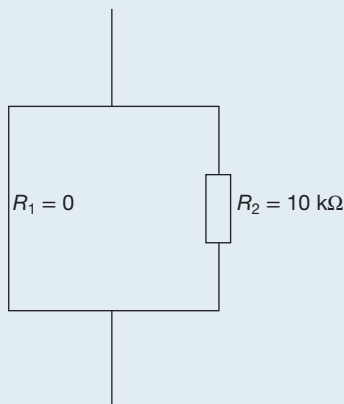
In this case, the current through the power supply passes through R_1 , but then flows through the short circuit, effectively avoiding R_2 and R_3 .

FIGURE 4.7 (a) Circuit diagram showing a short circuit (b) Hydraulic model of a short circuit



SAMPLE PROBLEM 9

The following figure shows a $10\text{ k}\Omega$ resistor that has been short circuited with a conductor of $0\ \Omega$ resistance. Calculate the effective resistance of this arrangement.



Teacher-led video: SP9 (tlvd-0031)

THINK

1. The two resistors are connected in parallel, so substitute the known values in:

$$\frac{1}{R_T} = \frac{1}{R_1} + \frac{1}{R_2}$$
2. The reciprocal gives the value of the resistance.
3. State the solution.

WRITE

$$\begin{aligned} \frac{1}{R_T} &= \frac{1}{R_1} + \frac{1}{R_2} \\ &= \frac{1}{0\ \Omega} + \frac{1}{10\,000\ \Omega} \\ &= \infty \\ \Rightarrow R_T &= 0\ \Omega \\ \text{The effective resistance is } 0\ \Omega. \end{aligned}$$

PRACTICE PROBLEM 9

Find the effective resistance when a $1.2\text{ k}\Omega$ resistor is placed in parallel with a $4.8\text{ k}\Omega$ resistor and a $500\ \Omega$ resistor.

4.3.4 The voltage divider

The **voltage divider** is an example of resistors in series. It is used to divide or reduce a voltage to a value needed for a part of the circuit. A voltage divider is used in many control circuits, for example, turning on the heating in a house when the temperature drops.

The voltage divider has an input voltage, V_{in} , and an output voltage, V_{out} .

A general voltage divider is shown in figure 4.8.

The current, I , flowing through R_1 and R_2 is the same since R_1 and R_2 are in series.

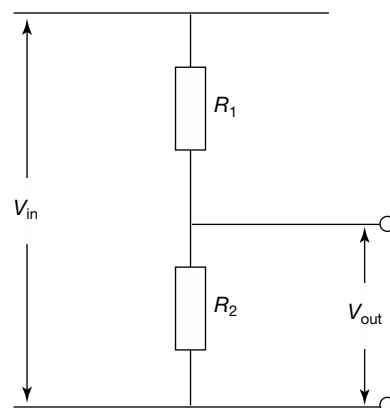
$$V_{\text{in}} = I(R_1 + R_2)$$

$$\Rightarrow I = \frac{V_{\text{in}}}{R_1 + R_2}$$

$$V_{\text{out}} = IR_2$$

$$\Rightarrow V_{\text{out}} = \frac{V_{\text{in}}}{R_1 + R_2} \times R_2$$

FIGURE 4.8 A general voltage divider



This can be rewritten as:

$$V_{\text{out}} = \left[\frac{R_2}{R_1 + R_2} \right] V_{\text{in}}$$

More generally:

$$V_{\text{out}} = \left[\frac{\text{resistance across which } V_{\text{out}} \text{ is taken}}{\text{sum of all resistances}} \right] V_{\text{in}} = \frac{R_{\text{out}}}{R_{\text{total}}} V_{\text{in}}$$

If R_1 and R_2 are equal in value, the voltage will be divided equally across both resistors. If R_1 is much greater than R_2 , then most of the voltage drop will be across R_1 .



Resources



Digital document Investigation 4.3 Determining emf and internal resistance (doc-31868)



Teacher-led video Investigation 4.3 Determining emf and internal resistance (tlvd-0813)

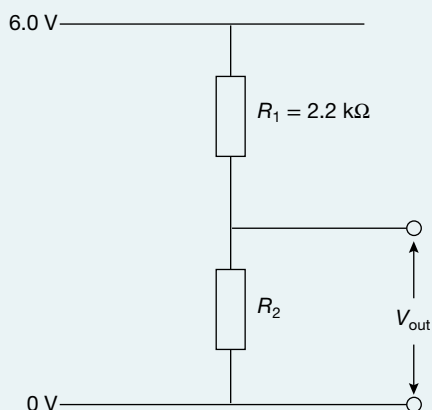


Interactivity Voltage dividers (int-6392)

SAMPLE PROBLEM 10

Calculate the value of the unknown resistor in the voltage divider shown in the following figure, if the output voltage is required to be 4.0 V.





Teacher-led video: SP10 (tlvd-0032)

THINK

1. Substitute known values in the formula,

$$V_{\text{out}} = \frac{R_2 V_{\text{in}}}{R_1 + R_2}$$
 for a two resistor voltage divider.
2. Solve by making R_2 the subject.
3. State the solution.

WRITE

$$V_{\text{out}} = \frac{R_2 V_{\text{in}}}{R_1 + R_2}$$

$$\Rightarrow 4.0 \text{ V} = \frac{6.0 \text{ V} \times R_2}{2.2 \text{ k}\Omega + R_2}$$

$$8.8 \text{ k}\Omega \text{ V} + 4.0 \text{ V } R_2 = 6.0 \text{ V } R_2$$

$$2.0 \text{ V } R_2 = 8.8 \text{ k}\Omega \text{ V}$$

$$R_2 = 4.4 \text{ k}\Omega$$

The value of the unknown resistor in the voltage divider is $4.4 \text{ k}\Omega$.

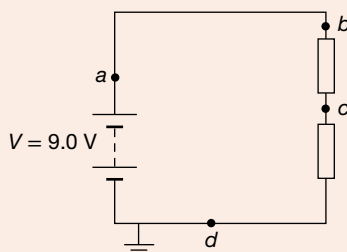
PRACTICE PROBLEM 10

Calculate the value of the unknown resistor in the voltage divider in sample problem 10 if the output voltage is to be 1.5 V .

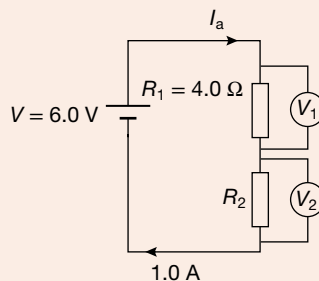
4.3 EXERCISE

To answer questions online and to receive **immediate feedback** and **sample responses** for every question go to your learnON title at www.jacplus.com.au.

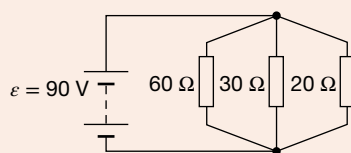
1. Find the effective resistance of the following sets of resistors if they are connected in series.
 - (a) 2.7Ω , 9.8Ω
 - (b) 12Ω , 20Ω , 30Ω
 - (c) $1.2 \text{ k}\Omega$, $3.2 \text{ k}\Omega$, $11 \text{ k}\Omega$
2. Find the voltage at the points a , b , c and d in the following figure, given that V_{bc} is 5.0 V .



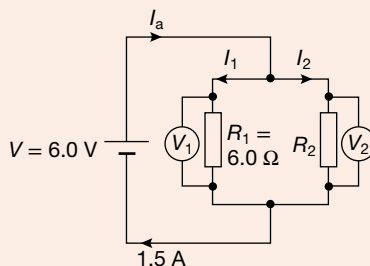
3. Find the unknown quantities in the series circuit shown in the following figure.



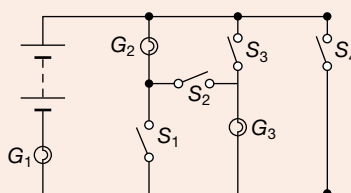
4. Find the effective resistance when the following resistors are connected in parallel.
- 30 Ω , 20 Ω
 - 5.0 Ω , 10 Ω , 30 Ω
 - 15 Ω , 60 Ω , 60 Ω
5. Two 10 Ω resistors are connected in parallel across the terminals of a 15 V battery.
- What is the effective resistance of the circuit?
 - What current flows in the circuit?
 - What is the current through each resistor?
6. Three resistors of 60 Ω , 30 Ω and 20 Ω are connected in parallel across a 90 V power source as shown in the following figure.



- Calculate the effective resistance of the circuit.
 - Find the current flowing through the source.
 - What is the current flowing through each resistor?
7. Find the unknown quantities in the parallel circuit shown in the following figure.



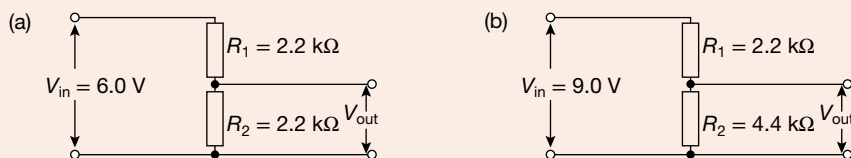
8. Three resistors, having resistance values of 6 Ω , 18 Ω and 9 Ω , are connected in parallel across a 36 V power supply.
- What current flows through each resistor?
 - What total current flows in the circuit?
 - What is the effective resistance of the circuit?
9. The following figure shows an arrangement of switches and globes connected to a source of emf.



Which globes would light up if the following sets of switches are closed?

- (a) Switch S_2 only
- (b) Switch S_3 only
- (c) Switch S_4 only

10. (a) Find the output voltage for the voltage divider shown in circuit (a).
 (b) What is the output voltage of circuit (b) if a load of resistance $4.4 \text{ k}\Omega$ is connected across the output terminals of the voltage divider?



studyon

To answer practice exam questions online and to receive immediate feedback and sample responses for every question go to your learnON title at www.jacplus.com.au.

studyON: Practice exam questions online only

Fully worked solutions and sample responses are available in your digital formats.

4.4 Non-ohmic devices in series and parallel

KEY CONCEPTS

- Calculate and analyse the effective resistance of circuits comprising parallel and series resistance and voltage dividers.
- 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 transducers.

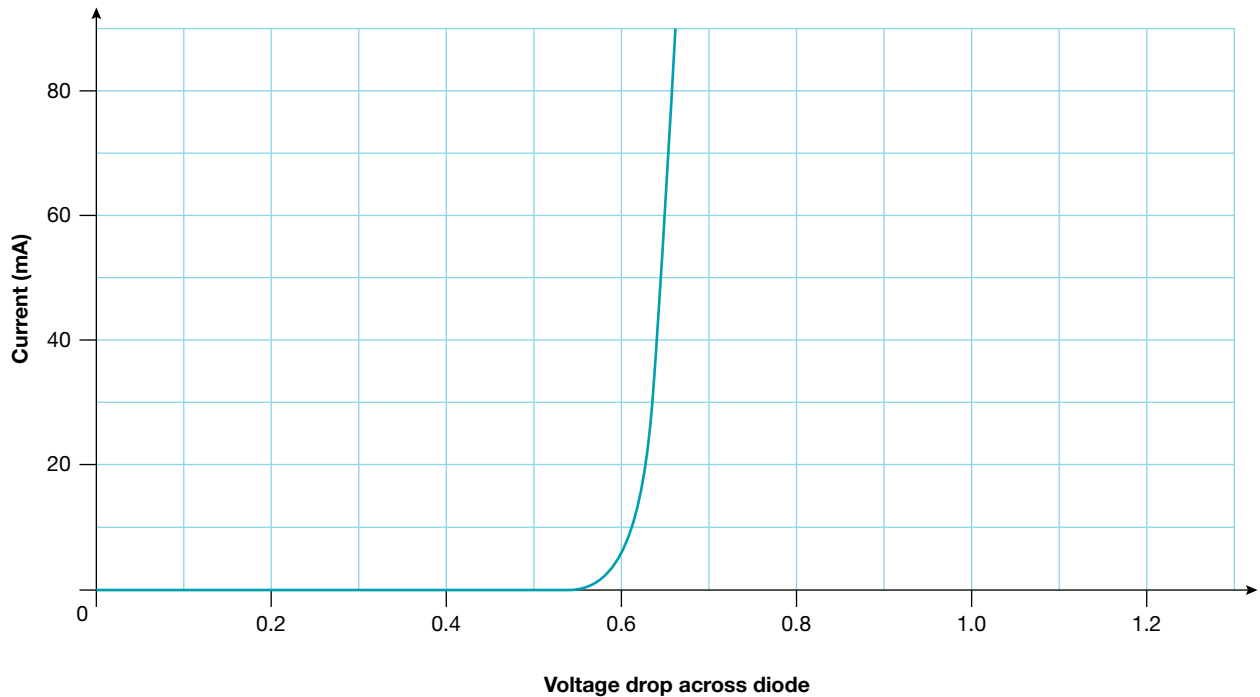
4.4.1 Non-ohmic devices

Non-ohmic devices do not obey Ohm's Law. Their current-versus-voltage characteristics can be presented graphically.

The value of $\frac{V}{I}$ is not constant for non-ohmic devices.

The rules for series and parallel circuits still apply when analysing circuits containing non-ohmic devices, such as light bulbs, diodes, thermistors, light dependent resistors (LDRs) and light-emitting diodes (LEDs). Devices in series have the same current and share the voltage. Devices in parallel have the same voltage and the current is shared between them. The actual values of the voltage or current are obtained from the current-versus-voltage (V – I) graphs for the devices.

FIGURE 4.9 Current-versus-voltage characteristic for a silicon diode

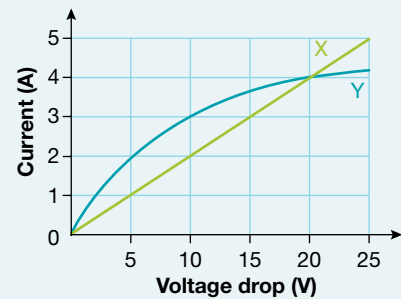


SAMPLE PROBLEM 11

The following figure shows the current-versus-voltage graph for two electrical devices.

If X and Y are in parallel and the current through X is 2 A, calculate:

- the voltage across Y
- the current through Y.



 **Teacher-led video:** SP11 (tlvd-0033)

THINK

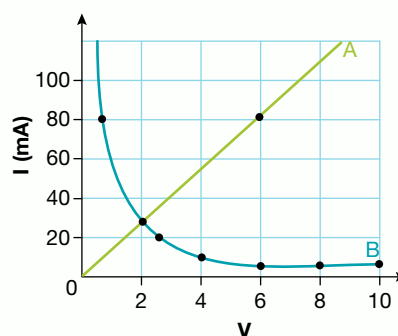
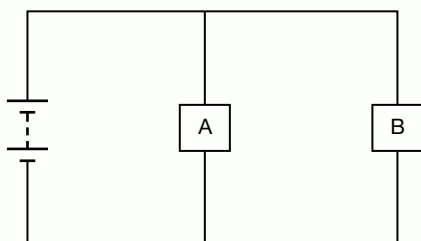
- As X and Y are in parallel, the voltage across X equals the voltage across Y. Use the graph to find the values.
- Again use the graph.

WRITE

- When the current through X is 2 A, the voltage is 10 V, so the voltage across Y is also 10 V.
- When the voltage across Y is 10 V, the current through Y is seen to be 3 A.

PRACTICE PROBLEM 11

The following figures show two electrical devices, A and B, connected in a simple circuit and the current-versus-voltage graph for A and B.



When the current through A is 80 mA, calculate:

- the voltage across B
- the current through B.

4.4.2 Transducers and sensors

Transducers are devices that convert energy from one form to another. They can be affected by, or can affect, the environment. The word *transducer* comes from the Latin for ‘to lead across’. Table 4.2 lists a range of transducers and their energy conversions.

TABLE 4.2 Examples of transducers

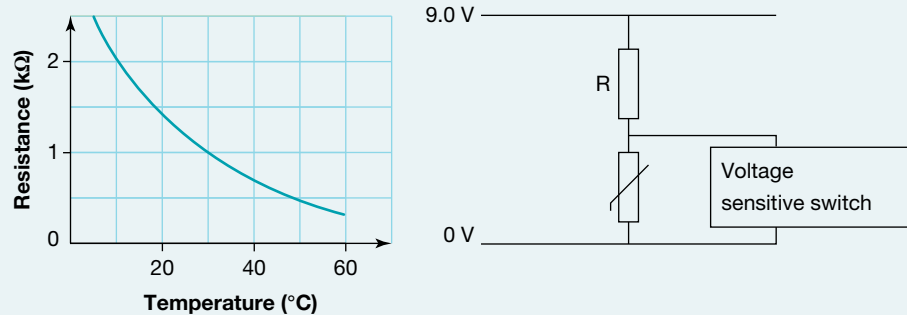
Transducer	Energy conversion	
	From	To
Solar cell	Light	Electrical
Loudspeaker	Electrical	Sound
Microphone	Sound	Electrical
LED	Electrical	Light
Antenna	Electromagnetic	Electrical
Thermocouple	Heat energy (temp. difference)	Electrical
Peltier cooler	Electrical	Heat energy (temp. difference)
Piezoelectric gas lighter*	Stored mechanical energy due to pressure	Electrical

*The piezoelectric effect is also used in strain gauges to measure the stress in construction materials and in the accelerometers found in video game controllers and guidance systems.

Sensors are a subset of transducers where the energy conversion is to electrical, that is, to a variation in voltage. Some sensors generate the voltage directly, for example, piezoelectric devices. Other sensors whose resistance changes, such as **LDRs** and **thermistors**, use a **voltage divider** circuit.

SAMPLE PROBLEM 12

The resistance of a thermistor changes with temperature as shown in the following graph. In the voltage divider circuit shown, the thermistor is one of the two resistors; the other is a resistor with a fixed resistance value.



As the temperature drops, the resistance of the thermistor increases. As the thermistor's resistance increases, its share of the voltage from the power supply also increases, while that of the fixed value resistor will decrease.

A voltage sensitive switch is placed across the thermistor. It is built to turn on a heater when the voltage across the thermistor is greater than 6 V. Your task as the circuit designer is to determine the resistance value required for the fixed-value resistor to turn on the heater at 19 °C.

Teacher-led video: SP12 (tlvd-0034)

THINK

1. Determine the resistance of the thermistor at 19 °C using the graph.
2. Substitute the resistance into the voltage divider equation.
3. Solve for R .
4. State the solution.

WRITE

From the graph, at 19 °C the thermistor has a resistance of 1.5 kΩ (1500 Ω).

$$V_{\text{out}} = \left[\frac{R_2}{R_1 + R_2} \right] V_{\text{in}}$$

$$6\text{V} = \left[\frac{1.5\text{ k}\Omega}{R + 1.5\text{ k}\Omega} \right] \times 9\text{V}$$

$$6 \times (R + 1500) = 1500 \times 9$$

$$6R + 9000 = 13\,500$$

$$6R = 4500$$

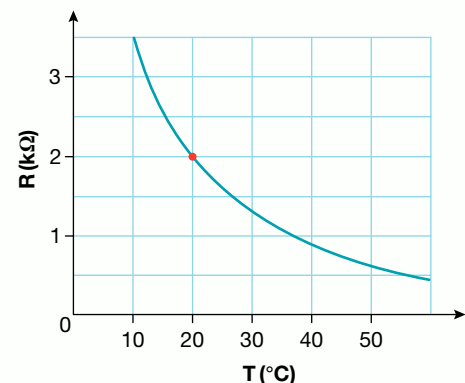
$$R = 750\ \Omega$$

The resistance required for the fixed-value resistor to turn on the heater at 19 °C is 750 Ω.

PRACTICE PROBLEM 12

The resistance-versus-temperature characteristics of a thermistor are shown in the following graph. The thermistor is connected in parallel with a fixed resistor similar to that shown in the circuit in sample problem 12.

The switch across the thermistor is designed to turn on a warning light when the voltage across the thermistor is 4 V or greater. Determine the resistance value required for the fixed value resistor to turn on the warning light at 20 °C.



SAMPLE PROBLEM 13

To reduce the heating bill from the heater in sample problem 12, it is decided that the heater should be turned on when the temperature is below 18 °C. Should the value of the fixed-value resistor be increased or decreased? Explain.

 Teacher-led video: SP13 (tlvd-0035)

THINK

The voltage to turn on the switch will still be 6 V, so the voltage across the two resistors will be unchanged. The ratio of their resistance values will therefore also be the same. From the graph in sample problem 12 it can be seen that at 18 °C the thermistor's resistance will be greater than it was at 19 °C. So to keep the ratio the same, R must increase.

This can also be explained using current. As the resistance of the thermistor is higher at the lower temperature, there will be less current through both resistors. As the voltage drop across R is to remain the same, its resistance will need to be greater ($V = IR$).

WRITE

The resistance must be increased.

PRACTICE PROBLEM 13

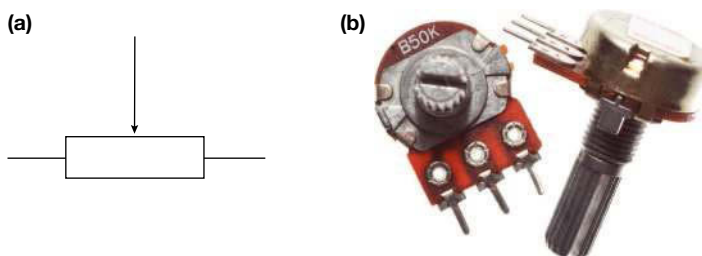
The thermistor and voltage sensitive switch from sample problem 12 are to be used for a cooling system. The cooling system is to turn on when the temperature is greater than 24 °C. To which resistor, the thermistor or the fixed resistor, should the voltage sensitive switch be connected so that the voltage is greater than 6 V for temperatures greater than 24 °C? Explain. What should be the value of the fixed resistor?

4.4.3 Potentiometers

A **potentiometer**, called a 'pot' for short, is a variable voltage divider. It consists of a fixed resistor, usually a length of wire, with a contact that can slide up and down, varying the amount of resistance in each arm of the voltage divider.

Potentiometers are commonly used as controls in radio equipment, either as a slide control or in a rotary form. They are also the basis of joysticks in game controls.

FIGURE 4.10 (a) The symbol for a potentiometer
(b) A potentiometer

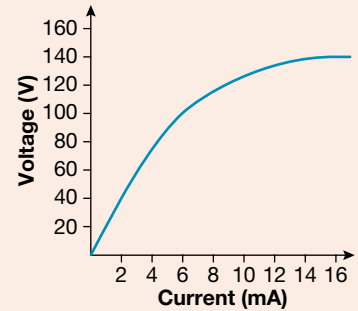


4.4 EXERCISE

To answer questions online and to receive **immediate feedback** and **sample responses** for every question go to your learnON title at www.jacplus.com.au.

1. The voltage-versus-current characteristic graph for a non-ohmic device is shown on the right.

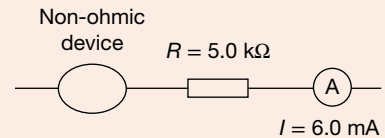
- What is the device's current when the voltage drop across it is 100 V?
- What is the voltage drop across the device when the current through it is 16 mA?
- What is the resistance of the device when it carries a current of 16 mA?



2. The device described in question 1 is placed in series with a 5.0 kΩ resistor and a voltage drop is applied across the combination. This arrangement is shown in the following figure.

The current in the resistor is measured to be 6.0 mA.

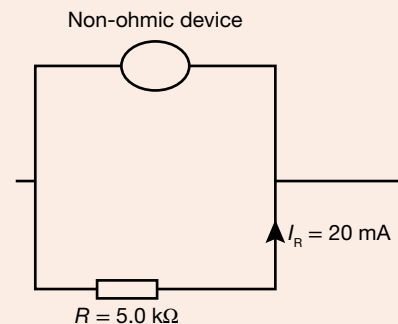
- What is the voltage drop across the resistor?
- What is the current in the device?
- What is the voltage drop across the device?
- What is the total voltage drop across the device and the resistor?



3. The device described in question 1 is now placed in parallel with a 5.0 kΩ resistor and a new voltage is applied across the combination. This arrangement is shown in the figure on the right.

The current in the resistor is measured to be 20 mA.

- Calculate the voltage drop across the resistor.
- What is the voltage drop across the device?
- What is the current in the device?
- What is the total current in the circuit?



studyon

To answer practice exam questions online and to receive immediate feedback and sample responses for every question go to your learnON title at www.jacplus.com.au.

studyON: Practice exam questions 

Fully worked solutions and sample responses are available in your digital formats.

4.5 Power in circuits

KEY CONCEPT

- Compare power transfers in series and parallel circuits.

Recall that the **power** being used in a circuit element is the product of the voltage drop across it and the current through it: $P = VI$. The total power being provided to a circuit is the sum of the power being used in, or 'dissipated by', the individual elements in that circuit. It does not matter if the elements are connected in series or in parallel.

$$P_T = P_1 + P_2 + P_3 = \dots$$

SAMPLE PROBLEM 14

A household electrical circuit is wired in parallel. Find the total current flowing in the circuit if the following appliances are being used: a 600 W microwave oven, a 450 W toaster and a 1000 W electric kettle. Household circuits provide a voltage drop of 230 V across each appliance.

 **Teacher-led video:** SP14 (tlvd-0036)

THINK

1. The total power being used in the circuit is the sum of the power used in each component.
2. Transpose the formula $P = IV$ to make I the subject, then substitute the known values.
3. State the solution.

WRITE

$$P_T = 600 + 450 + 1000 = 2050 \text{ W}$$

$$\begin{aligned} I_T &= \frac{P_T}{V} \\ &= \frac{2050 \text{ W}}{230 \text{ V}} \\ &= 8.91 \text{ A} \end{aligned}$$

The total current flowing in the circuit is 8.91 A.

PRACTICE PROBLEM 14

A household electrical circuit is wired in parallel. Find the total current flowing through a household circuit when the following devices are being used: a 400 W computer, a 200 W blender, a 500 W television and a 60 W lamp.

4.5 EXERCISE

To answer questions online and to receive **immediate feedback** and **sample responses** for every question go to your learnON title at www.jacplus.com.au.

1. Three resistors of value 25 Ω , 15 Ω and 10 Ω are connected in series to a 10 V power supply.
 - (a) Calculate the current in the circuit.
 - (b) What is the voltage drop across each resistor?
 - (c) At what rate is energy being transformed in each resistor?
 - (d) What is the total power rating of the circuit?
2. The three resistors in question 1 are connected in parallel.
 - (a) Calculate the current in the circuit.
 - (b) What is the voltage drop across each resistor?
 - (c) At what rate is energy being transformed in each resistor?
 - (d) What is the total power rating of the circuit?
3. Design a dimmer switch circuit for a light. Does the circuit consume more power when the light is bright or dull? Justify your answer.

studyon

To answer practice exam questions online and to receive immediate feedback and sample responses for every question go to your learnON title at www.jacplus.com.au.

studyON: Practice exam questions 

Fully worked solutions and sample responses are available in your digital formats.

4.6 Review

4.6.1 Summary

- An electric circuit is a closed conducting path containing a source of emf.
- In a series circuit the components are placed one after the other. There is only one path for the charge carriers to flow through.
- In a series circuit the current is the same at all points; the sum of the potential drops is equal to the emf of the circuit.
- The effective resistance of resistors placed in series is equal to the sum of the individual resistances.
- In a parallel circuit, there is more than one path for the current to flow through.
- Resistors in parallel have the same potential difference across them; the current in each resistor adds up to the total current flowing into the parallel branch.
- In a parallel arrangement of resistors, the reciprocal of the effective resistance is equal to the sum of the reciprocals of the individual resistances:

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

- A short circuit occurs when a conductor of negligible resistance is placed in parallel with a circuit element and stops current from flowing through it.
- Circuits containing non-ohmic devices can be analysed using the rules for series and parallel circuits with their current-versus-voltage characteristic graphs.
- The total power used in a circuit equals the sum of the powers used in individual devices.
- A voltage divider is used to reduce an input voltage to some required value.
- A voltage divider consists of two or more resistors arranged in series to produce a smaller voltage at its output.
- The output of a voltage divider can be calculated using the equation:

$$V_{\text{out}} = \left[\frac{R_2}{R_1 + R_2} \right] V_{\text{in}}$$

- A transducer is a device that can be affected by, or affects, the environment.

Resources

studyon

To access key concept summaries and practice exam questions download and print the **studyON: Revision and practice exam question booklet** (sonr-0029).

4.6.2 Key terms

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

A **conductor** is a material that contains charge carriers; that is, charged particles can move and travel freely through the material.

Electric charge is a basic property of matter. It occurs in two states: positive (+) charge and negative (–) charge. (page 3)

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

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

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

A **non-ohmic device** is one for which the resistance is different for different currents passing through it. Devices connected in **parallel** are joined together so that one end of each device is joined at a common point and the other end of each device is joined at another common point.

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

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

A **resistor** is used to control the current flowing through, and the voltage drop across, parts of a circuit. Devices connected in **series** are joined together one after the other.

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

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

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

A **potentiometer** is a variable voltage divider, with a fixed resistor that can slide up and down.

Transducers are devices that convert energy from one form to another form.

The **voltage divider** is used to reduce, or divide, a voltage to a value needed for a part of the circuit.

on Resources

 **Digital document** Key terms glossary (doc-32180)

4.6.3 Practical work and investigations

Investigation 4.1

Series circuits

Aim: To observe the voltage and current in a circuit set up in series

Digital document: doc-31866

Investigation 4.2

Parallel circuits

Aim: To observe the voltage and current in a circuit with resistors set up in parallel

Digital document: doc-31867

Investigation 4.3

Determining emf and internal resistance

Aim: To determine the emf and internal resistance of circuits with old and new dry cells with resistors of varying resistances

Digital document: doc-31868

Teacher-led video: tlvd-0813



on Resources

 **Digital document** Practical investigation logbook (doc-32181)

4.6 Exercises

To answer questions online and to receive **immediate feedback** and **sample responses** for every question go to your learnON title at www.jacplus.com.au.

4.6 Exercise 1: Multiple choice questions

Use the following information to answer questions 1 to 3.

Three resistors of $20\ \Omega$, $30\ \Omega$ and $50\ \Omega$ are connected in series across a $9.0\ \text{V}$ battery.

- What is the effective resistance of the three resistors?
 A. $0.01\ \Omega$ B. $0.33\ \Omega$ C. $100\ \Omega$ D. $330\ \Omega$
- What current flows in the circuit?
 A. $90\ \text{mA}$ B. $27\ \text{mA}$ C. $9\ \text{A}$ D. $27\ \text{A}$
- What is the total voltage drop across the circuit?
 A. $0\ \text{V}$ B. $0.09\ \text{V}$ C. $9\ \text{V}$ D. $900\ \text{V}$

Use the following information to answer questions 4 to 6.

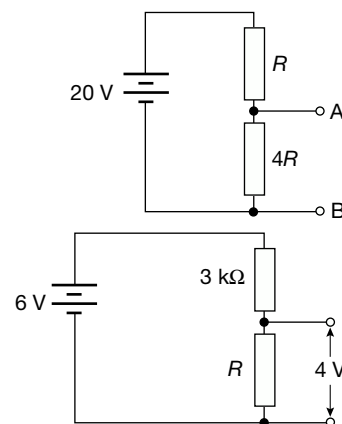
Three resistors of $6\ \Omega$, $18\ \Omega$ and $9\ \Omega$ are connected in parallel across a $36\ \text{V}$ power supply.

- What current flows through the $9\ \Omega$ resistor?
 A. $2\ \text{A}$ B. $4\ \text{A}$ C. $6\ \text{A}$ D. $12\ \text{A}$
- What is the effective resistance of the circuit?
 A. $3\ \Omega$ B. $4.5\ \Omega$ C. $12\ \Omega$ D. $33\ \Omega$
- What total current flows in the circuit?
 A. $2\ \text{A}$ B. $4\ \text{A}$ C. $6\ \text{A}$ D. $12\ \text{A}$
- Three resistors of value $25\ \Omega$, $15\ \Omega$ and $10\ \Omega$ are connected in series to a $10\ \text{V}$ power supply. What is the current in the circuit?
 A. $0.20\ \text{A}$ B. $0.40\ \text{A}$
 C. $0.70\ \text{A}$ D. $1.0\ \text{A}$

- In the circuit on the right what is the voltage drop between A and B?
 A. $0\ \text{V}$ B. $4\ \text{V}$
 C. $16\ \text{V}$ D. $20\ \text{V}$

- What is the value of the resistor shown in the circuit on the right?
 A. $3\ \text{k}\Omega$ B. $4\ \text{k}\Omega$
 C. $6\ \text{k}\Omega$ D. $12\ \text{k}\Omega$

- Which behaviour is more likely when a thermistor is connected in an electrical circuit?
 A. The resistance of the thermistor increases as the operating temperature increases.
 B. The ratio of the voltage across the thermistor to the current flowing through it is constant.
 C. When the potential difference across the thermistor is increased the current flowing through it is also likely to increase.
 D. The behaviour of the thermistor is not temperature dependent.

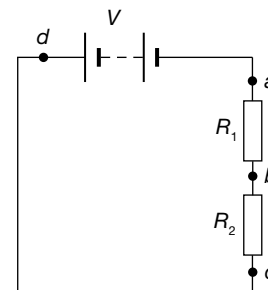


4.6 Exercise 2: Short answer questions

- In the series circuit shown in the figure on the right, $V_{ab} = 20\ \text{V}$, $R_2 = 30\ \Omega$, and $I_a = 2.0\ \text{A}$.

Find values for:

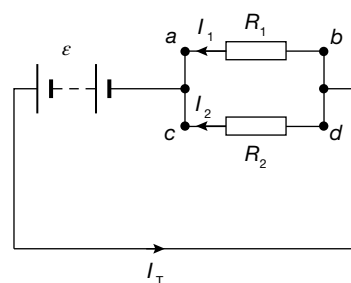
- I_b
- V_{bc}
- R_1
- R_T , the effective resistance of the circuit
- V , the emf of the battery.



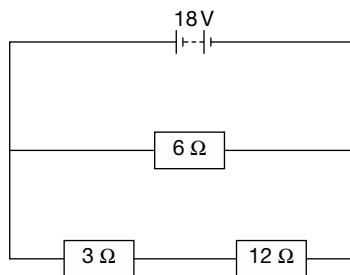
2. In the parallel circuit shown in the following figure, $I_1 = 0.20\text{ A}$, $R_1 = 60\ \Omega$ and $I_T = 0.50\text{ A}$.

Find values for:

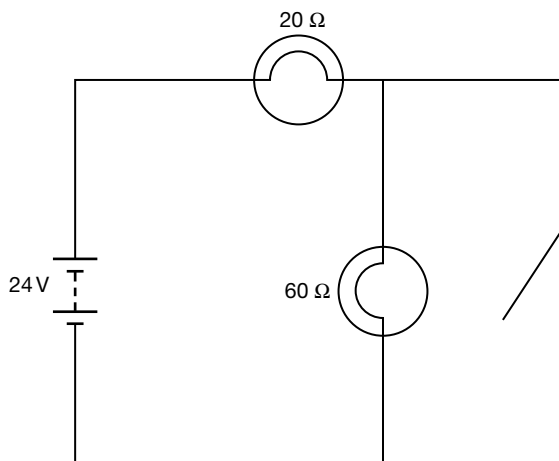
- V_{ab}
- V_{cd}
- $\mathcal{E}$
- I_2
- R_2 .



3. When the following circuit is powered by an 18 V power supply, what is the current through the $6\ \Omega$ resistor?

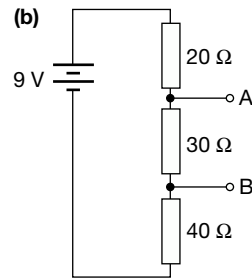
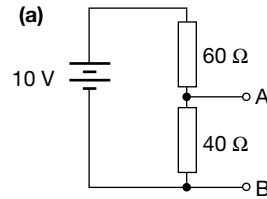


4. Two lamps labelled as $12\text{ V } 9\text{ W}$ and $12\text{ V } 24\text{ W}$ are connected in parallel with a 12 V battery.
- What is the effective resistance of the circuit?
 - Will the lamps be equally bright? Explain your answer.
5. Consider the following circuit.

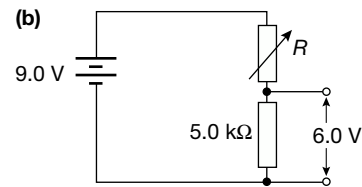
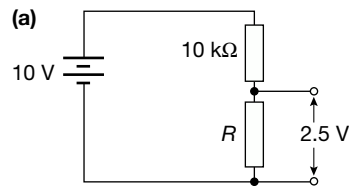


- What current passes through each resistor?
 - How much power is dissipated in each resistor?
- The switch is now closed.
- What current passes through each resistor?
 - How much power is dissipated in each resistor?
6. Some lighting circuits are controlled by two switches in different locations. Design a DC circuit to show how this could be achieved.

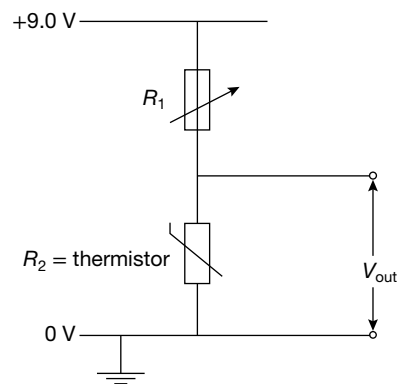
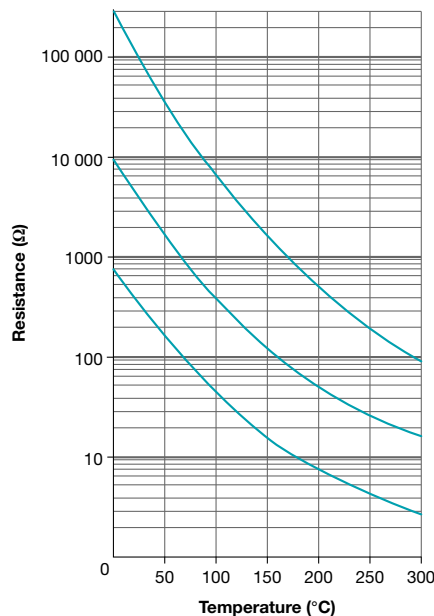
7. Find the voltage drop between A and B in each of the following voltage divider circuits.



8. Find the value of the unknown resistor in the voltage dividers shown.



9. A student connects a variable resistor and a lamp in series in a circuit to a fixed power supply.
- What will happen in the lamp as the resistance of the variable resistor is increased?
 - As the resistance of the variable resistor is increased will the power consumed in the circuit change? Justify your answer.
- The lamp and the variable resistor are now connected in parallel.
- What will happen in the lamp as the resistance of the variable resistor is increased?
 - What will happen to the power consumed in the circuit?
10. A thermistor has the temperature-versus-resistance characteristic shown by the bottom curve in the following graph. It is placed in the voltage divider shown in the circuit diagram.



- What is the resistance of the thermistor when the temperature is 150 °C?
- What is the value of the variable resistor if the temperature is 200 °C and V_{out} is 6 V?

4.6 Exercise 3: Exam practice questions

Question 1 (5 marks)

Consider two people connected in series with a 25 V source across them. The first person, R_1 , has a resistance of $1000\ \Omega$ and the second person, R_2 , has a resistance of $1500\ \Omega$.

a. Determine the current through each person.

1 mark

b. What is the voltage drop across each person?

1 mark

The two people now connect themselves in parallel with the 25 V power source.

c. Determine the current through each person.

2 marks

d. What is the voltage drop across each person?

1 mark

Question 2 (2 marks)

Prove mathematically that the resistance of a short-circuited resistor branch is 0.

Question 3 (3 marks)

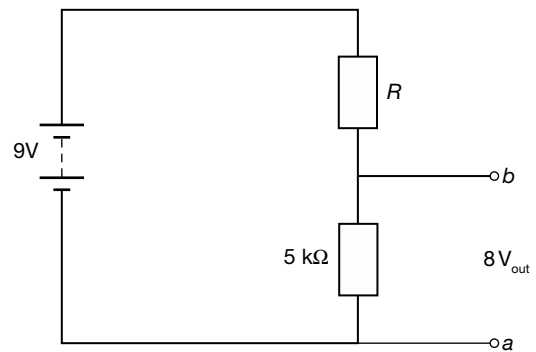
Consider the circuit on the right.

a. Find the value of the unknown resistor.

1 mark

b. What is the power of the circuit?

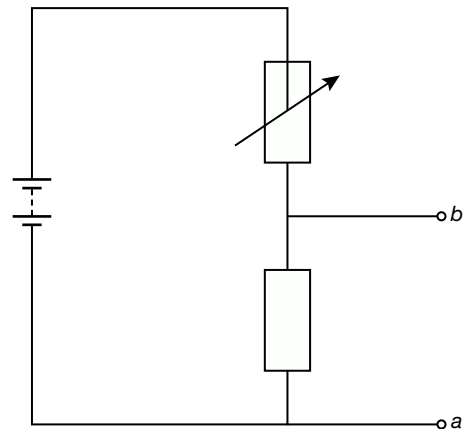
1 mark



The resistor is now replaced by a variable resistor as shown.

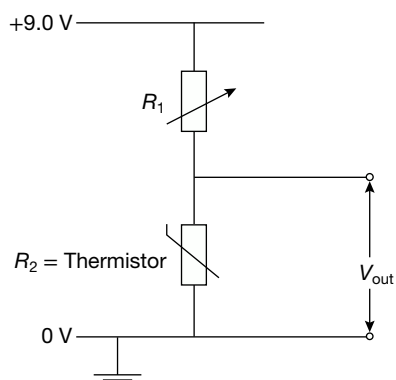
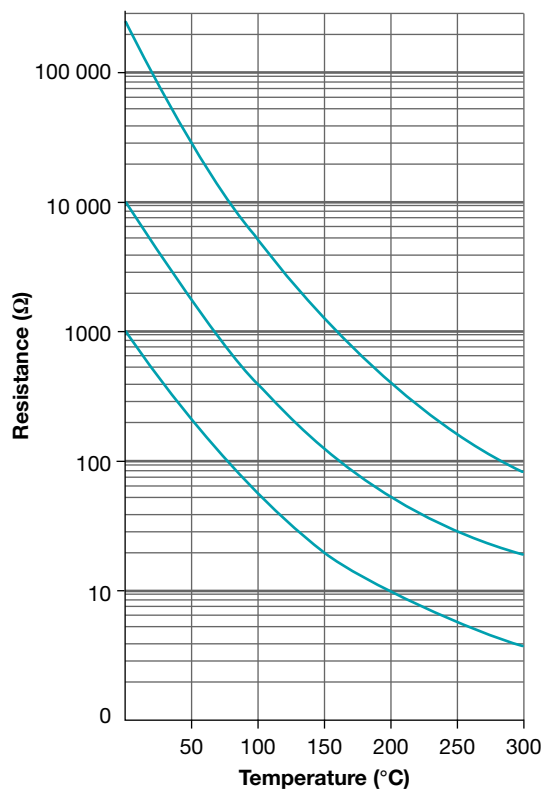
c. What happens to the voltage drop V_{ab} , when the resistance of the variable resistor decreases and the other resistance is unchanged?

1 mark



Question 4 (3 marks)

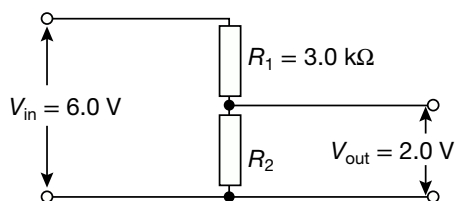
A thermistor has the temperature-versus-resistance characteristics shown by the top curve in the following graph. It is placed in the voltage divider shown in the following circuit diagram.



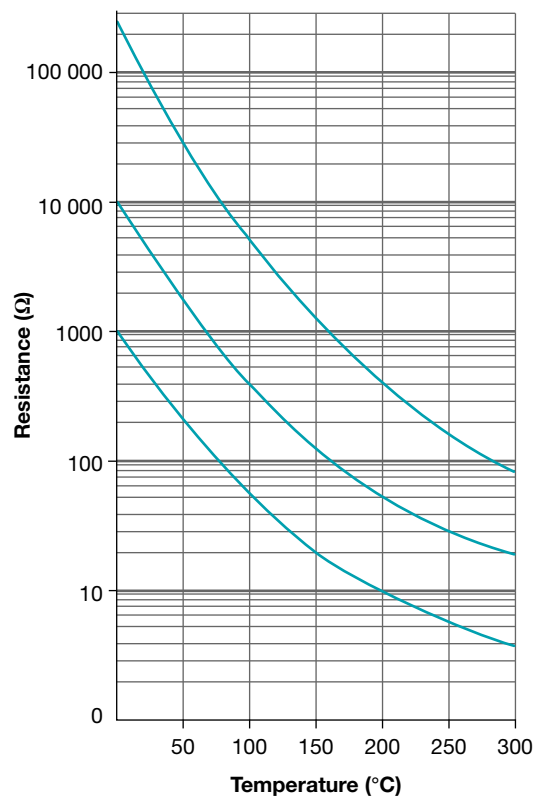
- a. What is the resistance of the thermistor when the temperature is 200°C ? **1 mark**
- b. Calculate the value of the variable resistor in the voltage divider if the temperature is 100°C and the output voltage is 4.5 V. **2 marks**

Question 5 (3 marks)

- a. Find the value of R_2 in the voltage divider in the following figure that would give an output voltage of 2.0 V. **2 marks**



The resistor R_2 is now replaced by the thermistor with a temperature-versus-resistance curve as shown by the middle curve in the following graph.



b. What is the value of V_{out} when the temperature of the thermistor is 100°C ?

1 mark

4.6 Exercise 4: studyON topic test online only

Fully worked solutions and sample responses are available in your digital formats.

teachon

Test maker

Create unique tests and exams from our extensive range of questions, including practice exam questions. Access the assignments section in learnON to begin creating and assigning assessments to students.

5 Using electricity and electrical safety

5.1 Overview

Numerous **videos** and **interactivities** are available just where you need them, at the point of learning, in your digital formats, learnON and eBookPLUS at www.jacplus.com.au.

5.1.1 Introduction

In this topic you will see how the basic rules for series and parallel circuits can be applied to household use of electricity. The safe use of electricity will also be discussed, as well as the effects of electric shocks on the human body.

Parallel circuits are usually preferred over series circuits because each device in a parallel circuit can be turned on and off independently. Devices in parallel circuits also have the same voltage drop. In series circuits, on the other hand, the devices have the same current flowing through them and the voltage is shared across the circuit. If one device is switched off, all the devices go off.

FIGURE 5.1 Light-duty all-electric and plug-in hybrid vehicles (combining electric drives with combustion engines) reduce reliance on petrol, increase efficiency and reduce greenhouse gas emissions.



5.1.2 What you will learn

KEY KNOWLEDGE

After completing this topic you will be able to:

- model household (AC) electrical systems as simple direct current (DC) circuits
- explain why the circuits in homes are mostly parallel circuits.
- model household electricity connections as a simple 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 treatment of electric shock in homes and identify the approximate danger thresholds for current and duration
- apply the kilowatt-hour (kW-h) as a unit of energy.

Source: VCE Physics Study Design (2016–2021) extracts © VCAA; reproduced by permission.

PRACTICAL WORK AND INVESTIGATIONS

Practical work is a central component of learning and assessment. Experiments and investigations, supported by a **Practical investigation logbook** and **Teacher-led videos**, are included in this topic to provide opportunities to undertake investigations and communicate findings.



Resources

Digital documents Key science skills — VCE Units 1–4 (doc-31856)

Key terms glossary (doc-32182)

Practical investigation logbook (doc-32183)



To access key concept summaries and practice exam questions download and print the **studyON: Revision and practice exam question booklet** (sonr-0030).

5.2 Household electricity and usage

KEY CONCEPTS

- Model household (AC) electrical systems as simple direct current (DC) circuits.
- Explain why the circuits in homes are mostly parallel circuits.
- Model household electricity connections as a simple circuit comprising fuses, switches, circuit breakers, loads and earth.
- Apply the kilowatt-hour (kW-h) as a unit of energy.

5.2.1 Household use of electricity

Houses connected to the main electrical grid are supplied with an AC voltage of $230\text{ V}_{\text{RMS}}$ at a **frequency** of 50 Hz. The term ' $230\text{ V}_{\text{RMS}}$ ' means that the AC voltage produces the same heating effect when applied across a conductor as would a DC voltage of 230 V applied across the same conductor. The actual value of the voltage oscillates between +325 V and –325 V. 'Root mean square' (RMS) refers to the mathematical process by which the equivalent DC voltage is calculated. A 'frequency of 50 Hz' means that the full cycle is completed 50 times each second. The voltage supplied is sinusoidal in nature.

Frequency (f) is a measure of how many times per second an event happens. The unit for frequency is the hertz (Hz). One hertz means one cycle or event per second.

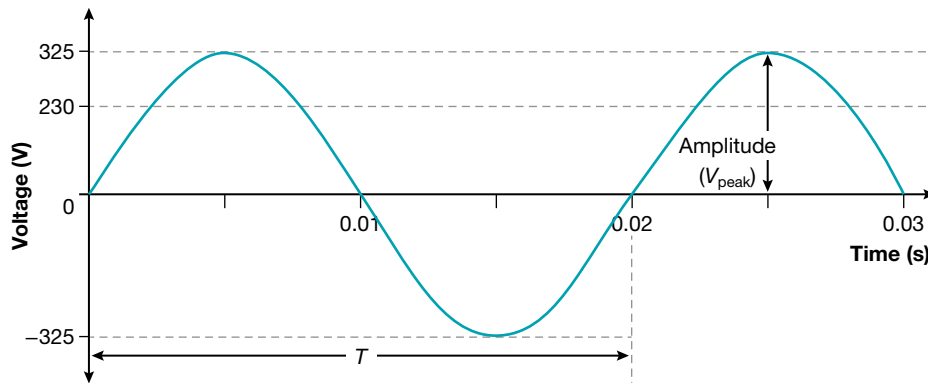
Period (T) is the amount of time one cycle or event takes, measured in seconds.

Period is the reciprocal of frequency:

$$T = \frac{1}{f} \text{ or } f = \frac{1}{T}$$

A frequency of 50 Hz means that the period is 0.02 seconds, as shown in figure 5.2.

FIGURE 5.2 The variation of voltage with time for a supply of 230 V_{RMS}, 50 Hz



Electricity is fed into the home through underground cables or overhead lines. It enters the house through a switchboard. This contains a mains switch which can cut off the supply of electricity to the house. There is also a meter that measures the amount of electrical energy transformed in the house. From the meter, the electricity enters a fuse box or circuit breaker box where it is divided among a number of parallel circuits. The role of fuses and circuit breakers is dealt with later in this topic.

The structure of household circuits differs from the structure of DC circuits studied in previous topics. Household circuits make use of the earth to complete the circuit. The **active wire** in a circuit is connected to the 230

V_{RMS} supply at the switchboard. Its voltage oscillates periodically between +340 V and -340 V relative to a reference voltage called 'earth'. The earth is defined as having a voltage of 0 V. The **neutral wire** is connected to the neutral link at the switchboard, which is connected to the earth through the supply wires and via a metal rod driven into the ground at the switchboard. The neutral wire is always at 0 V. The voltage drop between the active and the neutral wire oscillates between +340 V and -340 V.

FIGURE 5.3 Many houses have a meter and circuit breaker in their meter box. The circuit breaker is in the bottom left corner.



When an appliance is connected between the active wire and the neutral wire, current flows backwards and forwards between the active and neutral wires through the device, supplying it with energy.

Conventional current flows from a high voltage to a low voltage. When the active wire is positive, the current flows from the active to the neutral wire and so to the earth. When the active wire is negative, the neutral wire at 0 V will have the higher voltage and the current will flow from the neutral to the active wire.

In lighting circuits, only the active and neutral wires are used if there are no metal fittings. The current oscillates through the filaments of the globes, transforming energy. If metal fittings are used, they must be earthed. A typical lighting circuit is shown in figure 5.4.

In power circuits, a third wire is used. This is called the **earth wire**. It connects the case of the appliance being used to the earth as a safety device. Its function is discussed in section 5.3.8. Otherwise, a power circuit operates in exactly the same way as a lighting circuit, with the current oscillating between the active and neutral wires through the appliance. Figure 5.5 shows how three-point power sockets are connected in a typical power circuit.

FIGURE 5.4 A typical household lighting circuit

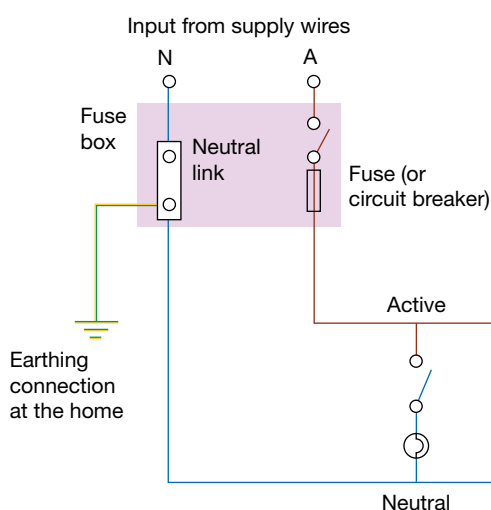


FIGURE 5.5 A typical power circuit

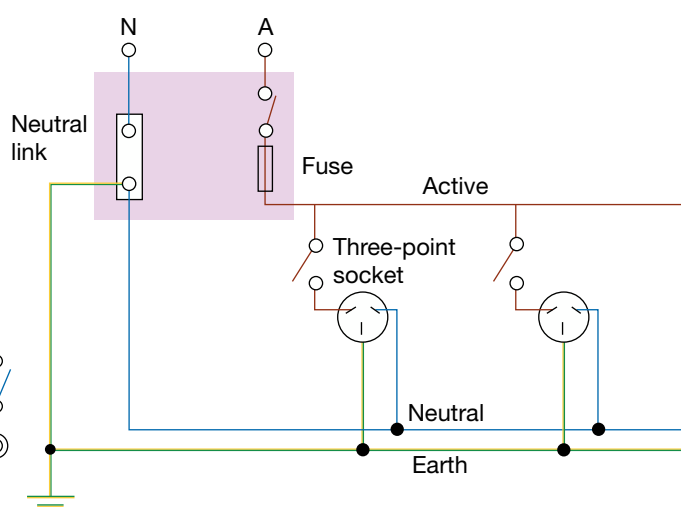
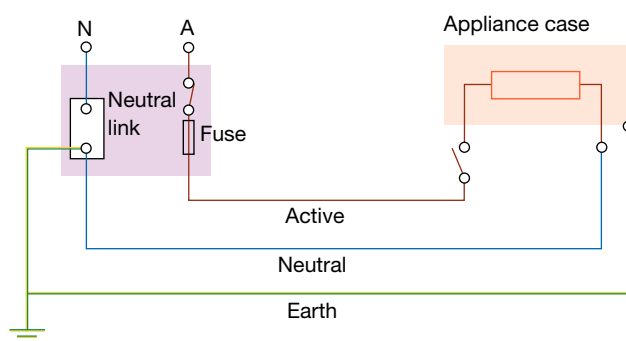


Figure 5.6 shows the connection of the earth wire to the case of an appliance.

FIGURE 5.6 The connection of the earth wire to the case of an appliance



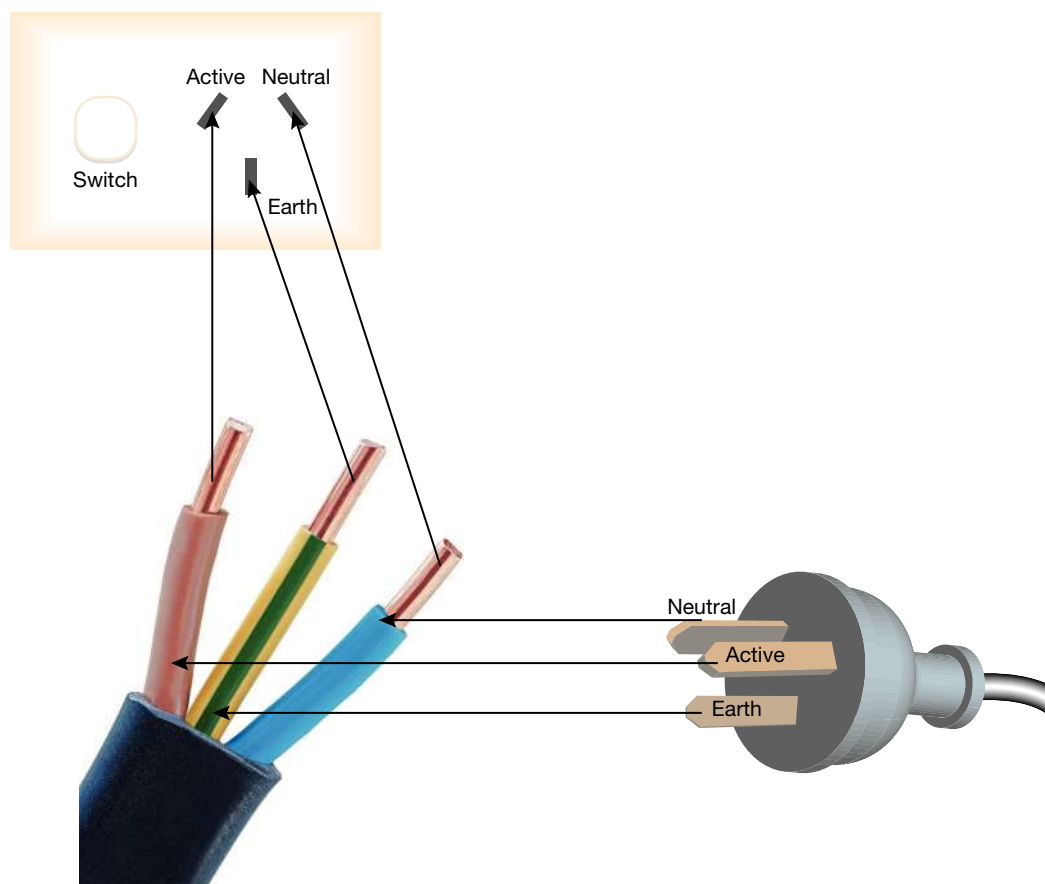
Note that in both the lighting and power circuits the switch is in the wire connecting the device to the active wire. A switch in the neutral wire would also turn off the device, but the functional parts of the device, such as the element of a toaster, would still be directly attached to the active wire and 'live'.

If you were to touch anything in contact with the active wire while you were in contact with the ground, there would be a voltage drop across you and a potentially lethal current could flow through you.

For this reason, if ever it is necessary to tamper with the functional parts of an electrical device, it must be unplugged first. The three-point socket may have been wrongly wired, and it is not worth taking the risk.

Different-coloured insulating plastic is used to distinguish the three wires from each other. In the modern system, the active wire is brown, the neutral wire is blue and the earth wire is striped green and yellow. In the old system, red was used for the active, black for the neutral and green for the earth wires.

FIGURE 5.7 A three-point socket. The top left point is the active connection (brown wire), the top right point is neutral (blue wire) and the bottom point is the earth (green/yellow wire). The switch is connected in the active wire.



5.2.2 Power ratings

The total power used in an electrical circuit, be it series or parallel, is the sum of the power used by each device in the circuit. Electrical appliances or devices are given a power rating, which is usually printed on them.

SAMPLE PROBLEM 1

A toaster is rated at 1400 W, 230 V.

- What current does the toaster draw when operating normally?
- What is the resistance of the toaster element when hot?

 **Teacher-led video:** SP1 (tlvd-0037)

THINK

1. Use the relationship between power, voltage and current to make I the subject.

WRITE

a. $P = VI$

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



2. Substitute the known values and solve for I .

$$P = 1400 \text{ W}, V = 230 \text{ V}$$

$$\begin{aligned} I &= \frac{P}{V} \\ &= \frac{1400 \text{ W}}{230 \text{ V}} \\ &= 6.09 \text{ A} \end{aligned}$$

3. State the solution.

When operating normally the toaster draws 6.09 A.

- b. 1. Use the relationship between voltage, resistance and current to make R the subject.

$$V = IR$$

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

2. Substitute the known values and solve for R .

$$V = 230 \text{ V}, I = 6.09$$

$$\begin{aligned} R &= \frac{V}{I} \\ &= \frac{230 \text{ V}}{6.09 \text{ A}} \\ &= 37.8 \Omega \end{aligned}$$

3. State the solution.

The resistance of the toaster element when hot is 37.8 Ω .

Alternatively:

1. The resistance could also have been calculated using the relationship: $P = \frac{V^2}{R}$.

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

2. Transpose to make R the subject.

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

3. Substitute in the values, $V = 230 \text{ V}$ and $P = 1400 \text{ W}$, and solve.

$$\begin{aligned} R &= \frac{230^2}{1400} \\ &= 37.8 \Omega \end{aligned}$$

PRACTICE PROBLEM 1

A compact fluorescent light globe is rated at 15 W, 230 V.

- Calculate the current through the globe when it is operating normally.
- Calculate the resistance of the globe when it is operating normally.

5.2.3 Paying for electricity

The meter on a household switchboard is used to measure how much electrical energy has been consumed on the premises. The amount of electrical energy used in a household can be determined by multiplying the rate of power transformation by the time. Since power is equal to the voltage drop multiplied by current, and the voltage drop across a household is 230 V, the meter on the switchboard records the total current that has passed through the premises over a certain period of time. This amount is converted into the amount of energy ‘consumed’ or transformed.

For domestic and commercial electrical consumption the joule is too small a measure. The unit used for measuring energy in these cases is the **kilowatt-hour** (kW-h). This is the amount of energy transformed by a 1000 W appliance when used for 1 hour.

SAMPLE PROBLEM 2

How many joules does 1 kilowatt-hour represent?

 **Teacher-led video:** SP2 (tlvd-0038)

THINK

1. Energy (kW-h) = power (kW) $\times$ time (hrs)
2. State the solution.

WRITE

$$\begin{aligned} 1 \text{ kW-h} &= 1 \text{ kW} \times 1 \text{ h} \\ &= 1000 \text{ W} \times (60 \times 60) \text{ seconds} \\ &= 3.6 \times 10^6 \text{ J} \\ &= 3.6 \text{ MJ} \\ 1 \text{ kW-h represents } 3.6 \text{ MJ.} \end{aligned}$$

PRACTICE PROBLEM 2

An oven used 8 kW-h of energy. In joules how much energy was used?

The cost to consumers of 1 kW-h of electrical energy can be found on electricity accounts. Find out what 1 kW-h of electrical energy costs in your household. To calculate the cost of running a particular appliance, calculate the energy in kW-h by multiplying the power rating of the appliance, in kilowatts, by the number of hours that it was used for.

If the power rating of the appliance is unknown the energy consumed can be found using the formula:

$$E = VIt$$

Where:

E = the energy consumed

V = the voltage drop across the device

I = the current flowing through the device

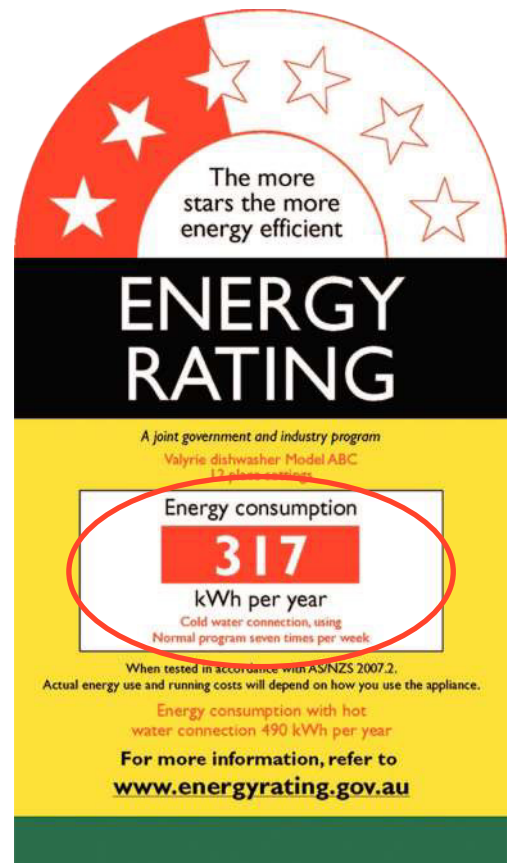
t = the time in seconds.

The amount of energy is then converted into kW-h by dividing by 3.6×10^6 .

To calculate the cost, use the formula:

$$\text{cost} = \text{energy} \times \text{rate}$$

FIGURE 5.8 Many appliances have a sticker outlining their energy rating and the average kW-h of energy consumed per year.



SAMPLE PROBLEM 3

A television draws 0.37 A of current when connected to a 230 V supply.

- What is the power rating of the television?
- How much energy does the television consume if it is operated for 5 hours a day for 4 weeks?
- What is the cost of running the television for this period of time if the consumer is charged at a rate of 16.381 cents per kW-h?

 **Teacher-led video:** SP3 (tlvd-0039)

THINK

- Substitute in $P = VI$.
 - State the solution.
- energy = power $\times$ time
 - State the solution.
- cost = energy $\times$ rate
 - State the solution.

WRITE

- $P = 230 \text{ V} \times 0.37 \text{ A}$
 $P = 85 \text{ W}$
The power rating of the television is 85 W.
- Power = 85 W
Time = 5 hours per day for 28 days
= 140 h
Energy = 85 W $\times$ 140 h
= 12 000 W-h
= 12 kW-h
The television consumes 12 kW-h if it is operated for 5 hours a day for 4 weeks.
- Cost = 12 kW-h $\times$ 16.381 cents
= 197 cents
= \$1.97
The cost of running the television is \$1.97.

PRACTICE PROBLEM 3

A home sound system consumes 2.4 W of electric power when it is on standby and connected to a 230 V supply.

- Calculate the current that flows through the system when it is on standby.
- Calculate the energy consumed by the system if it is left on standby for one week.
- Calculate the cost of leaving the system on standby for one week if electricity is priced at 12 cents per kW-h.

Resources

 **Weblink** Operating costs of electrical appliances

5.2 EXERCISE

To answer questions online and to receive **immediate feedback** and **sample responses** for every question go to your learnON title at www.jacplus.com.au.

- What is meant when it is said that a house is supplied with electricity at 230 V_{RMS}, 50 Hz?
- Why is an overload in a household circuit potentially dangerous?
- What coloured insulation is used for the active, neutral and earth wires in modern houses?
- Sketch a power point and plug. Label the active, neutral and earth in each case.
- Why do many appliances need to be connected to both the neutral and earth wires?

6. When is the earth wire used in household lighting circuits?
7. What is the cost of running a 300 W refrigerator for a year (365 days) if the refrigerator operates on average for 12 hours a day, and electricity costs 31.28 cents per kW-h?
8. The following table gives the power consumption of various products when they are on standby.

Product	Power (W)
Laptop computer	14.5
Modem	3.4
Cordless phone equipment	3.7
DVD player	2.4
Television	6.2

- (a) Calculate the energy used by each product if it is left on standby for one year.
- (b) Calculate the mass of greenhouse gases produced by these products if they are left on standby for one year, assuming that 1 kW-h of energy produces greenhouse gases that are equivalent to 1.444 kilograms of CO₂.

studyon

To answer practice exam questions online and to receive immediate feedback and sample responses for every question go to your learnON title at www.jacplus.com.au.

studyON: Practice exam questions online only

Fully worked solutions and sample responses are available in your digital formats.

5.3 Electrical safety

KEY CONCEPTS

- Compare the operation of safety devices including fuses, circuit breakers and residual current devices (RCDs).
- Describe the causes, effects and treatment of electric shock in homes and identify the approximate danger thresholds for current and duration.

5.3.1 A shocking experience

An **electric shock** is a violent disturbance of the nervous system caused by an electrical discharge or current through the body.

There are various factors that contribute to the severity of an electric shock. The first of these is the size of the voltage involved. Also, the human body is far more sensitive to alternating current than direct current. Voltages as low as 32 V AC and 115 V DC can be fatal.

It is not the voltage alone that causes damage to the human body. When you slide across a car seat, you can generate a voltage of several thousand volts. When you get out of the car and touch the ground, you are discharged and experience a shock,

FIGURE 5.9 A victim of electric shock in a home accident possibly caused by overloading the circuit



but with no serious consequences. The voltage drop across a person is one factor in determining the seriousness of an electric shock, but clearly other factors are involved.

The following information refers to shocks involving alternating currents with a frequency of 50 Hz.

5.3.2 Resistance of the human body

One contributing factor to the severity of an electric shock is the resistance of the human body. The interior of the body is a good conductor of electricity. The tissues and fluids beneath the skin conduct electricity due to the presence of ions in the fluids.

The skin provides the main resistance to the flow of electricity in the body. The resistance of the skin ranges in value from $10^6 \Omega$ for dry skin, to 1500Ω for a person with wet hands, and about 500Ω for a person sitting in a bath. This is a good reason for keeping electrical appliances away from water in the bathroom; tap water is also a reasonably good conductor.

Resistance to current flow is offered by the skin up to about 600 V, at which point the skin is punctured and offers little resistance to current flow. Breaks or cuts in the skin also reduce the resistance of the skin.

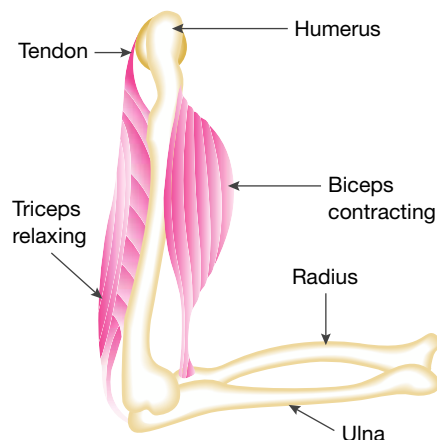
One of the main reasons for the high resistance of skin is the poor contact that is made between the skin and the electrical source. Water improves the contact. In hospitals, a conducting gel is used when a good electrical contact is required — for example, when using an electrocardiogram.

5.3.3 The effect of current

The second and most important factor to be considered in respect to the severity of an electric shock is the amount of current flowing through the body. This is important because impulses within the nervous system are themselves electrical in nature. Even very small currents passing along nerves make muscles contract. Skeletal muscles (muscles attached to the bones) work in pairs. To raise your forearm, for example, the biceps muscle contracts and the triceps muscle relaxes. To lower your forearm, the biceps muscle relaxes and the triceps muscle contracts. This arrangement of muscles is shown in figure 5.10.

One effect of passing a small current through the body is to make muscles contract. Another effect stimulates the nerves that send pain signals to the brain, causing the painful sensations associated with shocks.

FIGURE 5.10 Diagram showing the biceps and triceps in the human arm



AS A MATTER OF FACT

You may have heard of someone who received an electric shock being 'thrown across the room'. This is not due to any explosion, but to the violent contraction of the person's muscles.

A current of 9 mA AC across the chest causes shock. A current of twice that amount causes difficulty in breathing. A current of 20 mA causes muscles to become paralysed: they contract and stay contracted. A person unfortunate enough to touch a live conductor with the palm of their hand will grip onto the conductor and not be able to let go. Some electricians, if unsure whether a wire is live, may bring the back of the hand towards the wire. Any shock they receive will contract the muscles so that the hand is pulled away from the wire. This procedure is definitely not recommended.

A current as low as 25 mA through the trunk of the body can cause **fibrillation**. This is the disorganised rapid contraction of separate parts of the heart so that it pumps no blood, and death soon follows. Sometimes fibrillation subsides when the external voltage is removed.

HEART STARTER

Defibrillation is a medical intervention technique carried out on victims of heart attack. If the cardiac monitor shows that fibrillation is occurring, a current of 20 A at 3000 V is passed through the heart for about 5 milliseconds. This produces a major contraction of all the muscles in the heart, which usually jolts them back into the proper rhythm. The shock is applied above and below the heart via two large electrodes called paddles. Conducting gel is used to make good contact with the body. It is important that the operator and other staff are well insulated from the patient.

FIGURE 5.11 Automatic external defibrillators are vital to use on victims on heart attacks



5.3.4 The effect of current path

The third factor affecting the severity of an electric shock is the path of the current through the body. Respiratory arrest generally requires the current to pass through the back of the head. Ten milliamps of current through the forearm muscles make them contract sufficiently to hold the victim to any live conductor he or she is gripping. The most dangerous pathway for current is through the trunk of the body.

5.3.5 Time of exposure

The final factor contributing to the severity of a shock is the time of exposure to the current. The longer the current flows through the body, the greater the damage to tissue will be. Table 5.1 shows what effects current size and time duration have on the heart.

TABLE 5.1 Electric shock current-versus-time parameters

Current (mA)	Time (ms)	Effect
50	10–200	Usually no dangerous effect
50	> 4000	Fibrillation possible
100	10–100	Usually no dangerous effect
100	> 600	Fibrillation possible
500	> 40	Fibrillation possible

5.3.6 In the event of a shock

The first priority, when helping a victim of electric shock, is to make sure that the victim is not still connected to the electrical source. If the person is still connected and you grab them, you could be electrocuted too. (**Electrocution** is death brought about by an electrical shock.) Your muscles may contract and you will not be able to let go of the victim, becoming a victim yourself. Turn off the electric circuit or knock the victim away from the live conductor with an insulating material, for example, a wooden chair.

Artificial respiration should be given to the victim if breathing has ceased. Respiratory failure is a common cause of death among shock victims. This is true of people who have been struck by lightning also. An ambulance should be called immediately.

5.3.7 Safety in household circuits

Every year many lives are lost and much property is damaged or destroyed because of electrical ‘accidents’ or through electrical faults in both industrial and domestic situations. Accidents occur because basic safety precautions are not followed in dealing with electricity. The effects of electricity on the human body have already been discussed. This section looks at some common electrical faults and the safety devices employed to reduce the danger to people.

One common pitfall is overloading a circuit (see figure 5.12). In parallel circuits, the total current flowing in the circuit is the sum of the individual currents flowing through the devices in the circuit. Too many appliances operating on a single power circuit will produce a large current in the conducting wires. The wires will get hot and melt their insulation, potentially causing a fire in the walls or ceilings of the building.

A **short circuit** can occur when frayed electrical cords (see figure 5.13) or faulty appliances allow the current to flow from one conductor to another with little or no resistance. This allows the current to increase rapidly, with the same results as an overload.

Cheap extension cords are another source of overheating. They are not designed to carry more than 7 A safely and exceeding this amount may result in the insulation melting and allow arcing to occur.

FIGURE 5.12 Overloading of an electric circuit



FIGURE 5.13 Frayed electrical cords

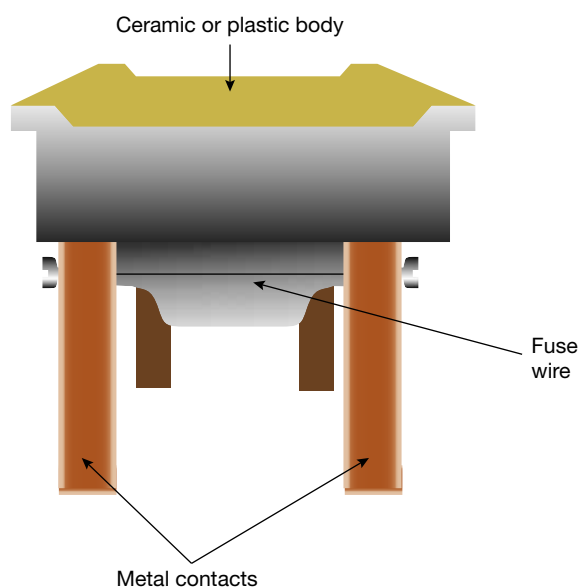


Fuses and circuit breakers

In domestic applications, each circuit is protected by either a **fuse** or a **circuit breaker**. A fuse is a short length of conducting wire or strip of metal that melts when the current through it reaches a certain value. The most common type of fuse is the plug-in type illustrated in figure 5.14. This has a ceramic body with metal prongs projecting from each end. A short piece of special fuse wire connects the metal prongs. When the current through the fuse exceeds a predetermined value, the wire melts, or ‘blows’, breaking the circuit. (Figure 5.16 shows a plug that includes a cartridge fuse.)

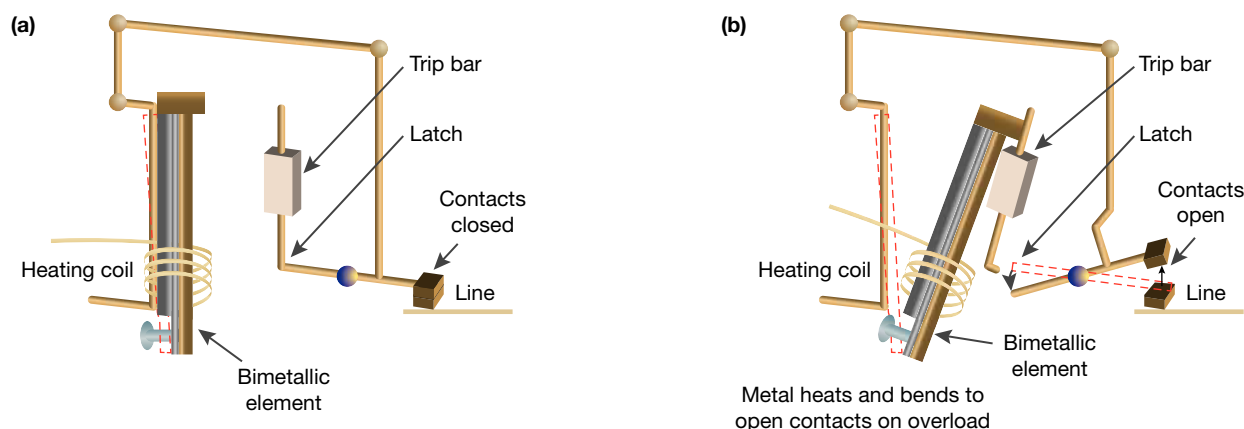
A circuit breaker carries out the same function as a fuse. It breaks the circuit when the current through the circuit exceeds a particular value. The advantage circuit breakers have over fuses is that they can be reset easily. There are two types of circuit breaker available: thermal and electromagnetic.

FIGURE 5.14 A plug-in fuse



When a current flows through a thermal circuit breaker, like the one illustrated in figure 15.15, the heating coil heats the bimetallic strip. The two metals in the bimetallic strip expand at different rates when heated, causing the strip to bend. When the current exceeds the predetermined amount, the bimetallic strip bends so much that it opens the catch and the circuit is broken. Because of the time it takes to heat up the strip, these circuit breakers will not trip if the current surge is of a short duration. This type of circuit breaker is not satisfactory if a short circuit occurs and offers little assistance in preventing electrocutions.

FIGURE 5.15 A thermal circuit breaker



The electromagnetic type uses the magnetic effects of electric currents: it uses an electromagnet to lift the catch and break the circuit. The bigger the current is in the coil, the stronger the electromagnetic force will be on the lever system. Again, these circuit breakers are designed to break the circuit at predetermined values of the current. To prevent this type of circuit breaker tripping when a short-duration current surge occurs, the switching mechanism is usually restrained in some way. The magnetic circuit breaker will trip almost instantly when a heavy overload occurs. It provides good protection against short circuits.

Both fuses and circuit breakers are placed in the active wire at the meter box. Light circuits are generally designed to take a maximum safe current of 5A, whereas power circuits have a maximum safe current of 15 A.

SAMPLE PROBLEM 4

A kitchen circuit has the following appliances operating in it: a 1000 W toaster, a 312 W refrigerator, a 1200 W kettle, a 600 W microwave oven and a 60 W juicer. The circuit is protected by a 15 A fuse and is connected to a 230 V, 50 Hz supply.

- What is the current flowing through the fuse when all the appliances are operating at the same time? Will the fuse ‘blow’?
- Will the fuse ‘blow’ if a 2400 W heater is used at the same time as the other appliances?

 **Teacher-led video:** SP4 (tlvd-0040)

THINK

- First, calculate the current through each appliance using their power ratings and the formula $P = VI$ or $I = \frac{P}{V}$.

WRITE

- Toaster:

$$I = \frac{1000 \text{ W}}{230 \text{ V}} = 4.35 \text{ A}$$

Refrigerator:

$$I = \frac{312 \text{ W}}{230 \text{ V}} = 1.36 \text{ A}$$

Kettle:

$$I = \frac{1200 \text{ W}}{230 \text{ V}} = 5.22 \text{ A}$$

Microwave oven:

$$I = \frac{600 \text{ W}}{230 \text{ V}} = 2.61 \text{ A}$$

Juicer:

$$I = \frac{60 \text{ W}}{230 \text{ V}} = 0.26 \text{ A}$$

2. The total current in the circuit is the sum of the individual currents of the appliances.
Add the currents to determine the current through the fuse. If the current is less than the capacity of the fuse, the fuse will not melt.

3. State the solution.

$$4.35 + 1.36 + 5.22 + 2.61 + 0.26 = 13.8 \text{ A}$$

The circuit is protected by a 15 A fuse, so the fuse will not melt.

- b. 1 Calculate the additional current is using $I = \frac{P}{V}$.

2. If the current is larger than 15 A it is at risk of 'blowing'.

3. State the solution.

b. $I = \frac{2400 \text{ W}}{230 \text{ V}} = 10.4 \text{ A}$

The 2400 W heater will draw an additional 10.4 A.

Total current in the circuit:

$$10.4 \text{ A} + 13.8 \text{ A} = 24.2 \text{ A}$$

24.2 A is much greater than 15 A, so the fuse will blow.

PRACTICE PROBLEM 4

A bathroom fan, light and heater system consists of one 75 W light globe, four 150 W heat lamps and one 100 W fan. It is connected to a 230 V supply.

- a. Calculate the total current through the system when the fan and light globe are in use.
b. Calculate the total current through the system when the fan and two heat lamps are in use.
c. Calculate the total current through the system when all the devices are in use.

5.3.8 Earthing

The earth wire is another safety measure used for power circuits (see figure 5.16). It connects the metal chassis of an appliance to the earth, which is at 0 V. This connection is made via a metal rod driven into the ground at the switchboard.

An electrical fault could occur if the active wire were to come into contact with the metal case of an appliance. The case would then carry an AC voltage, and anyone touching the case would receive a shock. The earth wire provides a lower resistance conducting path to the earth than the appliance and the person. The low resistance involved produces a large current in the circuit and the fuse blows or the circuit breaker trips.

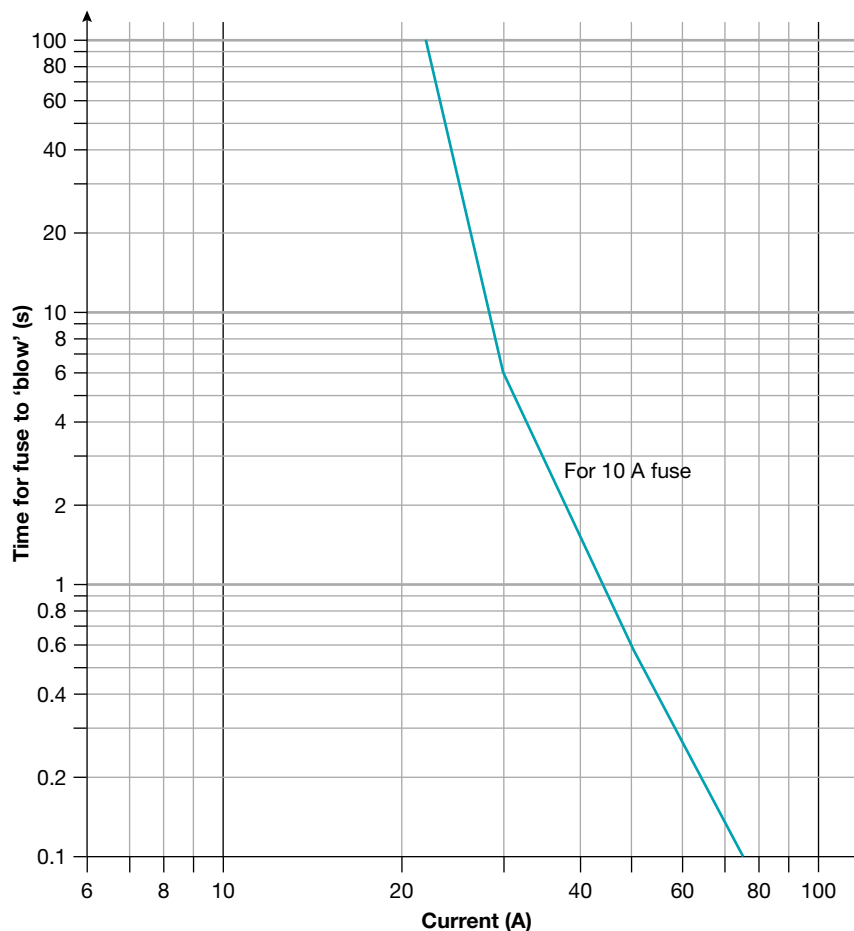
The earth wire does not provide the most reliable protection. As can be seen in figure 5.17, the amount of time it takes to blow a fuse depends on the size of the current. A quicker method of breaking the circuit is needed if lives are to be saved.

If the current is flowing through a person to the earth, the following principles should be followed: the current should be as small as possible and the time of exposure to the current should be as short as possible. Fuses are not designed to meet these requirements. Their main function is to prevent fires in buildings due to the overheating of wires when they carry too great a current.

FIGURE 5.16 A three-pin plug with its back cover removed. The earth wire is covered in a green and yellow coating. Also note the cartridge fuse inside the plug.



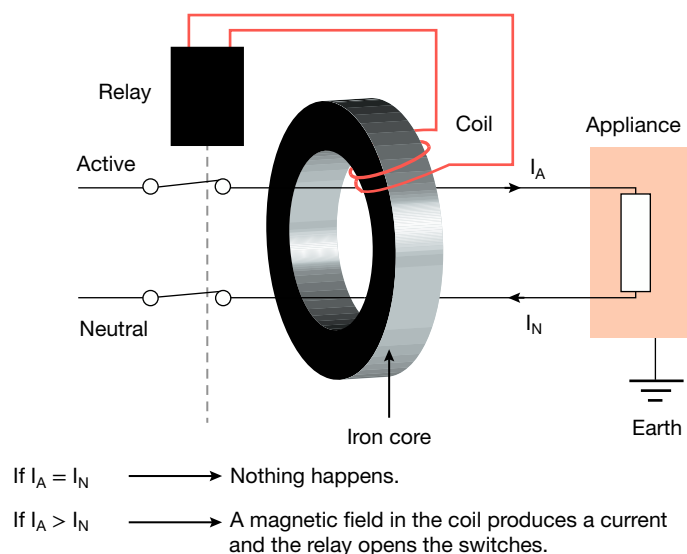
FIGURE 5.17 Time before a typical 10 A fuse 'blows', as a function of (RMS) current



5.3.9 Residual current device

The **residual current device** is illustrated in figure 5.18. It operates by making use of the magnetic effects of a current and is similar to a transformer. The current in the active wire flows in the opposite direction to the current in the neutral wire. Both currents pass through the iron loop. When the current in the active wire is equal in magnitude to the current in the neutral wire, each wire produces a magnetic field. These fields are equal in magnitude, but opposite in direction, and have no overall effect.

FIGURE 5.18 A residual current device



However, if there is an electrical fault and a residual current flows to the earth via the earth wire or a person, the current in the active will be greater than in the neutral. The residual current is the difference between the active and neutral currents. The magnetic effects of the two currents will no longer cancel. A current is then produced in the relay circuit and both the active and neutral wires of the circuit are broken by a switch.

A residual current device operates in about 40 milliseconds, limiting the current to 30 mA. At such values the shock will be perceptible, but not likely to have any harmful effects. The residual current device is useful only when the current flows to earth, not if the current flows through the person between the active and neutral wires.

5.3.10 Double insulation

Hand-held electrical tools and appliances, such as electric drills and hair dryers, are protected by double insulation. These appliances have only a two-pin plug, using only the active and neutral wires. They should not be earthed. The symbol  on the casing of an appliance means that it is double insulated.

As the name implies, double insulation means that the accessible metal parts cannot become live unless two independent layers of insulation fail. The inner layer is called the functional insulation. This layer has both electrical insulation and heat-resisting properties. The outer layer is called protective insulation and often forms part of the casing.

FIGURE 5.19 An electric hair dryer with the double insulation symbol seen on the casing



on Resources

	Digital documents	Investigation 5.1 Examination of an electrical device (doc-31869) Investigation 5.2 Model circuits (doc-31870)
	Teacher-led video	Investigation 5.1 Examination of an electrical device (tlvd-0814)
	Video eLesson	Electrical safety (eles-2517)
	Weblink	Electrical safety

5.3 EXERCISE

To answer questions online and to receive **immediate feedback** and **sample responses** for every question go to your learnON title at www.jacplus.com.au.

1. What is the difference between a shock and electrocution?
2. Describe factors that reduce the resistance of human skin.
3. Why is the amount of current flowing through the body important in determining the severity of an electric shock?
4. What is fibrillation?
5. What would happen if you touched a shock victim who was still conducting an electrical current?
6. How is the severity of a shock related to the time of exposure?
7. What is 'double insulation'?
8. A worker touched an overhead power line and was electrocuted. A newspaper reported the incident:
'He touched the cable and 50 000 V of electricity surged through his body.'

Evaluate this statement.

studyon

To answer practice exam questions online and to receive immediate feedback and sample responses for every question go to your learnON title at www.jacplus.com.au.

studyON: Practice exam questions 

Fully worked solutions and sample responses are available in your digital formats.

5.4 Review

5.4.1 Summary

- Household electricity is provided as alternating current with a frequency of 50 Hz.
- Household circuits include an active wire that oscillates between +325 and –325 volts relative to the earth, which is defined as having a voltage of zero. Household circuits also include a neutral wire, which is connected to the earth. Electric current flows backwards and forwards between the active wire and the neutral wire.
- In many circuits an earth wire is used as a safety device to connect the case of an appliance directly to the earth.
- The rules relating to series and parallel circuits can be applied to both AC and DC circuits.
- The kilowatt-hour is a unit widely used to measure the amount of electrical energy consumed.
- An electric shock is a violent disturbance of the nervous system caused by an electrical discharge or current through the body.
- The severity of an electric shock depends on a number of factors, including current, pathway through the body and time of exposure.
- Fuses and circuit breakers are safety devices that use different methods to break an electric circuit when a dangerous level of current flows through it.
- The residual current device opens switches in the active and neutral wires when the currents in these wires become unequal due to an electrical fault. It is designed to protect against electrocution and operates more quickly than a typical fuse.

To access key concept summaries and practice exam questions download and print the **studyON: Revision and practice exam question booklet** (sonr-0030).

5.4.2 Key terms

The **active wire** in a circuit is connected to the 240 V_{RMS} supply at the switchboard.

A **circuit breaker** carries out the same function as a fuse by breaking the circuit when the current through it exceeds a certain value.

The **earth wire** is used in power circuits as a safety device; it connects the case of the appliance being used to the earth.

An **electric shock** is a violent disturbance of the nervous system caused by an electrical discharge or current through the body.

Electrocution is death brought about by an electrical shock.

Fibrillation is the disorganised, rapid contraction of separate parts of the heart so that it pumps no blood; death may follow.

Frequency is a measure of how many times per second an event happens.

A **fuse** is a short length of conducting wire or strip of metal that melts when the current through it reaches a certain value, breaking the circuit.

A **kilowatt-hour** (kW-h) is the amount of energy transformed by a 1000 W appliance when used for one hour.

The **neutral wire** in a circuit is connected to the neutral link at the switchboard, which is connected to the earth.

Period is the amount of time one cycle or event takes, measured in seconds.

A **residual current device** operates by making use of the magnetic effects of a current to break a circuit in the event of an electrical fault.

A **short circuit** can occur when frayed electrical cords or faulty appliances allow the current to flow from one conductor to another with little or no resistance. The current increases rapidly, causing the wires to get hot and potentially cause a fire.

 **Digital documents** Key terms glossary (doc-32182)

5.4.3 Practical work and investigations

Investigation 5.1

Examination of an electrical device

Aim: To examine an electrical device and report on how it functions and what safety features it has

Digital document: doc-31869

Teacher-led video: tlvd-0814



Investigation 5.2

Model circuits

Aim: To apply the principles of series and/or parallel circuits to either household or car electrical systems through designing a circuit

Digital document: doc-31870

 **Digital documents** Practical investigation logbook (doc-32181)

5.4 Exercises

To answer questions online and to receive **immediate feedback** and **sample responses** for every question go to your learnON title at www.jacplus.com.au.

5.4 Exercise 1: Multiple choice questions

1. Which colour wire carries the larger voltage in an electrical cable connected to a 230V AC supply?
 - A. All carry the same voltage.
 - B. Green and yellow stripes
 - C. Brown
 - D. Blue
2. Which best describes the reason for building fuses into electrical devices?
 - A. Fuses are not used in electrical devices.
 - B. To protect the device from damage
 - C. To protect the circuit from current overload
 - D. To protect against electric shock
3. Under what condition is a fuse in a circuit most likely to blow?
 - A. When the current is too large
 - B. When the voltage is too large
 - C. When the current is too small
 - D. When the voltage is too small
4. Which statement best describes the function of a circuit breaker?
 - A. A circuit breaker diverts excess current to other parts of the circuit.
 - B. A circuit breaker is a resettable switch.
 - C. A circuit breaker comprises many fuses that are resettable.
 - D. A circuit breaker must be replaced after a circuit has blown.
5. What current is drawn by a 1.84 kW sandwich maker when it is connected to a 230 V supply?
 - A. 0.3 A
 - B. 2.8 A
 - C. 8.0 A
 - D. 14.7 A
6. When charged at 30 cents per kW-h, what will be the cost of leaving a 250 W computer switched on for two days?
 - A. \$1.80
 - B. \$3.60
 - C. \$5.40
 - D. \$7.20
7. An electric handtool with a power rating of 2 kW has a built-in fuse. Which of the following fuses would be most suitable?
 - A. 3 A
 - B. 5 A
 - C. 7 A
 - D. 9 A
8. Which of the following correctly describes the appearance and function of the earth wire?
 - A. It is coated in blue plastic and connects the appliance to the earth.
 - B. It is coated in brown plastic and provides a lower resistance conducting path to the earth than the appliance and the person.
 - C. It is coated in green and yellow plastic and connects the case of the appliance being used to the earth as a safety device.
 - D. It is coated in green plastic and is a safety measure in electric circuits.

9. Many hair dryers have a double insulation symbol () found on them. What does it mean for a hair dryer to have double insulation?
 - A. It has a two-pin plug with no neutral wire.
 - B. There are two layers that separate the live wire and the external metal casings.
 - C. There is a single insulating layer coating the wire, but it is double thickness.
 - D. It has double the number of wires than usual (two neutral, two earth and two live).
10. What is the first priority when someone is a victim of electric shock?
 - A. Calling an ambulance
 - B. Making sure the victim is not still connected to the electric source
 - C. Giving immediate CPR
 - D. Making sure that a defibrillator is available

5.4 Exercise 2: Short answer questions

1. A 3.6 kW domestic electric hot water system typically heats water for 3 hours per day.
 - a. How much energy will this appliance consume in one year?
 - b. If the cost of electricity is 28 cents per kW-h, how much will it cost to provide hot water for one year?
2. Two 10 A speakers are connected to a 230 V sound system.
 - a. Should these speakers be connected in series or parallel? Justify your answer.
 - b. How much power will these speakers use?
 - c. If the cost of electricity is 32 cents per kW-h, how much will it cost to operate the speakers at full volume for 6 hours?
 - d. There is a fuse in each speaker. What size fuse should be used? Justify your answer.
3. An oil heater is rated at 1000 W and runs off 230 V supply.
 - a. What current does the heater draw?
 - b. What is the effective resistance of the heater?
 - c. If electricity costs 17 cents per kW-h, what does it cost to run the heater for 5 hours?
4. Some household appliances such as electric kettles are encased with metal. When a person touches the metal casing they do not get a shock.
 - a. What stops someone from getting a shock when they touch the metal casing?
 - b. If someone did get a shock, why would this occur?
5.
 - a. What is meant by the terms electric shock and electrocution?
 - b. Under what circumstances is an electric shock likely to be fatal?
6. Describe the difference in operation and advantages of a fuse in a circuit and a circuit breaker.
7. A bedroom circuit has the following appliances operating in it: a 150 W gaming console, a 140 W television, a 60 W lamp, a 55 W DVD player and a 200 W mini fridge. The circuit is protected by a 15 A fuse and it is connected to a 230 V, 50 Hz supply.
 - a. What is the current flowing through the fuse when all the appliances are operating at the same time?
 - b. Will the fuse 'blow' if a 2400 W air conditioner is used at the same time as the other appliances?
8. Why is the length of time a current is flowing through the body important in determining the severity of an electric shock?
9. An individual uses a hair dryer immediately after getting out of the shower to dry their hair, with their hands still wet. Explain why having wet hands leads to a greater risk of electric shock than having dry hands.
10. Compare the operation of residual current devices and circuit breakers and how they improve safety of electrical circuits.

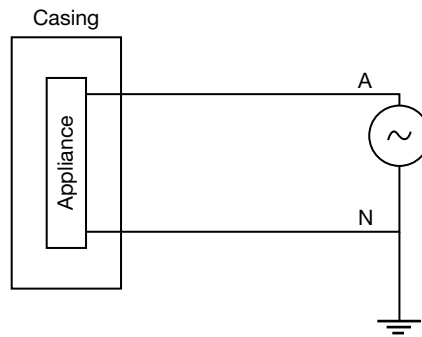
5.4 Exercise 3: Exam practice questions

Question 1 (3 marks)

A person is holding an electric appliance that is connected to a 230 V AC supply. If the insulation between the case and the rest of the appliance is short circuited, the person could receive an electric shock. Describe the factors that will determine the severity of the shock they could receive?

Question 2 (5 marks)

An appliance with a metal case is unsafely wired directly into a simple AC circuit as shown in the following figure.

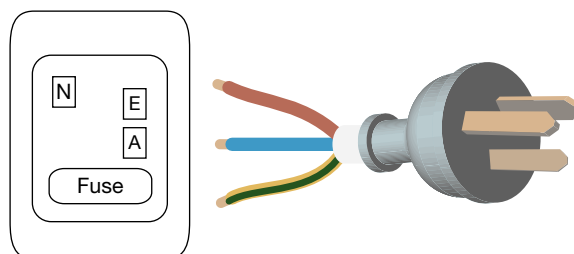


- a. On the diagram show what safety features should be provided to help avoid electric shocks and possible damage to the appliance. **3 marks**

- b. For the safety features you identify, explain how they improve the safety of the system. **2 marks**

Question 3 (3 marks)

The metal cased appliance in question 2 is to be re-wired to a three-pin plug so that it can be plugged into a domestic 230 V AC socket. On the following diagram show where each wire should be connected to the appliance.



Question 4 (6 marks)

The following table gives the power consumption of various products when they are on standby.

Product	Power (W)
Laptop computer	14.5
Microwave	4.2
Laser printer	8.5
Set top box	11.2
Television	6.2

- a. Calculate the energy used by each product if it is left on standby for one year. **3 marks**
- b. Calculate the mass of greenhouse gases produced by these products if they are left on standby for one year, assuming that 1 kW-h of energy produces greenhouse gases that are equivalent to 1.444 kg of CO₂. **2 marks**
- c. If you were charged 50 cents per kW-h, how much would you be required to pay in one year if the devices were left on standby? **1 mark**

Question 5 (5 marks)

A person stands on a rubber mat that connects an electric appliance to a 230 V mains power outlet. However, the appliance, which has a metal casing, has short circuited.

- a. What is likely to happen if the person has a resistance of 600 k Ω ? Justify your answer. **2 marks**
- b. What is the smallest voltage on the case of the appliance that could cause fibrillation of the heart? **1 mark**
- c. What would most likely happen if the person stands on a wet floor in bare feet where their resistance is effectively 3 k Ω ? Justify your answer. **2 marks**

5.4 Exercise 4: studyON topic test online only

Fully worked solutions and sample responses are available in your digital formats.

teachon

Test maker

Create unique tests and exams from our extensive range of questions, including practice exam questions.
Access the assignments section in learnON to begin creating and assigning assessments to students.

UNIT 1 | AREA OF STUDY 2 REVIEW

AREA OF STUDY 2

How do electric circuits work?

OUTCOME 2

Investigate and apply a basic DC circuit model to simple battery-operated devices and household electrical systems, apply mathematical models to analyse circuits, and describe the safe and effective use of electricity by individuals and the community.

PRACTICE EXAMINATION

STRUCTURE OF PRACTICE EXAMINATION		
Section	Number of questions	Number of marks
A	20	20
B	3	20
Total		40

Duration: 50 minutes

Information:

- This practice examination consists of two parts. You must answer all question sections.
- Pens, pencils, highlighters, erasers, rulers and a scientific calculator are permitted.
- You may use the VCAA Physics formula sheet for this task.



Resources



Weblink VCAA Physics formula sheet

SECTION A — Multiple choice questions

All correct answers are worth 1 mark each; an incorrect answer is worth 0.

1. Students in a class are each provided with a battery. Each battery has an emf of 15 V. In an experiment, a student measured that a total 375 C of charge has passed through her battery. How much energy has been supplied by the battery to these charges?

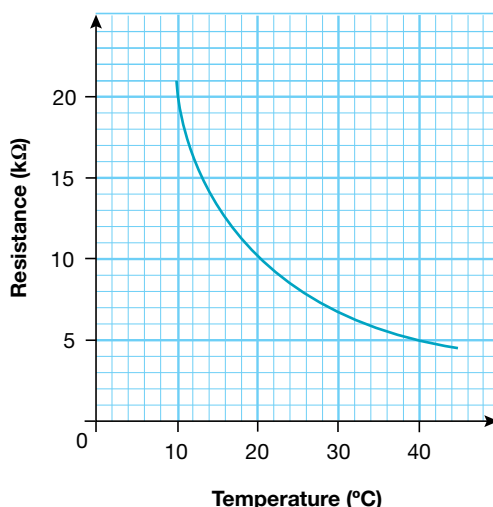
- A. 1625 J
- B. 2650 J
- C. 5625 J
- D. 6250 J

Use the following information to answer questions 2 and 3.

A model electric motor is connected with a 12 V battery. When the motor is running normally, the current through the motor is measured to be 2.5 A.

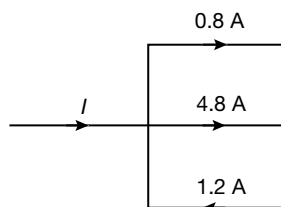
2. What is the resistance of the motor?
- A. 2.0 Ω
 - B. 4.8 Ω
 - C. 7.2 Ω
 - D. 9.6 Ω

3. How much energy was consumed by the electric motor after 30 seconds?
 - A. 75 J
 - B. 360 J
 - C. 720 J
 - D. 900 J
4. An electrical pump operating normally has 9 A of current flowing through it. The electrical resistance of the pump is $8\ \Omega$. Which of the following is the best estimate of its power?
 - A. 72 W
 - B. 576 W
 - C. 648 W
 - D. 764 W
5. Anja and Cris are provided with a thermistor for a physics investigation. The characteristic curve of the thermistor is shown as follows.



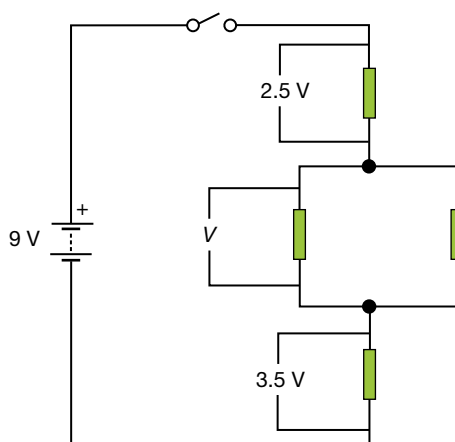
- They measured the resistance of the thermistor when the temperature is $25\ ^\circ\text{C}$. What is the expected value of the resistance?
- A. 5 kΩ
 - B. 8 kΩ
 - C. 12 kΩ
 - D. 15 kΩ
6. An LED is connected in series with a $290\ \Omega$ resistor and a 9.0 V battery. The diode has a switch-on voltage of 3.20 V and is forward-biased in this circuit. Which of the following is the best estimate of the current in the circuit?
 - A. 2.0 mA
 - B. 11 mA
 - C. 20 mA
 - D. 31 mA
 7. An ohmic device with a resistance of $7.5\ \Omega$ is connected to a circuit, and the current through the device and the voltage across it are measured. Which of the following combination of voltage and current could be approximate readings of this set up?
 - A. $V = 20.0\ \text{V}$ and $I = 3.2\ \text{A}$
 - B. $V = 24.0\ \text{V}$ and $I = 4.2\ \text{A}$
 - C. $V = 28.8\ \text{V}$ and $I = 3.8\ \text{A}$
 - D. $V = 32.4\ \text{V}$ and $I = 4.8\ \text{A}$

8. The following diagram shows part of an electrical circuit with the values of the current in different parts of the circuit.



Which of the following is closest to the value of the current I ?

- A. 3.6 A
 - B. 4.4 A
 - C. 5.6 A
 - D. 6.8 A
9. The following diagram is a battery circuit. When the switch is closed, the voltages across the different resistors are shown on the diagram.



Which of the following is closest to the value of the voltage V ?

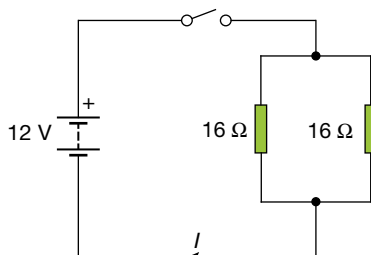
- A. 2.5 V
- B. 3.0 V
- C. 3.5 V
- D. 4.0 V

Use the following information to answer questions 10 and 11.

Charlene and Deen found a box full of electrical resistors with resistances of either $7\ \Omega$ or $12\ \Omega$. There are no other types of resistors. They decide to construct an electrical circuit with a laboratory power supply and connecting wires.

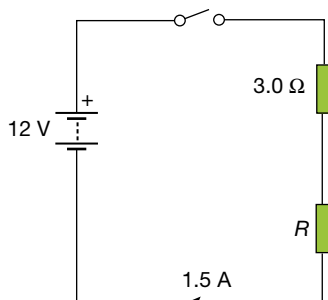
10. Charlene and Deen connected a $7.00\ \Omega$ resistor and a $12.0\ \Omega$ resistor in parallel and measured their total resistance. Which of the following is closest to the value of the reading on the resistance meter?
- A. $4.42\ \Omega$
 - B. $5.42\ \Omega$
 - C. $6.42\ \Omega$
 - D. $7.42\ \Omega$

11. One electrical circuit requires a resistance of $20.0\ \Omega$. Which of the following combination of $7.00\ \Omega$ and $12.0\ \Omega$ resistors could give them the required $20.0\ \Omega$?
- Series connection of a $7.00\ \Omega$ and $12.0\ \Omega$ resistors
 - Parallel connection of two $7.00\ \Omega$ resistors, then in series with a $12.0\ \Omega$ resistor
 - Parallel connection of two $12.0\ \Omega$ resistors, then in series with a $7.00\ \Omega$ resistor
 - Parallel connection of two $12.0\ \Omega$ resistors, then in series with two $7.00\ \Omega$ resistors
12. The following circuit shows a 12 V battery connected with two parallel resistors, each with a resistance of $16\ \Omega$.



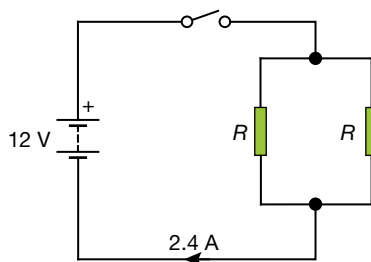
Which of the following is closest to the value of the current, I ?

- 0.75 A
 - 1.5 A
 - 3.0 A
 - 4.5 A
13. The following circuit shows a 12 V battery connected in series with a $3.0\ \Omega$ resistor and another resistor with an unknown resistance, R . The current, I , is 1.5 A .



Which of the following is closest to the value of R ?

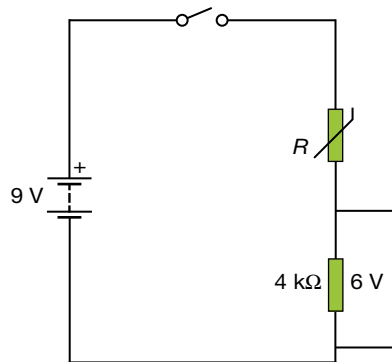
- $4.0\ \Omega$
 - $5.0\ \Omega$
 - $6.0\ \Omega$
 - $8.0\ \Omega$
14. The following circuit shows a 12 V battery connected with two parallel resistors, each of which has an unknown resistance, R . The current, I , is 2.4 A .



Which of the following is closest to the value of R ?

- A. $7.2\ \Omega$
- B. $8.4\ \Omega$
- C. $10\ \Omega$
- D. $14\ \Omega$

15. The following circuit is a voltage divider circuit with a 9 V battery connected to a thermistor in series with a $4\ \text{k}\Omega$ resistor. The output voltage, V_{out} , is 6 V.



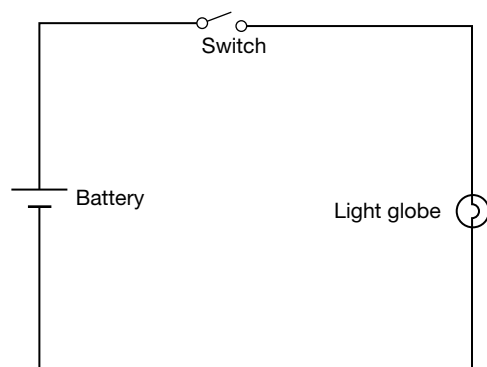
Which of the following is closest to the value of the resistance of the thermistor, R ?

- A. $1\ \text{k}\Omega$
 - B. $2\ \text{k}\Omega$
 - C. $3\ \text{k}\Omega$
 - D. $4\ \text{k}\Omega$
16. The Australian Standards specify that the AC electrical supply to households has a root mean square voltage of 230 V. What does this mean in relation to the power supply?
- A. It has a peak voltage of 230 V.
 - B. It has a peak-to-peak voltage of 460 V.
 - C. It will provide the same heating effect as an DC supply of 325 V.
 - D. It will provide the same heating effect as an DC supply of 230 V.
17. What colour is the active wire in household electrical wiring?
- A. Blue
 - B. Brown
 - C. Green and yellow
 - D. Red
18. A dishwasher is rated at 1800 W and is operated for 2.5 hours. The cost of energy is 30 cents per kW-h. How much does it cost to operate the dishwasher?
- A. 75 cents
 - B. 135 cents
 - C. 75 000 cents
 - D. 135 000 cents
19. What is the operating principle of a residual current device (RCD)?
- A. It measures the difference between the current of the active wire and the current of the neutral wire.
 - B. It melts due to the dangerously high current.
 - C. It provides an alternative path to current that flows through the casing of an electrical appliance.
 - D. It activates an electromagnet to switch off the circuit.
20. Which of the following values is in the range of the electrical resistance of a dry hand?
- A. $500\ \Omega$
 - B. $2000\ \Omega$
 - C. $500\ \text{k}\Omega$
 - D. $2\ \text{M}\Omega$

SECTION B — Short answer questions

Question 1 (8 marks)

Consider the following circuit.



A battery is connected to a light globe and a switch. The emf of the battery is 4.2 V. The switch is currently open.

a. What is the voltage across the switch? **1 mark**

The switch is now closed. During each second, 1.4 C of charge pass through the battery when the switch closed.
 $1\text{C} = 6.24 \times 10^{18}$ electrons.

b. What is the current flowing out of the battery? **1 mark**

c. How much energy does the battery supply to each coulomb of charge? **1 mark**

d. State the potential difference across the switch when it is closed. **1 mark**

e. Calculate the number of electrons that flow through the battery each second. **1 mark**

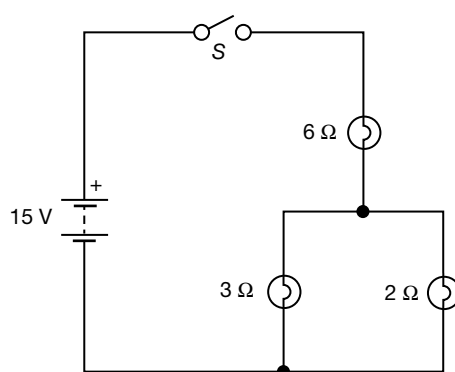
f. What is the power that the battery is transferring to the circuit? **1 mark**

g. How much electrical potential energy is transformed into light and heat by the globe in 3 minutes? **1 mark**

h. Calculate the resistance of the light globe. **1 mark**

Question 2 (8 marks)

Consider the following circuit where a 15 V battery is connected to a switch S and there are three light globes with the labelled resistances.



a. Determine the total resistance of the circuit.	2 marks
b. Calculate the current flowing through the $6\ \Omega$ light globe.	2 marks
c. What is the potential difference across the $2\ \Omega$ light globe?	2 marks
d. Find the current flowing through the $3\ \Omega$ light globe.	1 mark
e. Calculate the power supplied by the battery.	1 mark

Question 3 (4 marks)

An electrician decided to break open an old toaster and examine the various safety features.

- a. Within the plug, he noted the presence of an earth wire. Describe the appearance of the earth wire, and explain how this works as a safety feature. **2 marks**

The electrician decides the toaster is still fine to use and plugs it back into his kitchen circuit. The circuit already has a 500 W fridge, a 800 W coffee machine and a 1000 W fan plugged into it. This is connected to a 230 V supply and protected by a 10.5 A fuse.

- b. If the toaster is 700 W, will the fuse blow when the toaster is added to the circuit? Justify your response using calculations. **2 marks**

ASSESSMENT TASK — PROPOSED SOLUTION TO A SCIENTIFIC OR TECHNOLOGICAL PROBLEM

In this task, you will be required to investigate and apply a basic DC circuit model to household electrical systems, apply mathematical models to analyse circuits and describe the safe and effective use of electricity by individuals.

- A scientific calculator is permitted.

Total time: 50 minutes (5 minutes reading and 45 minutes writing)

Total marks: 40 marks

SUPPLYING ELECTRICAL POWER TO A SHED

A farmer, Alisa, is considering how to supply electrical power to a shed containing farming equipment. The farming equipment is designed to work safely from a power supply with a voltage of 30 V to 50 V DC.

The main problem is that the shed is 1 kilometre from the power lines that service her farmhouse. Alisa has two choices:

1. to purchase a generator and position it next to the shed
2. to construct additional power lines that connect the shed to the existing power lines that service her farmhouse.

Part A: Using a generator

A review of generators shows that they come with different attributes, which need to be analysed to assist Alisa in solving her problem.

1. One generator states that it is an AC generator while a second model states that it is a DC generator. In what way are the two generators different in terms of the electrical current they produce when connected to a load such as a piece of farming equipment?

Alisa reviews two DC generators, X and Y, as a possible solution to her problem.

2. Alisa finds that DC generator X outputs a voltage of 32 V, while generator Y outputs a voltage of 48 V. Explain how the generators differ by clearly explaining in terms of energy transfer what the different voltages mean.
3. Each generator has a cut-off safety switch if the current drawn exceeds the maximum specified current. The maximum current of the 32 V generator is 36 A and is slightly lower in the 48 V generator, at 32 A. Which generator, X or Y, is capable of producing the greatest power output at maximum current? Use an appropriate calculation to support your choice.
4. What would be the electrical resistance of farming equipment if 36 A were drawn from the 32 V generator?
5. What would be the electrical resistance of farming equipment if 32 A were drawn from the 48 V generator?

Alisa measures the electrical resistance of the farming equipment and finds it to be $1.20\ \Omega$.

6. If Alisa connected the farming equipment to each of the generators in turn, what current would each generator supply to the equipment?
7. (a) How much power would the farming equipment consume when using the 32 V generator?
(b) How much power would the farming equipment consume when using the 48 V generator?
(c) The farming equipment is required to run for 8 hours per day. What is the total energy delivered to the farming equipment if generator X is used? Express your answer in joule and kW-h.
8. (a) Is there a problem using either of the generators with the existing farming equipment?
(b) Of the two generators she has reviewed, which one would be more suitable? Explain your choice.

Part B: Using power lines

The potential difference of the power lines to Alisa's farmhouse is 240 V DC. It would normally be an AC voltage, but for this assessment we will simplify the task and make the voltage a 240 DC voltage.

9. If Alisa is to use power lines, how much cable (in km) will she need to supply electricity to the shed from her farmhouse?



10. She finds that she can purchase the cable, but it has a resistance of $1.60\ \Omega$ per km. What would be the total resistance of the power lines?
11. Draw a circuit of a 240 V DC power supply and power lines that connects to the farming equipment. In your diagram include a switch S that can isolate the farming equipment from the 240 V power supply. Alisa has previously measured the resistance of the farming equipment to be $1.20\ \Omega$.
12. What would be the total resistance of the circuit containing the power lines and the farming equipment?
13. Determine the current that would be in the circuit if the switch S were closed and the farming equipment turned on.
14. (a) By determining the voltage across the farming equipment, if the switch were closed, assess whether the system would be safe. Remember that the farming equipment is designed to operate safely with a voltage of between 30 V and 50 V.
(b) If you find the system would not be safe, give one possible modification that would change the situation and explain how it would enable this. If you find the system would be safe to operate, explain why.

Part C: Proposing a solution

15. Sum up your findings from Part A and B, identifying which of the two choices you would recommend to solve Alisa's problem. Justify your response ensuring you compare both choices.



Resources



Digital document School-assessed coursework (doc-32274)

6 Origins of atoms

6.1 Overview

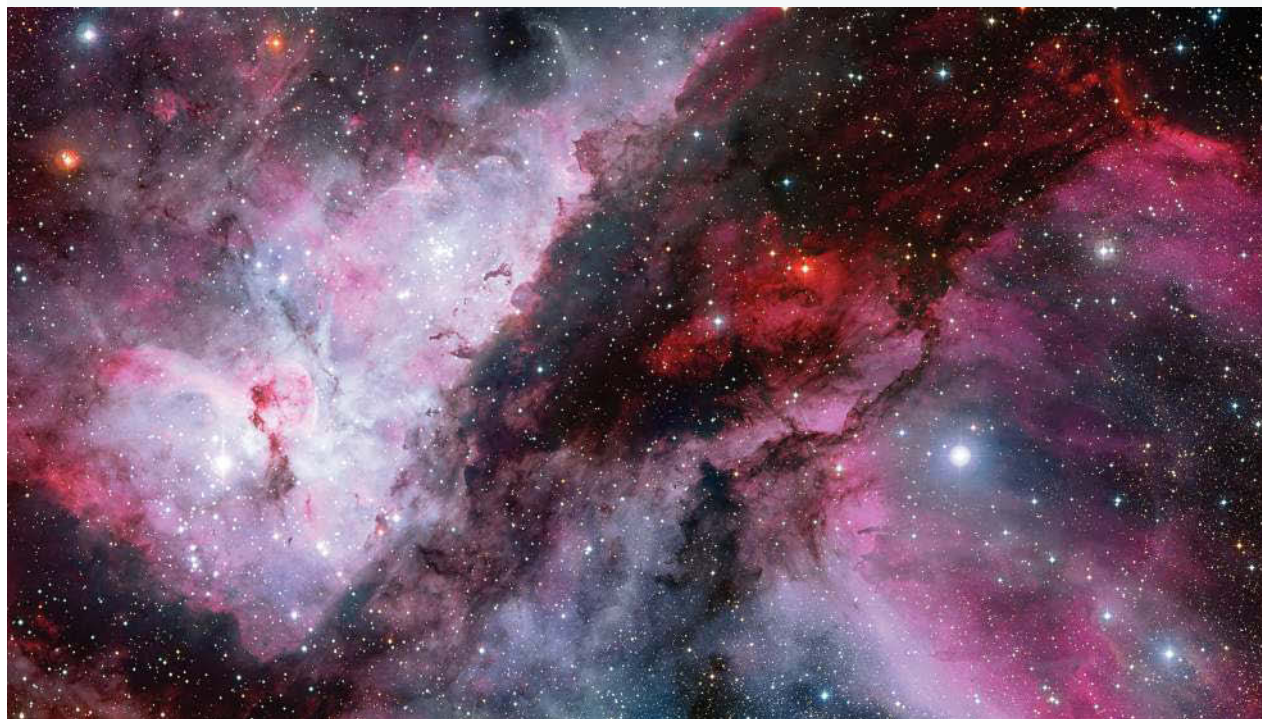
Numerous **videos** and **interactivities** are available just where you need them, at the point of learning, in your digital formats, learnON and eBookPLUS at www.jacplus.com.au.

6.1.1 Introduction

Scientists find it useful to analyse matter in terms of the atoms that form it. This is the basis of chemistry, and our understanding of biology and geology. These atoms contain a dense nucleus of protons and neutrons surrounded by a cloud of electrons. But atoms did not always exist; they only exist under the right conditions. Through an amazing journey of exploration, physicists are now confident that the first atoms formed about 13.8 billion years ago, a mere 380 000 years after the universe itself came into being. This topic explores how physicists have come to this conclusion.

To understand the origin of atoms, we need to understand how the universe began. The Big Bang is the name given to the theory that scientists use to explain why the universe is as it is. The Big Bang model of the universe is a triumph of decades of observation, measurement, theory and scientific exploration. However, there is still a lot that is not known, and there are alternative interpretations. The universe is a very active research field with new and surprising discoveries being made and new questions being asked.

FIGURE 6.1 Spectacular panoramic view of the Carina nebula and the unique star Eta Carinae in the heart of the nebula



6.1.2 What you will learn

KEY KNOWLEDGE

After completing this topic you will be able to:

- describe the Big Bang as a currently held theory that explains the origins of the universe
- describe the origins of both time and space with reference to the Big Bang Theory
- explain the changing universe over time due to expansion and cooling
- apply scientific notation to quantify and compare the large ranges of magnitudes of time, distance, temperature and mass considered when investigating the universe
- explain the change of matter in the stages of the development of the universe including inflation, elementary particle formation, annihilation of anti-matter and matter, commencement of nuclear fusion, cessation of fusion and the formation of atoms.

Source: VCE Physics Study Design (2016–2021) extracts © VCAA; reproduced by permission.

PRACTICAL WORK AND INVESTIGATIONS

Practical work is a central component of learning and assessment. Experiments and investigations, supported by a **Practical investigation logbook** and **Teacher-led videos**, are included in this topic to provide opportunities to undertake investigations and communicate findings.



Resources



Digital documents Key science skills — VCE Units 1–4 (doc-31856)

Key terms glossary (doc-32184)

Practical investigation logbook (doc-32185)



To access key concept summaries and practice exam questions download and print the **studyON: Revision and practice exam question booklet** (sonr-0031).

6.2 Early developments of the Big Bang Theory

KEY CONCEPTS

- Describe the Big Bang as a currently held theory that explains the origins of the universe.
- Describe the origins of both time and space with reference to the Big Bang Theory.
- Explain the changing universe over time due to expansion and cooling.

6.2.1 Scientific theories

A theory in science is not a wild guess. It is the best attempt by scientists to explain the results of experiment and observation. In this subtopic we look at the major evidence about the nature of the universe and the particles of matter that form it. This evidence is used by scientists to form what is known as the Big Bang Theory. A good theory can be tested by observation and often helps scientists predict phenomena yet to be observed. The Big Bang Theory has allowed scientists to explain observations of the universe and make successful predictions of what would be observed in the future.

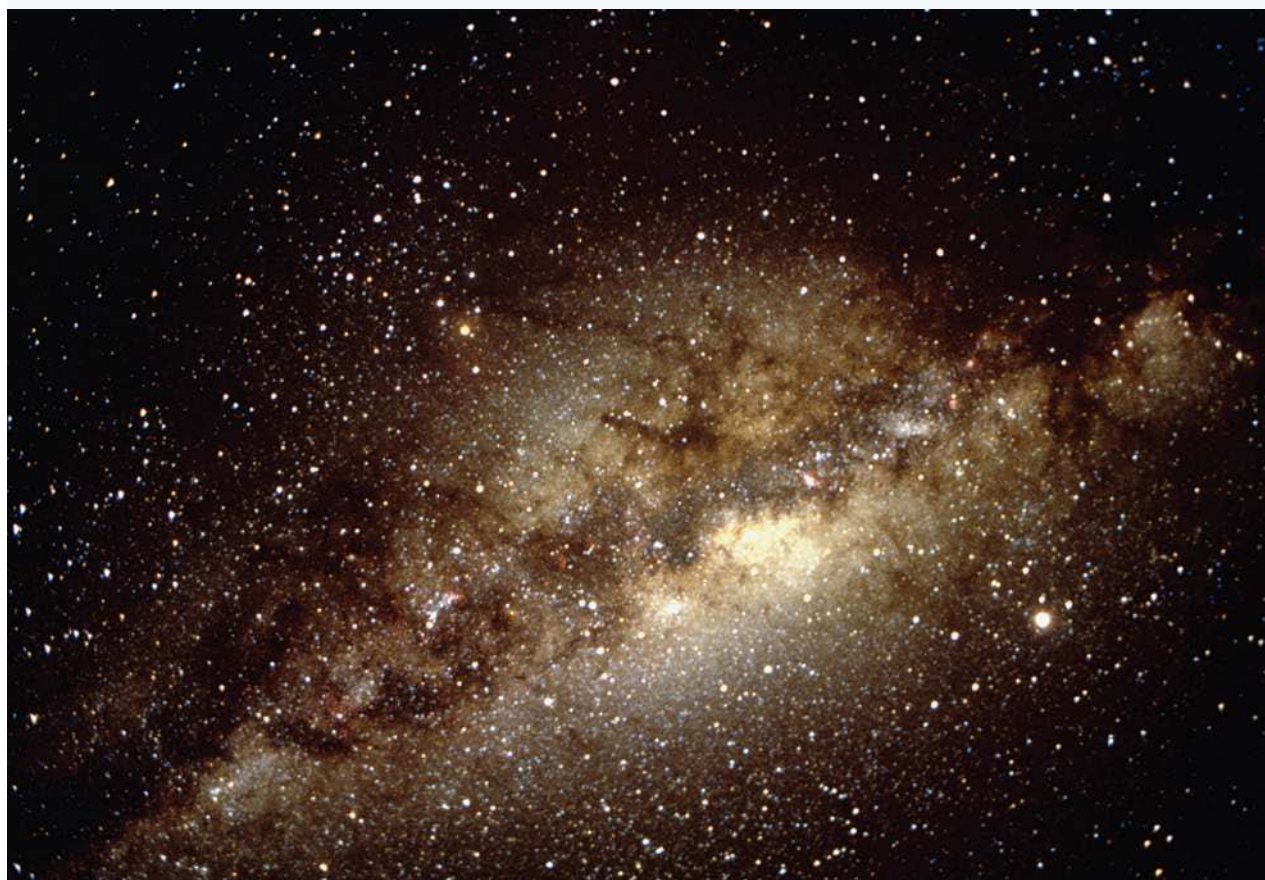
6.2.2 Discovering the universe of galaxies

In the early twentieth century, significant progress was made in our understanding of atoms and subatomic particles with the discovery of the nuclear atom, made up of protons, neutrons and electrons. At the same time, our understanding of the universe was advancing at a tremendous pace. At the turn of the twentieth century, there was little comprehension of how large the universe was. Astronomers knew there were a very large number of stars and that these stars seemed to be clustered into a region of space known as the Milky Way. It was not yet clear whether the Milky Way was the extent of the universe, or just one population of stars among many.

FIGURE 6.2 The Big Bang Theory of the universe is a triumph of decades of observation.



FIGURE 6.3 The Milky Way



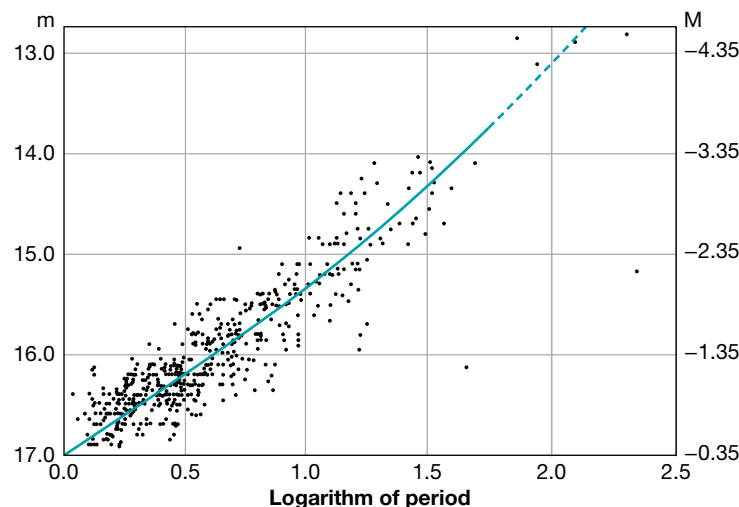
In 1912, Henrietta Leavitt (1868–1921) made a discovery that was about to shine light on this. She investigated a type of star called a **Cepheid variable**. These stars vary in brightness overtime in a regular way. Leavitt studied the two clouds of stars called the Large Magellanic Cloud and the Small Magellanic Cloud. She reasoned that the stars in each of these ‘clouds’ would all be approximately the same distance from us, meaning that any variation in their brightness could be attributed to an actual difference in luminosity, rather than just being the result of varying distance. As with all light sources, stars become dimmer the further away they are. Working with the stars from the Magellanic Clouds proved to be a very powerful technique. Leavitt plotted a graph of the maximum luminosity of the stars versus the period of their variation in brightness. She discovered a clear relationship between the luminosity and period: the more luminous the Cepheid variable, the longer its period.

The period is the time it takes for one occurrence of a repeating event. For example, the period of the Earth rotating on its axis is 24 hours; the period of the motion of the second hand on a clock is 60 seconds.

FIGURE 6.4 Henrietta Leavitt investigated the relationship between period and luminosity in Cepheid variables.



FIGURE 6.5 The vertical axis measures the brightness of the star. As they are all in the same body of stars, they are similar distances from us meaning that the brightness varies in the same way as the luminosity. The horizontal axis shows increasing period plotted on a logarithmic scale; the scale is 10 to the power of the numbers on the axis.



By 1919, Harlow Shapley (1885–1972) had used this relationship to determine how far the Earth is from groups of stars called globular clusters and the Large Magellanic Cloud. All he needed to do was measure the period of the variation in brightness of the Cepheid variable stars in these clusters and use Leavitt’s relationship to determine the luminosity of the star. By comparing this luminosity to the brightness he could measure the distance to the stars, and hence the distance to the clusters they were in. Most of the stars in the Milky Way lie in a plane in the shape of a spiral. Shapley found that the globular clusters group around the centre of the Milky Way in a sphere.

Globular clusters are spherical clusters of thousands, and sometimes millions, of stars. Shapley used his mapping of globular clusters to determine the general shape and size of the Milky Way **galaxy** and found that the clusters formed a spherical shell whose centre lay in the direction of the constellation of Sagittarius. This suggested that the centre of the galaxy was in this direction and that our solar system was located towards the edge. Until Shapley's measurements, the solar system was thought to be near the centre of the galaxy.

Shapley's estimate of the size of the galaxy included the Magellanic Clouds and assumed that the Andromeda nebula was within the Milky Way. He had made quite an error in his estimate. By this time thousands of nebulae in the shape of spirals and ellipses had been catalogued. Some of them seemed to be very small. How could they all be in our galaxy?

From 1919 to 1926, Edwin Hubble (1889–1953) examined the Andromeda nebula in great detail using the large telescopes at Mount Wilson, California. He took long exposure photographs of the spiral arms and counted numerous novae (singular nova; bright stars that were not in previous photographs) and Cepheid variables. Using these, Hubble established the size and distance of the Andromeda nebula from Earth and found that it lay well beyond our galaxy and was comparable in size to the Milky Way. It seemed that our galaxy was only a tiny portion of the universe after all.

One of the most significant results in the history of **cosmology** came from the work of Shapley and Hubble. In 1919, Shapley noticed that the velocities of nebulae, later found to be galaxies, indicated that they were nearly all moving away from us. Hubble explored further and, in 1929, showed that the more distant the galaxies were from us, the faster they were moving away. The speeds were enormous; one measurement suggested that a galaxy was moving away from us at $42\,000\text{ km s}^{-1}$, more than one-tenth of the speed of light!

FIGURE 6.6 Globular cluster



FIGURE 6.7 Edwin Hubble



FIGURE 6.8 The Andromeda galaxy contains most of its stars in a flat disk similar to the Milky Way. The globular clusters are not restricted to this disk.



SAMPLE PROBLEM 1

The discovery that stars form enormous structures called galaxies and that the rate galaxies recede from the Earth increases with their distance from us depended on a discovery by Henrietta Leavitt. Describe her discovery and how it enabled these great discoveries by Edwin Hubble and his collaborators.

THINK

1. Identify what Henrietta Leavitt discovered.
2. Link this discovery to the use of it by Hubble and others to discover galaxies and their recession.

WRITE

Leavitt discovered that a type of star called a Cepheid variable varied in luminosity in such a way that the more luminous the star, the longer its period of variation. This provided a method to determine the luminosity of the star and therefore its distance could be determined by the difference between its luminosity and its brightness when viewed from Earth. Hubble used this discovery to show that clouds of stars were well beyond the limits of the Milky Way galaxy and therefore separate galaxies in their own right. He also found that the more distant the galaxies, the faster they were receding from us.

PRACTICE PROBLEM 1

Henrietta Leavitt discovered that Cepheid variables varied in luminosity over a period of time which increased the more luminous the stars were. Knowing this relationship, astronomers could determine the luminosity of the star by measuring its period. Why can't astronomers simply measure the luminosity of a star by observing how bright it is?

6.2.3 The expansion of space

Everywhere that astrophysicists looked in the sky, they found galaxies moving away from us. This information was astonishing and very unexpected. All galaxies are experiencing the same thing. If people in another galaxy looked at us, they would see us racing off in the opposite direction. In fact, it is not the galaxies themselves that are moving away; rather, space is expanding and taking the galaxies with it! Galaxies do also move through space due to gravitational interactions with other galaxies; we know that the Milky Way is currently colliding with the relatively tiny Sagittarius Dwarf Elliptical Galaxy. But these motions of neighbouring galaxies do not explain why distant galaxies are moving away from each other with a speed that increases with distance.

Galaxies and tightly bound clusters of galaxies do not expand as they are held together by gravity. The Milky Way is part of a cluster of galaxies known as the Local Group. The Local Group includes over 30 galaxies, the two largest being Andromeda and the Milky Way. The Large and Small Magellanic Clouds are also members of the Local Group. The Andromeda galaxy is actually *approaching* us at enormous speed due to gravitational attraction, but as we look at more distant galaxies beyond the Local Group, the expansion of space dominates gravitational forces.

Hubble jumped to the obvious conclusion. All of the galaxies are racing away from each other, so if we imagine running time backwards, we would see that they had all come from the same spot. It was as though

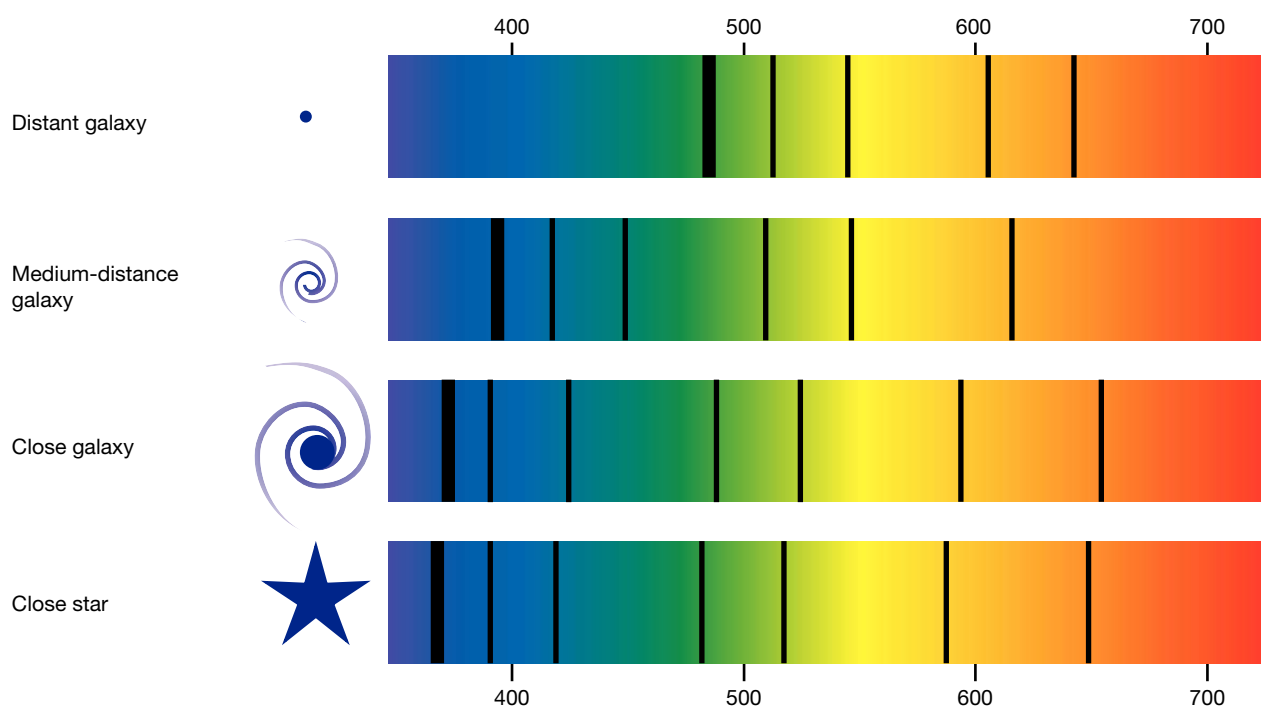
the universe was born from some form of explosion that threw space and matter out in all directions. This was the first scientific evidence that the universe had a beginning. Prior to this, scientists assumed that the universe had existed forever. This was the beginning of time and space, which has expanded ever since.

6.2.4 Measuring expansion

Hubble measured the expansion of space using a phenomenon called the **red shift**.

Light emitted by a star or galaxy that is moving away from us is shifted towards the red end of the spectrum. The faster the galaxy moves away, the greater the red shift. Stars or galaxies moving towards us have their light shifted towards the blue end of the spectrum, which is called blue shift.

FIGURE 6.9 Light from astronomical objects observed through a spectroscope reveals spectra showing red shift. The scale indicates the wavelength in nanometres.



The visible spectrum of light contains red, orange, yellow, green, blue, indigo and violet. The spectrum continues into invisible forms of radiation, including infra-red at lower frequencies than red and ultraviolet at higher frequencies than violet.

Hubble observed that the red shift was greater for more distant galaxies.

The red shift of all distant galaxies could be explained if space were expanding. As the light from a distant source travels through space en route to Earth, the space it passes through stretches, increasing the light's wavelength. The longer the light travels through space (that is, the further away the galaxy), the greater the increase in wavelength due to expanding space, and so the greater the red shift.

This effect can be quickly demonstrated using a rubber band to represent space. Mark a rubber band every 2 mm along a 2 cm length. The distance between neighbouring marks represents the wavelength of light. As you stretch the rubber band a little, you will see each mark move away from all of the others. As time goes on the universe keeps expanding, like stretching the rubber band further. As a consequence, the wavelength of light from distant galaxies gets longer over time.

FIGURE 6.10 (a) The rubber band before stretching (b) The stretched rubber band — each dot has moved away from all of the other dots



SAMPLE PROBLEM 2

What major discovery about the nature of our universe did Hubble make when he considered the red shift effect in his analysis of spectra from galaxies?

THINK

1. Identify what Hubble saw when observing the red shift of galaxies.
2. Connect his observation with the nature of the universe.

WRITE

When Hubble measured the red shift of distant galaxies he noticed that it increased the further the galaxy was from us.

This was interpreted by physicists as meaning that the universe must be expanding. Prior to this discovery they thought it was static.

PRACTICE PROBLEM 2

Explain how the light from distant galaxies has come to be red shifted before it reaches us?

SAMPLE PROBLEM 3

Explain why expansion is observed on the large scale for distant galaxies, but not on the relatively small scale of nearby galaxies.

 **Teacher-led video:** SP3 (tlvd-0043)

THINK

1. State that expansion is seen when observing distant galaxies.
2. Explain the difference in gravitational effects over different distances.

WRITE

When Hubble measured the motion of more distant galaxies, he found that they were moving away from us, but some nearer ones were moving towards us.

Gravity is a force that weakens with distance. Gravity can cause galaxies near to each other to move toward each other; but for galaxies separated across a greater distance, the gravity becomes too weak and the expansion of space overrides its effect.

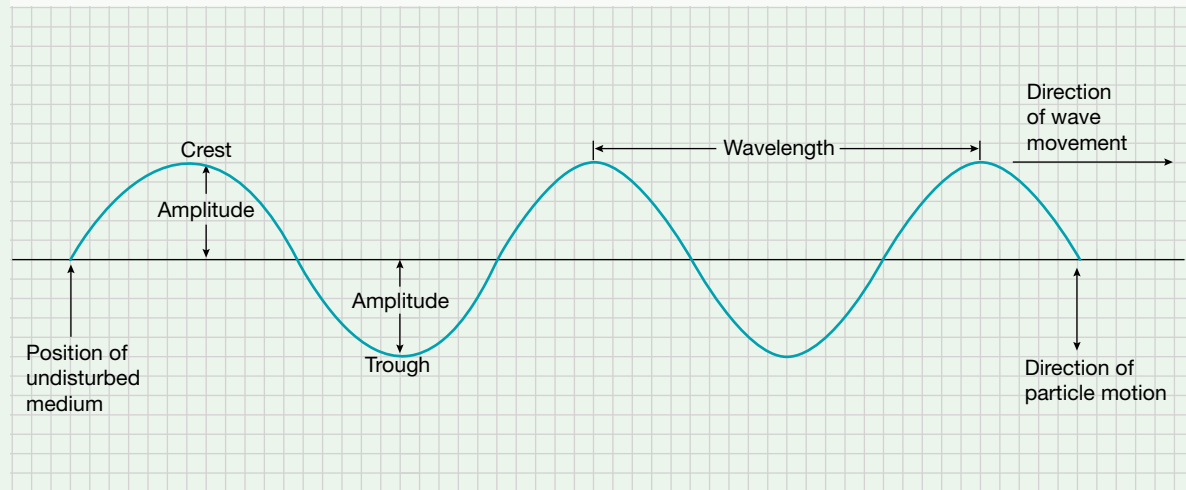
PRACTICE PROBLEM 3

What did Hubble observe about all of the galaxies that were not near to the Milky Way?

UNDERSTANDING WAVES

Waves can be described in terms of their period, frequency, speed and wavelength. The wavelength is the distance between successive corresponding parts of a periodic wave — the length of one cycle. The period of a periodic wave is the time for one part of the wave to travel one wavelength. The frequency of a periodic wave is the number of cycles that occur every second.

FIGURE 6.11 Transverse periodic waves in a piece of string



6.2.5 Einstein and general relativity

In parallel to the experimental work of Shapley, Hubble and other astronomers, theoretical physics was making tremendous progress. In particular, Albert Einstein published his General Theory of Relativity in 1915, which provided a new way of understanding gravity. Until then, scientists had used Isaac Newton's theory of gravity, which essentially stated that masses exert an attractive force on each other. Einstein's theory was that mass curves space and other masses move in response to the curvature of space. However, there was a problem with both theories. Newton wondered why the universe was not collapsing, given that all masses attract each other, and decided that the universe must be infinite. The idea that the universe is infinite in size and has existed forever endured until the Big Bang Theory was developed. Einstein's theory did not provide a satisfactory answer to the collapsing universe problem either, so he inserted what became known as a cosmological constant in his equations to counter the curvature of space.

Beginning in 1917, scientists proposed other cosmological models based on the General Theory of Relativity. Aleksandr Friedman (1888–1925) found that there were a number of solutions to the equations of general relativity, each of which is equally valid in terms of the theory, but of course only one could represent our universe. In some solutions the universe expands forever, in others the universe would expand for a time and then collapse back on itself. This theoretical work led Willem de Sitter (1872–1934) to encourage Hubble to measure the red shift of the galaxies.

FIGURE 6.12 Aleksandr Friedman

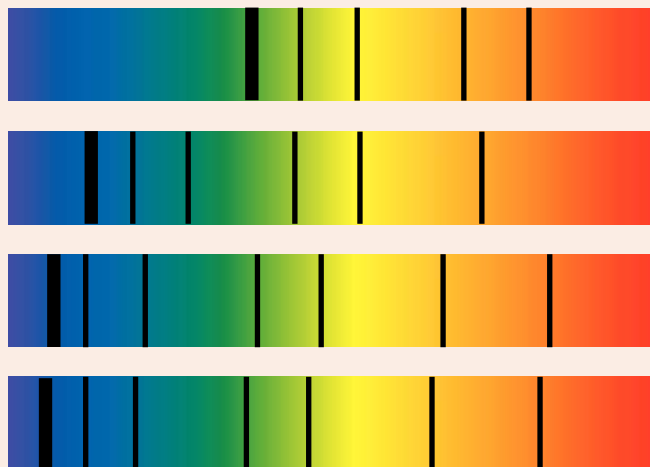


Georges Lemaître (1894–1966) was both a Catholic priest and professor of physics. He was fascinated by what physics might say about the birth of the universe. In 1927, he used general relativity to produce an early version of what became known as the **Big Bang Theory**.

6.2 EXERCISE

To answer questions online and to receive **immediate feedback** and **sample responses** for every question go to your learnON title at www.jacplus.com.au.

1. What is a galaxy?
2. Using Cepheid variables of equal distance from Earth, Henrietta Leavitt discovered a relationship between their luminosity and their period of variation.
 - (a) Describe this relationship.
 - (b) What does this relationship enable astronomers to measure?
 - (c) Why did she need to use Cepheid variables that were similar distances from the Earth to determine the relationship?
3. What did Hubble notice about all the more distant galaxies?
4. Which of these spectra of three distant galaxies would be from the most distant galaxy? Give your reason.



5. Which great theory of Albert Einstein's was used in the development of the Big Bang Theory?
6. It is easy to read about the red shift of the galaxies in all directions and jump to the conclusion that the Earth is at the centre of an expanding universe. Use the rubber band analogy, with each dot on the rubber band representing a galaxy, to explain why this is not so.
7. Why did proof of the expansion of space still come as such a surprise to scientists, even though those working with the General Theory of Relativity had already shown an expanding universe was possible?
8. Why did Einstein adjust his theory with a cosmological constant?
9. The light from the Andromeda galaxy is blue shifted. Explain why it is not red shifted like the light from most galaxies.

studyon

To answer practice exam questions online and to receive immediate feedback and sample responses for every question go to your learnON title at www.jacplus.com.au.

studyON: Practice exam questions 

Fully worked solutions and sample responses are available in your digital formats.

	Digital document	Investigation 6.1 Expansion of the universe (doc-31871)
	Teacher-led videos	Investigation 6.1 Expansion of the universe (tlvd-0816)
	Video eLesson	The expansion of the universe (eles-0038)
	Interactivity	Shifting stars (int-6395)

6.3 Further developments of the Big Bang Theory

KEY CONCEPTS

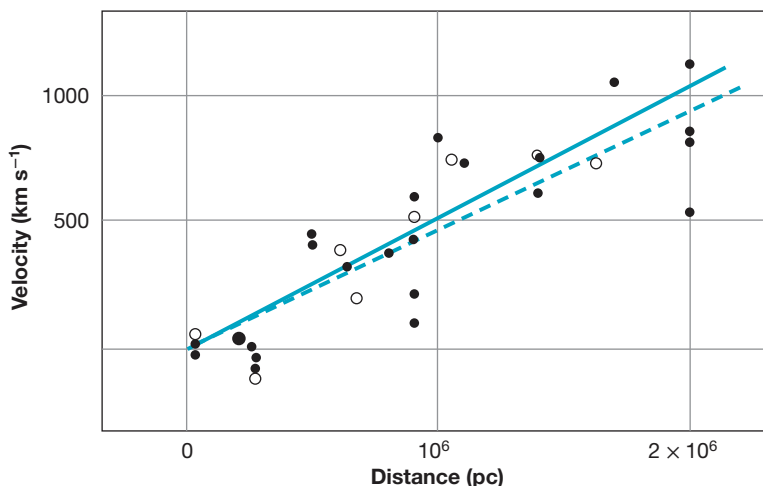
- Describe the Big Bang as a currently held theory that explains the origins of the universe.
- Describe the origins of both time and space with reference to the Big Bang Theory.
- Explain the changing universe over time due to expansion and cooling.

6.3.1 An expanding, cooling universe

By 1929 there was both a theoretical basis for the expansion of space, through the work of Lemaître, de Sitter and Friedman, and the observational evidence of the red shift of galaxies to support it; however, it was by no means generally accepted.

Hubble plotted the velocity (red shift) of galaxies versus their distance from Earth and ambitiously fitted a straight line to the data, well aware that the distance calculations had large uncertainties. If the galaxies really did fit this straight line rule, then it would be easy to judge the distance to other galaxies; simply measure their red shift and divide by the gradient of the line. This gradient became known as **Hubble's constant** (H) and the relationship between velocity and distance as **Hubble's Law** ($\frac{1}{H}$ gives physicists a means of calculating the age of the universe).

FIGURE 6.13 Hubble's data. The solid dots are the results for galaxies treated individually and the solid line is the line of best fit for these data. The dashed line is fitted to the circles, which are the result of treating galaxies in clusters. One parsec (pc) is 3.09×10^{16} m or 3.26 light-years. Notice the group of blue-shifted galaxies at about 2.5×10^5 parsecs. This corresponds to the Andromeda galaxy and its satellites.



Source: Adapted from Edwin Hubble, 'A relation between distance and radial velocity among extra-galactic nebula', *Proceedings of the National Academy of Science*, vol. 15, no. 3, 15 March 1929, Mount Wilson Observatory, Carnegie Institution of Washington. Communicated 17 January 1929.

The value of Hubble's constant has been measured with increasing accuracy since Hubble's time and discoveries in recent years have established its value to a small margin of uncertainty. Using the simplest scenario — that the universe has expanded at a constant rate — Hubble's early measurements put the age of the universe at 2 billion years, but the age of the Earth appeared to be greater than that. Improvements in measurement, including a better understanding of Cepheid variable stars and measuring the red shift of much more distant galaxies, have since put the age of the universe at about 13.8 billion years.

SAMPLE PROBLEM 4

Use the solid line in the graph of Hubble's data to estimate the age of the universe. Compare this with his estimate of 2 billion years.

THINK

1. As the unit for speed here is km s^{-1} , convert the distance to kilometres.
2. Hubble's constant is the gradient of the graph.
3. The age of the universe is the reciprocal of Hubble's constant.
4. State the answer.

WRITE

$$2 \times 10^6 \text{ pc} = 2 \times 10^6 \times 3.09 \times 10^{13} \\ = 6.2 \times 10^{19} \text{ km}$$

$$H = \frac{1100}{6.2 \times 10^{19}} \\ = 1.78 \times 10^{-17} \text{ s}^{-1}$$

$$t = \frac{1}{H} \\ = \frac{1}{1.78 \times 10^{-17}} \\ = 5.62 \times 10^{16} \text{ s}$$

$$= 1.8 \times 10^9 \text{ years}$$

The universe is 1.8×10^9 years old. This is 2 billion years to one significant figure, so consistent with Hubble's estimate.

PRACTICE PROBLEM 4

Given the currently accepted age of the universe is 13.8 billion years, is Hubble's trendline with this early data too steep or not steep enough in gradient?



Resources



Weblink The expansion of the universe and Brian Schmidt

Other evidence for the expansion model of the universe included surveys showing that galaxy density in distant space was greater than the density of galaxies closer to Earth. This is expected with the expansion model because when we observe distant galaxies, we see them as they were billions of years ago — due to the limit of the speed of light — when the universe had undergone much less expansion.

The young universe must have been very hot and we will learn that a significant event called **recombination** resulted in photons (light) being able to travel freely for the first time without interacting with electrons. The wavelength of a photon depends on its energy. As the universe expanded, the wavelengths of the photons would have expanded, stretching out to form microwaves with much less energy than when the photons were initially released. These microwaves have become known as **cosmic microwave background** radiation (CMB) and correspond to a background temperature of about -270°C or 2.7 K. Arno Penzias and Robert Wilson discovered this radiation in 1965 when they were trying to

eliminate some noise coming from their radio telescope. The identification of this noise as the missing energy left over from the beginning of the universe was the turning point for the Big Bang Theory. The theory had predicted the existence of greatly red shifted energy left over from the early universe. With the discovery of CMB, this energy had been found — cooled from 3000 K at recombination to 2.7 K today by the expansion of the universe.

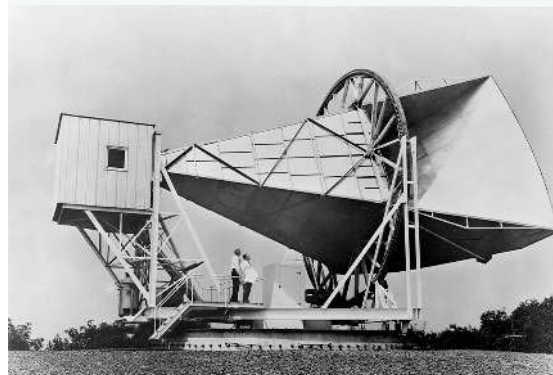
The name ‘Big Bang’ came from an early opponent of the theory, Fred Hoyle, in 1950. It is not a particularly accurate description as it implies that the creation of the universe was like an enormous explosion pushing matter through space, which is not the case. Instead of pushing matter through space, space and time were created in the Big Bang and the expansion of the universe with time carries matter with space.

In summary we have discovered that:

- the universe is vast, filled with billions of galaxies each containing billions of stars
- these galaxies are moving away from each other at a rate that increases the more distant the galaxies are
- the more distant galaxies (the older ones) are more densely packed than those closer to us
- the predicted CMB has been detected.

Most scientists concluded that these discoveries meant the universe had a beginning — in a relatively small volume — and has expanded ever since. This idea is the Big Bang Theory.

FIGURE 6.14 Penzias and Wilson discovered the cosmic microwave background radiation (CMB) in 1965.



STEPHEN HAWKING AND THE BIG BANG

The Big Bang Theory raises many questions. What happened before the Big Bang? What is outside the universe? What is the universe expanding into? Famous physicist Stephen Hawking, in collaboration with others, posed answers to these questions. He reminded us that in the past people contemplated what would happen if you sailed off the edge of the world. That question turns out to not need an answer because we have a completely different view of the shape of the world; it is a globe, so we never reach an edge. The question of what happened off the edge of the world only arose because of our misunderstanding of the shape of the world, thinking that it was flat.

In his PhD thesis in the mid-1960s, Stephen Hawking proved that Einstein’s Theory of General Relativity required the universe to have a beginning in what was called a ‘singularity’. A singularity is a point of infinite density that is achieved when we think of what happens if we run time backwards so that the expanding universe collapses back to its beginning. This was a stunning result for general relativity. If the universe was initially very dense, it must also have been incredibly hot and that energy should still be found throughout the universe. This energy was found soon after Hawking’s initial work on singularities in the form of the CMB. This radiation is central to the subject of this topic, the origin of atoms.

Later Hawking showed that time becomes like another dimension of space under extreme conditions. It makes no more sense to ask what happened before the Big Bang than to ask what is south of the South Pole. Hawking asked us to imagine the passing of time as being like decreasing degrees of latitude away from the South Pole. The latitude is 90° at the South Pole and as we move north it becomes 89°, 88°, and so on. There is no 91° of latitude and there is no ‘before the Big Bang’. Time began with the Big Bang and space has no edge to fall off, or to step outside of, to discover what the universe is expanding into.

FIGURE 6.15 Stephen Hawking



6.3 EXERCISE

To answer questions online and to receive **immediate feedback** and **sample responses** for every question go to your learnON title at www.jacplus.com.au.

1. What is the connection between the observed cosmic microwave background and the Big Bang Theory?
2. Explain how Hubble's observation of receding galaxies led to the idea that the universe had a beginning.
3. What does the Big Bang Theory say about time and space before the beginning of the universe?
4. What does the Big Bang Theory have to say about space since the beginning of the universe?
5. Explain how the energy left over from the Big Bang has cooled as a result of the universe's expansion.
6. How does the Big Bang Theory explain Hubble's observation that the more distant the galaxy, the greater its red shift?
7. Why would the galaxies have been more densely packed in the universe in the past?

studyon

To answer practice exam questions online and to receive immediate feedback and sample responses for every question go to your learnON title at www.jacplus.com.au.

studyON: Practice exam questions 

Fully worked solutions and sample responses are available in your digital formats.

6.4 Measurements of the universe

KEY CONCEPT

- Apply scientific notation to quantify and compare the large ranges of magnitudes of time, distance, temperature and mass considered when investigating the universe.

The universe is on a scale that is very difficult to comprehend with the usual numbers we are accustomed to. For example, when measuring distance on Earth, measurements in metres or kilometres are sufficient for most situations. For small objects millimetres or centimetres are often used. Using these units, even the vastness of the circumference of the Earth is not too unwieldy. The circumference of the Earth is around 40 000 km. It is a big number, but manageable. When looking beyond the Earth, physicists and astronomers find other units and notations easier to work with.

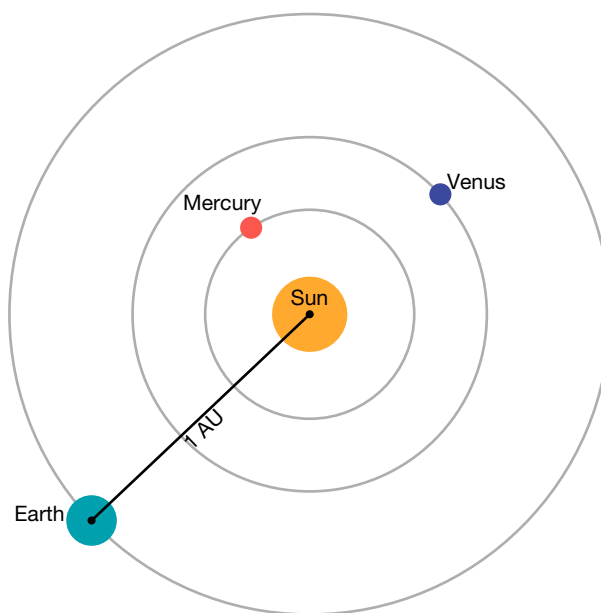
6.4.1 The astronomical unit

One of the earliest measurements of the vastness of space was the distance from the Earth to the Sun. This was an important measurement because it could be used to work out the distance to the other planets. The main reason for Captain James Cook's voyage, which eventually led him in 1770 to the east coast of what is now Australia, was to measure this distance by observing a transit of Venus at Tahiti. The average distance from the Earth to the Sun is known as an astronomical unit (AU), as shown in figure 6.16. It provides an alternative unit for measuring distance on the scale of the solar system.

To see the effectiveness of the astronomical unit consider the following:

$$1 \text{ AU} = 150\,000\,000 \text{ km or } 150\,000\,000\,000 \text{ m}$$

FIGURE 6.16 The distance from the Earth to the Sun is 1 AU.



The average distance from the Sun to Saturn is 1.4 billion km or 1 400 000 000 000 m.

When performing calculations with these numbers it is easy to make a mistake, such as including an extra zero. The metre, or even the kilometre is not a very useful reference on the scale of the solar system. It can be easier to understand that Saturn is 9.6 AU, or 9.6 times as far as the Earth is from the Sun.

However, the astronomical unit is not very helpful on the scale of the universe. The nearest star is 270 000 AU. The distance to the nearest large galaxy is 160 000 000 000 AU.

SAMPLE PROBLEM 5

The planet Mars has an elliptical orbit. It is 1.38 AU from the Sun at its closest (perihelion) and 1.67 AU from the Sun at its furthest (aphelion). Calculate these distances in metres.

 **Teacher-led video:** SP5 (tlvd-0045)

THINK

1. Recall the number of metres in 1 AU.
2. Multiply this value by the number of astronomical units.
3. State the solution in metres.

WRITE

$$1 \text{ AU} = 150\,000\,000\,000 \text{ m}$$

$$\text{At aphelion: } 1.67 \times 150\,000\,000\,000$$

$$\text{At perihelion: } 1.38 \times 150\,000\,000\,000$$

$$\text{At aphelion: } 250\,500\,000\,000 \text{ m}$$

$$\text{At perihelion: } 207\,000\,000\,000 \text{ m}$$

PRACTICE PROBLEM 5

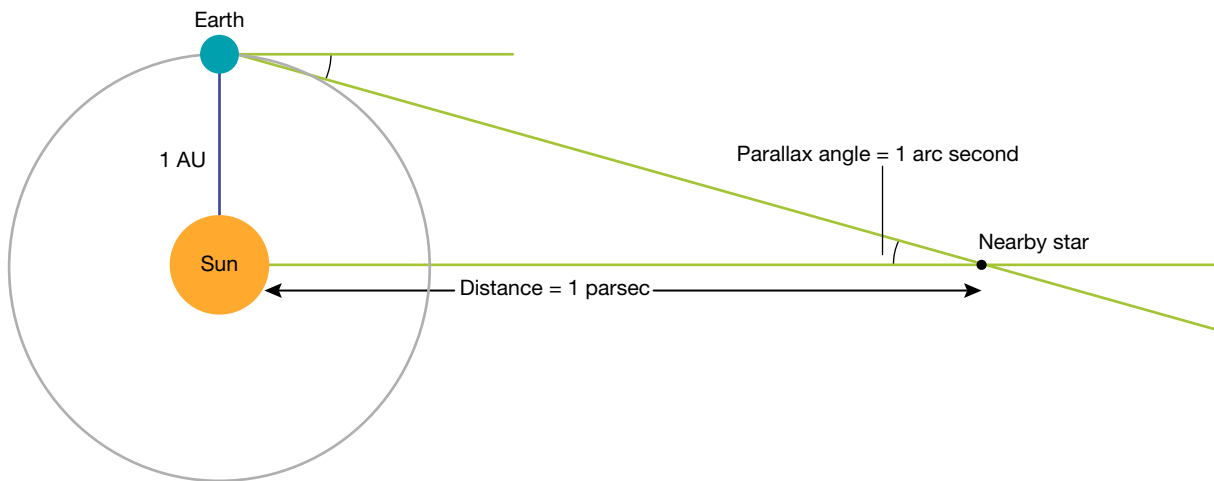
- a. Venus has an average orbital radius of 0.72 AU. What is the average distance of Venus from the Sun in metres?
- b. The distance from the Earth to the Moon averages about 385 000 kilometres. What is this in astronomical units?

6.4.2 The parsec

Measurement of the distance to nearby stars uses a technique called parallax. This involves observing the tiny change in position of the nearby star against the distant background stars as the Earth moves around the Sun. This change in position is so tiny that it is very difficult to measure, even with the largest telescopes. The lack of parallax observed is one of the reasons that it took a long time to accept that the Earth moved around the Sun, rather than the other way around as most ancients believed.

The change in position is measured as an angle, but no changes as big as 1 degree were observed. Even one-sixtieth of that, one minute of arc, was too large a unit. Astronomers measure parallax in fractions of seconds of arc. The distance of an object that would cause one second of parallax as the Earth moved around the Sun is called a parallax second, or parsec (pc). The nearest star, Proxima Centauri is 1.3 parsec from Earth. The parsec is equivalent to 30 900 000 000 000 000 m.

FIGURE 6.17 1 parsec is the distance of a nearby star (object) with a parallax angle of 1 arc second.



SAMPLE PROBLEM 6

Alpha Centauri is 1.339 pc from Earth and Rigel is 265 pc from Earth. How many times further away is Rigel than Alpha Centauri?

 **Teacher-led video:** SP6 (tlvd-0046)

THINK

1. What is the distance from Earth to Rigel and Alpha Centauri in the same units?
2. Divide the distance to Rigel by the distance to Alpha Centauri.
3. State the solution.

WRITE

265 pc and 1.339 pc

$$\frac{265}{1.339} = 197.9$$

Rigel is about 198 times as far away as Alpha Centauri.

PRACTICE PROBLEM 6

The Andromeda galaxy is 778 000 pc from the Earth, while the Large Magellanic Cloud is 48 500 pc away. How many times further away is the Andromeda galaxy than the Large Magellanic Cloud?

6.4.3 The light-year

A unit often used in the measurements of distances in space is the distance that light travels in one year. The light-year is 9 460 000 000 000 000 m. The light-year is informative because it describes how long it has taken the light to reach Earth. A galaxy that is observed as 4 billion light-years away is observed as it was 4 billion years ago. That galaxy will not currently be four billion light-years away as it has moved relative to the Earth in the meantime. The unit of measurement takes this complication into account.

$$1 \text{ light-year} = 9\,460\,000\,000\,000\,000 \text{ m} = 9.46 \times 10^{15} \text{ m}$$

SAMPLE PROBLEM 7

The Andromeda galaxy is measured to be 2.5 million light-years away. How long has it taken the light from it to reach our eyes and telescopes?

 **Teacher-led video:** SP7 (tlvd-0047)

THINK

1. Determine the distance in light-years.
2. Write that distance as the number of years the light has travelled.

WRITE

2.5 million light-years

The light has travelled for 2.5 million years to reach us.

PRACTICE PROBLEM 7

How long has it taken light to reach the Earth from Betelgeuse, which is measured as being 643 light-years away?

6.4.4 Working in metres

Astronomical units, parsecs and light-years are excellent units for working on astronomical scales but ultimately scientists need to be able to relate distances to common units like metres. This involves dealing with very large numbers. Rather than write them out in full as has been done so far in this subtopic, scientists use scientific notation (also known as standard form). This is a number between one and ten multiplied by multiples of ten.

For example, the light-year is the unwieldy 9 460 000 000 000 000 m. In scientific notation this is written as 9.46×10^{15} m. A number like 1 000 000 000 000 becomes 10^{12} . This is so much quicker to write and is much easier to read.

Scientific notation makes it easy to compare very large numbers. It makes use of the powers of ten.

$$10^0 = 1$$

$$10^1 = 10$$

$$10^2 = 100$$

$$10^3 = 1000 \dots \text{and so on}$$

Try comparing the following numbers 9 450 000 000 000 and 3 600 000 000 000. It is much easier to compare 9.45×10^{12} and 3.6×10^{12} . Immediately it becomes clear that the first number is bigger than

the second by a factor of less than three. To find that factor exactly all that is needed is to perform the calculation $\frac{9.45}{3.6} = 2.625$. The rest of the number (10^{12}) cancels out so can be ignored. If the numbers did not have the same power of ten, they can be written so that they do. Consider the numbers 2.6×10^{16} and 1.2×10^{15} . To compare the numbers the first could be written as 26×10^{15} , then they can be compared on the same scale.

Big numbers are everywhere in distance in the universe, from the diameters of stars to the circumference of a galaxy. Scientific notation is an effective way of managing these large numbers.

SAMPLE PROBLEM 8

Add the numbers 2.5×10^8 and 1.2×10^9 .

 **Teacher-led video:** SP8 (tlvd-0048)

THINK

1. Write the two numbers so the powers of ten are the same.
2. Now that they have common powers of ten, add the numbers together.
3. Write with the multiple of ten.
4. Rewrite in scientific notation if necessary.

WRITE

$$\begin{aligned} 2.5 \times 10^8 \\ 1.2 \times 10^9 &= 12 \times 10^8 \\ 2.5 + 12 &= 14.5 \\ 14.5 \times 10^8 \\ 1.45 \times 10^9 \end{aligned}$$

PRACTICE PROBLEM 8

Add 2.3×10^7 and 4.3×10^6 .

6.4.5 Numbers and time

The universe is not only grand on the scale of distances; the scale of time is also difficult to comprehend. The age of the universe is currently measured to be close to 13.8 billion years (1.38×10^{10} years).

[illegible]

0.000 000 000 000 000 000 000 000 000 000 000 000 000 1 is much easier to read as a power of ten.

$$\begin{aligned} 1 &= 10^0 \\ 0.1 &= 10^{-1} \\ 0.01 &= 10^{-2} \\ 0.001 &= 10^{-3} \dots \text{and so on} \end{aligned}$$

The time when the force of gravity is understood to have first been active as a separate force in the universe was when the universe was 10^{-43} seconds old.

Temperatures and masses also require extremely large and small numbers to describe them. Temperatures range from 2.7 K in deep space to 1.47×10^{32} K, the temperature at which physics as we know it cannot explain what happens — the Planck temperature. Masses vary enormously too. An electron has a mass of 9.1×10^{-31} kg, while the observable universe has an estimated mass of 1.5×10^{53} kg.

SAMPLE PROBLEM 9

The mass of the Sun is 1.989×10^{30} kg. Write this number in full decimal notation.

THINK

1. Identify the number that needs to be converted.
2. Write the digits without the power of ten, then move the decimal point 30 places to the right, adding zeros where necessary.

WRITE

1.989×10^{30} kg
1 989 000 000 000 000 000 000 000 000 000 kg

PRACTICE PROBLEM 9

The Earth is understood to be 4.54×10^9 years old. Write this age in full decimal notation.

SAMPLE PROBLEM 10

The temperature at the centre of the Sun is approximately 15 000 000 K. Write this number in scientific notation to two significant figures.

THINK

1. Identify the number to be converted.
2. Write down the first digits to the appropriate number of significant figures.
3. Add a decimal point to make the number between 1 and 10.
4. Count the number of places the decimal point would have to move to obtain the original number.
5. Write the number as the product of part 3 and 10 to the power of part 4, including units.

WRITE

15 000 000 K
15
1.5
7
 1.5×10^7 K

PRACTICE PROBLEM 10

The mass of Saturn is 568 300 000 000 000 000 000 000 kg. What is the mass of Saturn in scientific notation to four significant figures?

6.4 EXERCISE

To answer questions online and to receive **immediate feedback** and **sample responses** for every question go to your learnON title at www.jacplus.com.au.

1. The average distance from the Sun to Neptune is 30.1 AU. Convert this distance to metres.
2. The distance from the Earth to Mercury averages 77 million kilometres. How far is that in astronomical units?
3. The solar system lies about 8 kpc from the centre of the galaxy. The radius of the galaxy is approximately 15 kpc. Describe our location within our galaxy.
4. Sirius, the brightest star in the night sky, is about 8.6 light-years from Earth. How long has it taken the light that we see on Earth to reach us from Sirius?
5. The distance from the Sun to Neptune is 4.495 billion kilometres. Write this in scientific notation in metres.
6. The light from the most distant galaxy observed has travelled 1.3339×10^{10} years to reach us. Write this number in decimal notation.

7. When the universe was a second old the Big Bang Theory estimates its temperature was about 10 000 000 000 K. Write this number as a power of ten.
8. The mass of Earth is about 5.98×10^{24} kg and the mass of the Moon about 7.35×10^{22} kg. Without using a calculator determine the total mass of the Moon and Earth to three significant figures.
9. The mass of Jupiter is 1.90×10^{27} kg and the mass of Earth is 5.98×10^{24} kg. Calculate the ratio of mass of Jupiter to mass of Earth to two significant figures.

studyon

To answer practice exam questions online and to receive immediate feedback and sample responses for every question go to your learnON title at www.jacplus.com.au.

studyON: Practice exam questions 

Fully worked solutions and sample responses are available in your digital formats.

6.5 The formation of the first atoms

KEY CONCEPT

- Explain the change of matter in the stages of the development of the universe including inflation, elementary particle formation, annihilation of antimatter and matter, commencement of nuclear fusion, cessation of fusion and the formation of atoms.

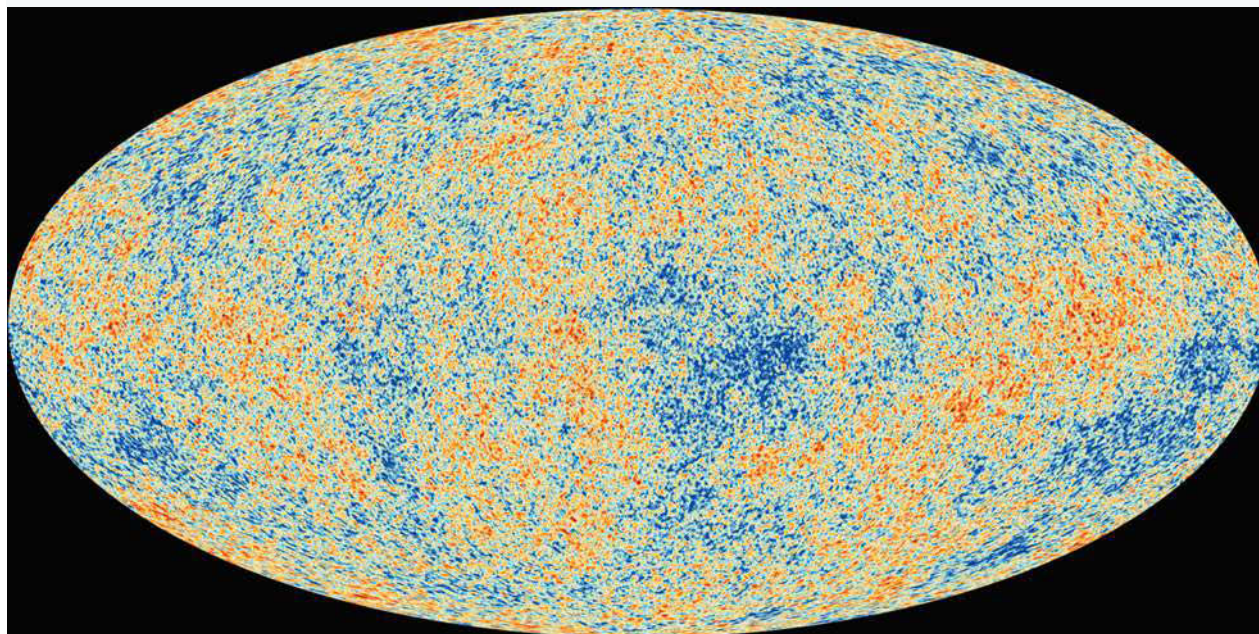
6.5.1 Looking back in time

To look into space is to look back in time. This is a consequence of the speed of light and the vast distances involved. Light travels faster than anything else in the universe, but it still only travels at just under 300 000 000 metres per second. The distance light travels in a year is called a light-year. The light from Earth's nearest star, other than the Sun, takes more than four years to reach us, so we see it as it was more than four years ago. When we look out to the nearest large galaxies we see them as they were over 2.5 million years ago. This is still recent in the universe's history.

Looking at the most distant galaxies, we see them as they were over 13 billion years ago. These distant galaxies are incredibly faint and our current telescopes cannot see further. But even if we could, we don't expect to see much more because physicists believe that the first stars would have only begun to shine at this time. A little over 13 billion years ago the matter in the universe was hydrogen and some helium in vast clouds, collapsing due to gravity on their way to producing the first stars and galaxies. This period is known as the Dark Ages (borrowed from a term used to describe the period in history following the fall of the Roman Empire). The Dark Ages marks the period from 380 000 years following the beginning of the universe until stars began to shine 150–800 million years later.

To look further back in time, we don't see objects, we see the remnants of an event. This is CMB, the energy in the form of photons left over from the early universe. Prior to the universe reaching 380 000 years of age, this energy was trapped in a state of constant scattering, a bit like light in a cloud. It was not water molecules that scattered this light but the charged particles that filled the universe. These protons and electrons were too energetic, too hot, to combine to form atoms until the expansion of the universe had cooled it enough for the bonds between electrons and protons and the other nuclei to form. This event is called recombination and marks the time when atoms first formed 380 000 years after the beginning of the universe. The CMB provides physicists with a picture of what the universe was like at 3.8×10^5 years of age because the light that formed it was free to travel through the universe from that time. The CMB has been red shifted uniformly in all directions by the expansion of the universe.

FIGURE 6.18 The CMB as measured by the Planck satellite. The differences in colour indicate temperature differences that correspond to differences in the density of the universe when it was 380 000 years old.



Source: ESA and the Planck Collaboration

SAMPLE PROBLEM 11

What event was the origin of the cosmic microwave background?

 **Teacher-led video:** SP11 (tlvd-0051)

THINK

1. Recall what the cosmic microwave background is.
2. Recall what event resulted in the cosmic background radiation.

WRITE

The cosmic microwave background radiation is a uniform low temperature radiation throughout space in all directions.

Energy from the Big Bang was constantly scattered by charged particles until the universe was cool enough for electrons to remain bonded to the hydrogen and helium nuclei that had formed. This event produced the first atoms and is called recombination. The photons of energy were able to propagate through space after this point and it is the greatly red shifted photons that are observed as the cosmic microwave background.

PRACTICE PROBLEM 11

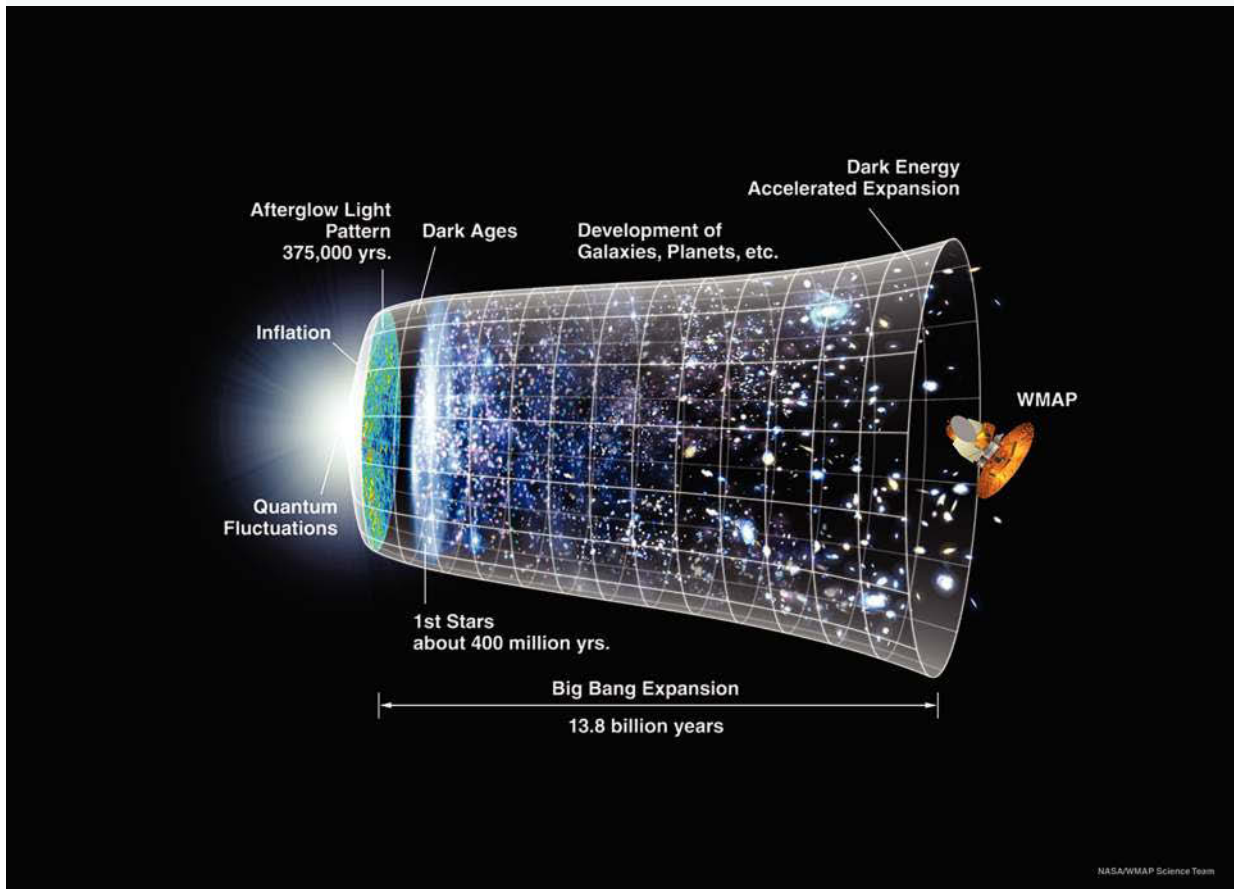
Why is it not possible to view the universe using light as it was prior to recombination?

6.5.2 The early universe

The CMB marks the earliest observation we have of the universe. To understand what happened prior to this event, physicists rely on particle physics and the Theory of General Relativity to help them make sense of their observations of the CMB and the universe that followed. Particle physics experiments, such as those

in the Large Hadron Collider that discovered the Higgs boson at CERN, create conditions that existed for particles in the early universe, so physicists do have experimental evidence for much of what happened prior to recombination.

FIGURE 6.19 Diagram of the evolution of the universe (observable part) from the Big Bang (left) to the present



Source: NASA WMAP Science Team

Let's piece the story together from the beginning until the formation of the first atoms, summarised in figure 6.20.

Planck era

The first 10^{-43} seconds

This is known as the Planck era and current theories of physics cannot explain what happened in the conditions that were present. The universe was too small, too dense, too hot and existed for too short a time for current physics to say anything precise about it. Physicists refer to what existed prior to when the universe was 10^{-43} seconds old as a singularity. In this period space and time began. Gravity became a distinct force at the end of the Planck era. The temperature was 10^{32} degrees Celsius and the universe was 10^{-35} cm across.

Grand unified era

10^{-43} seconds to 10^{-36} seconds

This tiny interval of time in the early universe is known as the grand unified era. During this period, physicists believe that the strong nuclear force, the weak nuclear force and the electromagnetic force did not yet exist as separate forces. The first matter began to form, but for each particle of matter, there was a particle of antimatter. As soon as a particle was formed, it would meet an antiparticle and be annihilated.

Inflation era

10^{-36} seconds to 10^{-32} seconds

This next period of time is known as the inflation era. During this time, a period of exponential expansion has been proposed to explain a number of features of the universe. The universe is thought to have expanded in size by a factor of 10^{26} , so that the observable universe was about 10 cm across. This rapid expansion explains, among other things, why the CMB is so uniform, being close to 2.7 degrees above absolute zero in all directions.

Alan Guth proposed this radical idea in 1980.

It was a response to some of the limitations of the standard Big Bang model that worked well for most of the evidence, but fell short when it came to explaining the relative uniformity of the CMB in all directions and what is known as the ‘flatness’ of the universe. At first, inflation may look like a crazy idea invented just to explain away problems. However, in all of the time since, no-one has come up with a more successful explanation of why the visible universe is so uniform in temperature or why the universe appears so ‘flat’. In a flat universe, parallel lines remain an equal distance apart. In a curved universe, they could be more like north–south lines on the surface of the Earth, which meet at the poles. It is thought that rapid expansion during this era smoothed out deviations in the flatness of the universe that would otherwise have grown with time. A flat universe only just avoids eventual gravitational collapse.

The small variations in the cosmic microwave background detected by the Planck orbiting observatory are consistent with a universe that underwent a period of inflation and resulted in the clumping of matter into clusters of galaxies.

Electroweak era

10^{-32} seconds to 10^{-12} seconds

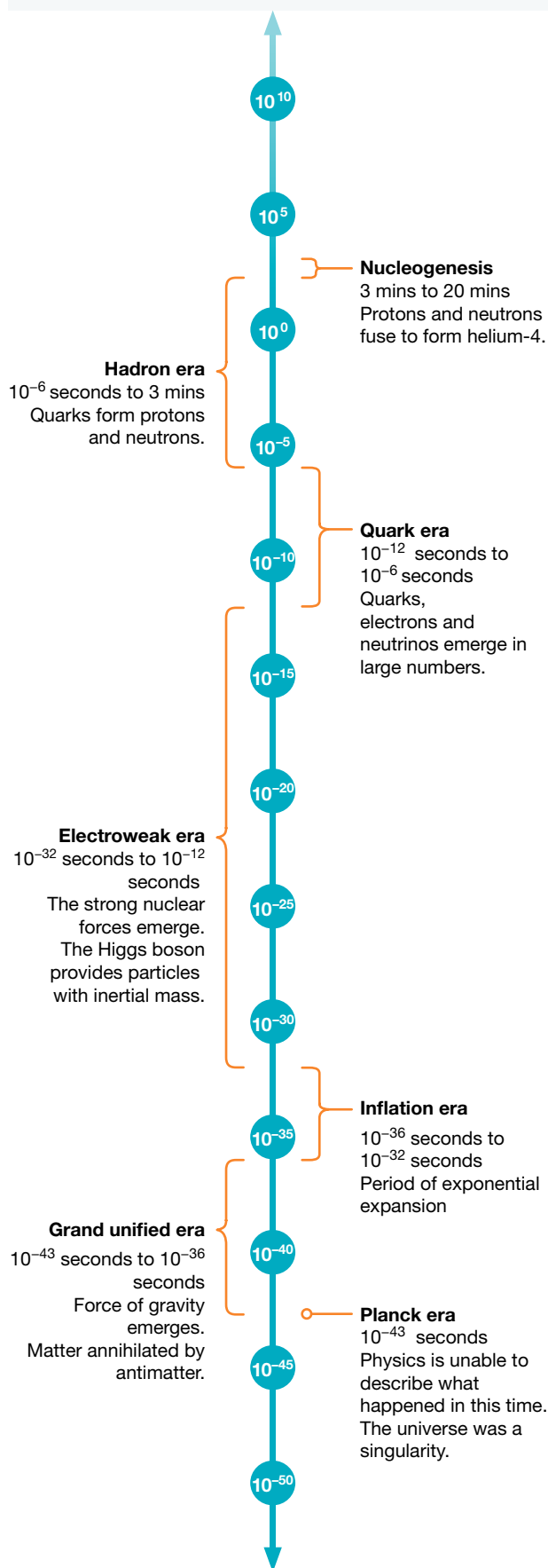
The electroweak era was the period when the strong nuclear force came into play. The Higgs boson formed, enabling particles to have mass.

Quark era

10^{-12} seconds to 10^{-6} seconds

The quark era was when particles began to appear in large numbers. These included quarks, electrons and neutrinos. Most particles still formed in pairs with an antiparticle, but a bias towards particles resulted in matter that was not annihilated through contact with antimatter. The source of this bias is not well understood.

FIGURE 6.20 Timeline of the early universe



Hadron era

10^{-6} seconds to 3 minutes

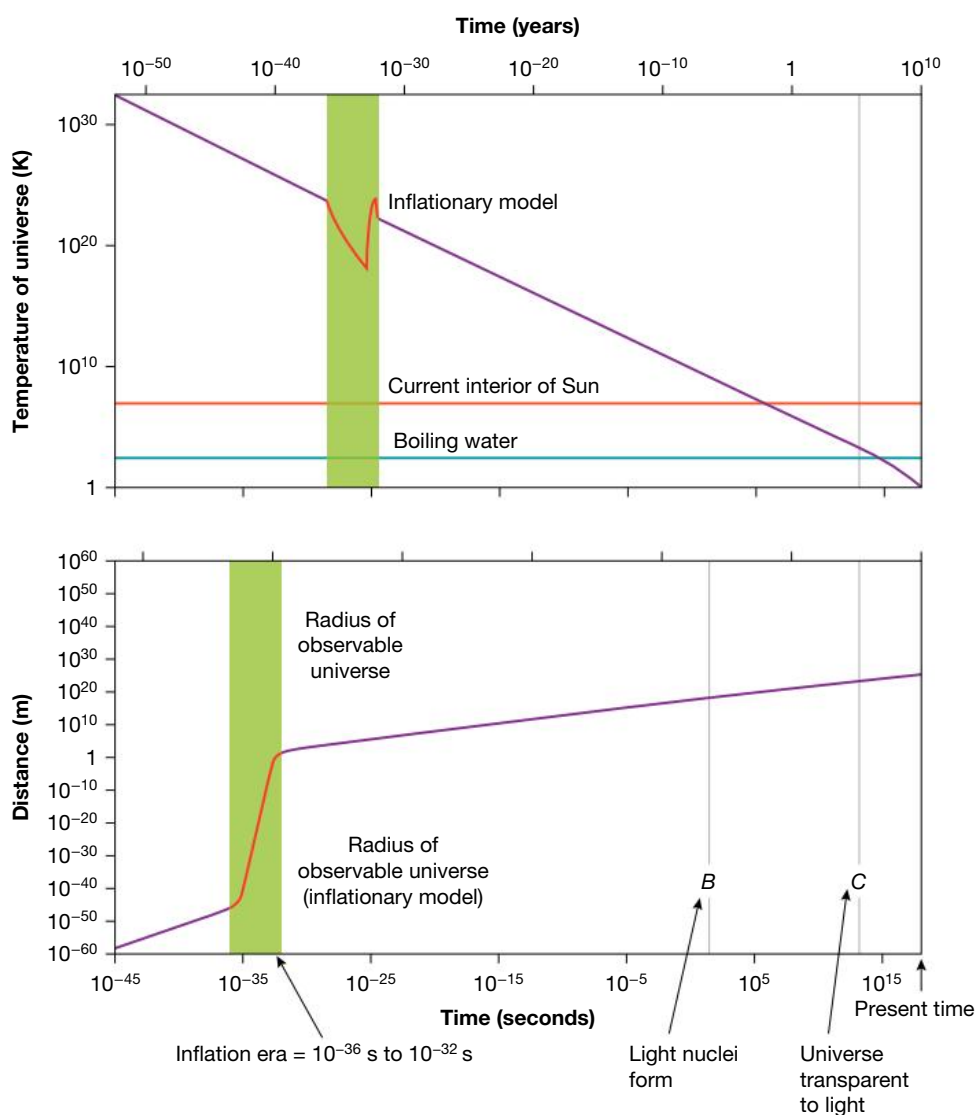
The hadron era was the period when the temperature of the universe had dropped to the point where three quarks could form protons and neutrons (particles like neutrons and protons made from three quarks are called hadrons). Most are annihilated by contact with their antiparticles, and leptons such as electrons dominate.

Nucleogenesis

3 minutes to 20 minutes

Nucleogenesis occurs. During this era, annihilation with antimatter became less significant and the critical phase of fusion occurred. During these few minutes most of the nuclei in the universe formed. The following section outlines this in detail.

FIGURE 6.21 Temperature and size of the universe over time



SAMPLE PROBLEM 12

What separates the quark era from the other eras of the early universe?

 **Teacher-led video:** SP12 (tlvd-0052)

THINK

1. Recall the details of the quark era.
2. Identify the details that distinguish it from other eras.

WRITE

The quark era was when particles such as quarks, electrons and neutrinos began to appear in large numbers and matter began to dominate over antimatter.

Prior to the quark era particles were annihilated by their antiparticles as soon as they formed. Quarks existed as individual particles. In subsequent eras, quarks have been only found combined with other quarks to form larger particles like protons and neutrons.

PRACTICE PROBLEM 12

What distinguishes the electroweak era from other eras of the early universe?

6.5.3 Nucleogenesis (the birth of atoms)

In 1948, George Gamow (1904–1968) and Ralph Alpher (1921–2007) proposed a model that explained how over 99% of the atoms found in the universe could have formed. The protons and neutrons in the early period of the universe readily interacted with the abundance of electrons and neutrinos present, causing them to change from proton to neutron, and vice versa. This produced equal numbers of each, but as the universe cooled, fewer protons interacted with electrons with sufficient energy to form neutrons. This resulted in more protons being formed than neutrons in a ratio of about 7 to 1. This formed a universe of hydrogen. Under the right temperature and pressure protons and neutrons can fuse, one at a time, to form helium-4. These conditions were present when the early universe was about 400 seconds old, allowing nuclei up to a mass number of 4 to form.

This produced:

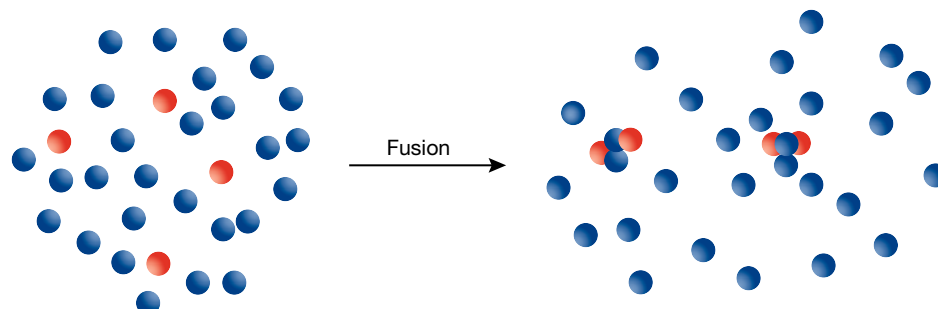
- hydrogen (1 proton)
- deuterium (an isotope of hydrogen with 1 proton and 1 neutron)
- tritium (an isotope of hydrogen with 1 proton and 2 neutrons)
- helium-3 (2 protons and 1 neutron)
- helium-4 (2 protons and 2 neutrons).

No stable isotope with a mass number of 5 exists (this has been tested in the laboratory), so fusion of nuclei beyond helium-4 was very limited. Tiny quantities of lithium-7 and beryllium-7 were produced through fusion of helium nuclei, but the step to heavier elements involving the fusion of three helium nuclei to form carbon takes too long. The universe rapidly cooled through its expansion to the point where the conditions no longer supported fusion. This provided the young universe with its composition of about 75% hydrogen and 25% helium by mass.

To understand the prediction of the proportion of hydrogen to helium, consider the ratio of protons to neutrons, which is 7:1. To form a helium-4 nucleus, 2 protons and 2 neutrons are required. According to the 7:1 ratio, for every 2 neutrons in the universe, there were 14 protons. The formation of helium-4 would take 2 neutrons and 2 protons, leaving 12 protons in the mix. That leaves 4 nucleons in helium and 12 in hydrogen, or 25% of the mass in helium and 75% in hydrogen. The fusion in these first moments of the

universe was so rapid and complete that virtually all of the available neutrons went into helium-4. Only a tiny proportion remained as deuterium or tritium (which decays to helium-3) so this simple calculation gives a very good prediction of the composition of the universe prior to star formation.

FIGURE 6.22 In the early universe protons outnumbered neutrons 7 to 1.



For nearly 20 minutes, conditions in the universe were sufficiently hot and dense for protons to fuse with neutrons ensuring that virtually all neutrons were bound in helium-4 nuclei. One of the strongest pieces of measured evidence for the Big Bang model of the universe (along with the observed expansion and CMB) is this predicted proportion of hydrogen and helium. As astrophysicists measure the proportions of the elements in regions of the universe not greatly affected by fusion in stars, the elements are found in this predicted abundance.

So we have the formation of nuclei in the early universe, but there are no atoms. That will take more time because although the universe has cooled sufficiently for nuclei to form, it is still way too hot for electrons to stay bound to those nuclei. Before atoms could form, 380 000 years would pass.

Table 6.1 outlines significant events in the early universe.

TABLE 6.1 Significant events in the early universe

Time since beginning of universe (seconds)	Temperature (K)	Event
10^{-36} to 10^{-32}		Inflation occurs
10^{-12} to 10^{-6}	10^{16}	Elementary particles including quarks and leptons form
10^{-6} to 100	10^{12}	Annihilation of antimatter and matter leave relatively small amount of matter
10^2	10^9	Commencement of nuclear fusion
10^3		Cessation of fusion
10^{13} (380 000 years)	3000	Formation of atoms (recombination), CMB produced
10^{13} to 10^{16}		Dark Ages (stars yet to form)
10^{16} (800 000 000 years)		First stars and galaxies form; most atoms re-ionised
10^{17} (9.3 billion years)		Earth and solar system form
10^{18} (13.82 billion years)	2.7	Today

It was not until 800 million years into the universe's life that the story of the atom resumed, when the first stars formed and new elements began to form in nuclear fusion in their interiors. In the centres of these enormous stars, the temperature and pressure was sufficient for long enough for fusion to continue beyond the formation of helium-4, resulting ultimately in the genesis of all of the elements in nature.

SAMPLE PROBLEM 13

A section of space contained 20 neutrons prior to nucleogenesis. How many helium-4 nuclei would have formed in this section of space during nucleogenesis?

 **Teacher-led video:** SP13 (tlvd-0053)

THINK

1. Recall how many neutrons and protons are required to make a helium-4.
2. Recall that there were seven protons for every neutron.
3. Count how many helium-4 nuclei could have formed from this raw material.

WRITE

2 neutrons and 2 protons per helium-4

7 protons for every neutron were present, so in a space containing 20 neutrons we could expect $7 \times 20 = 140$ protons — plenty to make helium-4 from every neutron available.

Each helium-4 requires 2 neutrons, so 20 neutrons would produce 10 helium-4 nuclei.

PRACTICE PROBLEM 13

A section of space formed 2×10^{30} helium-4 nuclei in the nucleogenesis era of the early universe. How many hydrogen-1 nuclei would have been produced in the same section of space?



Resources



Weblinks NASA — the Big Bang
Planck data
The early universe

6.5 EXERCISE

To answer questions online and to receive **immediate feedback** and **sample responses** for every question go to your learnON title at www.jacplus.com.au.

1. Outline how the quark era differed to the electroweak era.
2. What first happened in the hadron era?
3. When did the force of gravity first exist as a defined force?
4. How long into the universe's existence did protons and neutrons begin to appear in significant numbers?
5. Why were particles in the earliest moments of the universe so short lived?
6. Provide two problems that the inflation hypothesis solves.
7. What prevented nuclear fusion occurring prior to 3 minutes and later than 20 minutes into the life of the universe?
8. Explain how the Big Bang Theory predicts a ratio of hydrogen to helium of 3:1 in terms of mass.
9. What prevented electrons from binding to nuclei to form atoms in the first 380 000 years of the universe's existence?

studyon

To answer practice exam questions online and to receive immediate feedback and sample responses for every question go to your learnON title at www.jacplus.com.au.

studyON: Practice exam questions 

Fully worked solutions and sample responses are available in your digital formats.

6.6 Review

6.6.1 Summary

- Our galaxy, the Milky Way, is only one of billions of galaxies.
- All distant galaxies are moving away from us, and the further away they are, the faster they are receding.
- The expansion of space provided the first evidence that the universe had a beginning, now determined to have occurred 13.8 billion years ago.
- In the earliest moments of the universe, there was a period called inflation, where the size of the universe grew exponentially within a fraction of a second.
- After about 20 minutes, the universe consisted of hydrogen and helium nuclei with 25% of the mass in helium and 75% in hydrogen.
- Atoms first appeared 380 000 years into the universe's history when the universe was cool enough for electrons to stay bound to nuclei.
- Light was then free to travel through the universe, which is now visible as the cosmic microwave background radiation.
- Production of heavier elements did not occur until the first stars began fusing hydrogen and helium in their cores, 800 000 000 years after the beginning of the universe.
- The Big Bang is the name given to the theory that describes the universe beginning from a point of infinite density and expanding to create space and time as we see it today.
- The key evidence for the Big Bang includes: the expansion of the universe, the higher density of galaxies in the past, the proportion of elements in the universe and the cosmic microwave background radiation.
- Stephen Hawking showed that the universe may have no boundaries of space or time — time began with the universe, and space and time outside of the universe have no meaning.
- When measuring distance, temperature, mass and time in the universe, the numbers can be unmanageably large or small. To reduce this problem numbers can be expressed in scientific notation where a number between 1 and 10 is multiplied by a power of 10. For very small numbers, the power of ten is negative.
- Alternative units for distance are used in measuring space. The astronomical unit (AU) is the distance from Earth to the Sun. It is useful for measuring the solar system. The parsec (pc) is the distance that produces a parallax angle of one arc second as the Earth moves around the Sun. A light-year is the distance light travels in one year.

Resources

studyON

To access key concept summaries and practice exam questions download and print the **studyON: Revision and practice exam question booklet** (sonr-0031).

6.6.2 Key terms

The **Big Bang** is the name for the dramatic beginning of the universe from an infinitely dense, small point.

A **Cepheid variable** is a type of star that has a relationship between its period of variation in luminosity and its maximum luminosity. They are useful for measuring distances to galaxies.

The **cosmic microwave background** is radiation that can be found in all regions of empty space. It is left over energy from the Big Bang.

Cosmology is the study of how the universe began, has evolved and will end.

A **galaxy** is a collection of hundreds of billions of stars. Stars are organised into galaxies, with very few stars existing between galaxies.

A **globular cluster** is a very old, densely packed cluster of stars in the shape of a sphere.

Hubble's constant is the constant of proportionality relating the speed that galaxies are receding from Earth and their distance from Earth.

Hubble's Law states that the speed of recession of galaxies is proportional to their distance from Earth.

Recombination is the event when electrons could remain bound to nuclei to form atoms. Prior to 380 000 years after the Big Bang, electrons had too much energy due to the temperature to remain bound to nuclei.

Red shift is the increase in wavelength that results from a light source moving away from the observer.

on Resources

 **Digital document** Key terms glossary (doc-32184)

6.6.3 Practical work and investigations

Investigation 6.1

Expansion of the universe

Aim: To model the expansion of the universe in two dimensions, using the surface of a balloon

Digital document: doc-31871

Teacher-led video: tlvd-0816



on Resources

 **Digital document** Practical investigation logbook (doc-32185)

6.6 Exercises

6.6 Exercise 1: Multiple choice questions

- Which of the following correctly describes scientific theories?
 - Well thought out scientific explanations
 - Guesses
 - Beyond dispute
 - Measured facts
- What does the Big Bang Theory predict?
 - The ratio of hydrogen to helium is 3:2.
 - Galaxies are further apart as we look further into space.
 - There is a relationship between distance and red shift of distant galaxies.
 - The expansion of the universe will cause the universe to heat up.
- Which of the following facts did Hubble use to measure distances to galaxies?
 - Super novae have a known luminosity.
 - Some stars have a luminosity related to their period of variation.
 - Globular clusters contain old stars.
 - The CMB is nearly uniform.

4. What did Hubble discover that was important evidence for the Big Bang Theory?
 - A. Red shift of galaxies increases with distance.
 - B. Red shift of galaxies decreases with distance.
 - C. The CMB is nearly uniform.
 - D. There is three times the amount of hydrogen by mass than there is helium.
5. What is the explanation for the photons of the CMB having much less energy than 13 billion years ago?
 - A. The photons have worn out with age.
 - B. Photons are more dispersed through the expanded universe.
 - C. They have lost energy through interaction with matter.
 - D. Their wavelengths have been stretched as they travel through the expanding universe.
6. Which of the following numbers is the smallest?
 - A. 3.4×10^8
 - B. 2.34×10^9
 - C. 3.39×10^8
 - D. 3×10^8
7. Which of the following is *not* written in correct scientific notation?
 - A. 25×10^3
 - B. 2.3×10^{25}
 - C. 1.006×10^6
 - D. 7×10^{-7}
8. Which of the following is correct?
 - A. Matter formed before the quark era.
 - B. The strong nuclear force emerged in the inflation era.
 - C. The first atoms formed during nucleogenesis.
 - D. Electrons existed in the quark era.
9. When did the Dark Ages in cosmology occur?
 - A. Before recombination
 - B. After recombination and prior to the first stars
 - C. During inflation era
 - D. Before the quark era
10. When did inflation occur most dramatically?
 - A. Prior to the appearance of gravity
 - B. After atoms formed
 - C. After the strong nuclear force emerged
 - D. After the grand unified era

6.6 Exercise 2: Short answer questions

1. What did Hubble discover in 1929 that led to the formulation of the Big Bang Theory?
2. The light from the Andromeda galaxy is blue shifted. Explain why it is not red shifted like the light from most galaxies.
3. How is the Big Bang different from normal explosions in terms of space and time?
4. List the key evidence in favour of the Big Bang Theory.
5. Why was the CMB discovery so important in establishing the Big Bang Theory?
6. Why is scientific notation preferred when writing very large and very small numbers?
7. The inflation era is the time when the universe was between 10^{-36} and 10^{-32} seconds old. Write these times in decimal notation.
8. Why did nucleogenesis in the early universe only produce light nuclei like hydrogen and helium?
9. List the following events in chronological order: particle–antiparticle annihilation, ignition of the first stars, nuclear fusion, inflation, the formation of atoms.
10. What metaphor did Stephen Hawking use to help explain how time has a beginning?

6.6 Exercise 3: Exam practice questions

Question 1 (4 marks)

- a. Sketch a graph of red shift versus distance that summarises Hubble's observations of galaxy red shifts. **2 marks**
- b. How did Hubble determine the speed of recession of galaxies? **1 mark**
- c. What type of star did Hubble use in his distance measurements for the galaxies? **1 mark**

Question 2 (3 marks)

- a. Describe the source of the cosmic microwave background radiation. **2 marks**
- b. The variations in CMB measured by the Planck space observatory are about 0.000 57 K. Write this in scientific notation. **1 mark**

Question 3 (1 mark)

What tools do physicists use to improve their understanding of what happens to matter in the conditions in the early universe?

Question 4 (1 mark)

What needs to happen to energy in order to explore earlier periods?

Question 5 (1 mark)

As physicists explored the earliest moments of the universe they noticed that the four fundamental forces — gravity, weak nuclear force, strong nuclear force and electromagnetic force — were not always separate. In what order did the forces appear after the beginning of the universe?

Question 6 (4 marks)

For just a few minutes in the early universe, nuclear fusion could take place.

- a. What were the products of this fusion? **2 marks**
- b. Why were the products limited to these? **2 marks**

6.6 Exercise 4: studyON topic test

Fully worked solutions and sample responses are available in your digital formats.

teachon

Test maker

Create unique tests and exams from our extensive range of questions, including practice exam questions. Access the assignments section in learnON to begin creating and assigning assessments to students.

7 Particles in the nucleus

Numerous **videos** and **interactivities** are available just where you need them, at the point of learning, in your digital formats, eBookPLUS and learnON at www.jacplus.com.au.

7.1 Overview

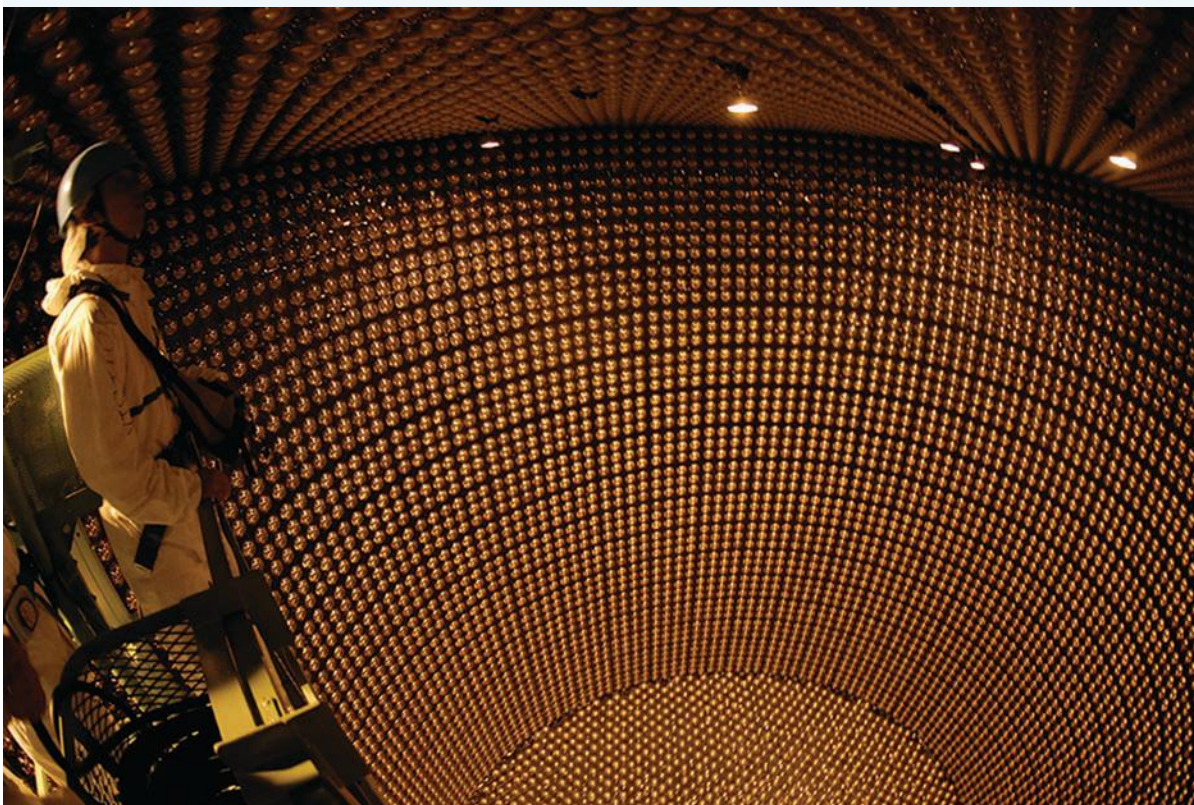
7.1.1 Introduction

The nucleus was first described in 1911 by Ernest Rutherford. Earlier discoveries such as X-rays in 1895 by Wilhelm Röntgen, radioactivity by Henri Becquerel in 1896 and new radioactive elements in 1898 by Marie and Pierre Curie were both explained by and made possible by the nuclear model of the atom developed by Rutherford.

By further investigating the nucleus, scientists have been able to identify a set of fundamental particles that are the building blocks of all matter. These particles, and the way they interact with each other, form the Standard Model of particle physics.

Understanding the Standard Model is essential in identifying some of the major challenges we face, whether they be scientific, economic, technological, environmental or medical. That understanding is the focus of this topic. The next topic will focus on how the nucleus relates to energy production.

FIGURE 7.1 The Super-Kamiokande neutrino observatory is situated 1000 metres underground to insulate it from other subatomic particles. Neutrinos are incredibly difficult to detect, with observatories such as Super-Kamiokande detecting only a handful each month.



7.1.2 What you will learn

KEY KNOWLEDGE

After completing this topic you will be able to:

- explain nuclear stability with reference to the forces that operate over very small distances
- describe the radioactive decay of unstable nuclei with reference to half-life
- model radioactive decay as random decay with a particular half-life, including mathematical modelling with reference to whole half-lives
- apply a simple particle model of the atomic nucleus to explain the origin of α , β^- , β^+ and γ radiation, including changes to the number of nucleons
- explain nuclear transformations using decay equations involving α , β^- , β^+ and γ radiation
- analyse decay series diagrams with reference to type of decay and stability of isotopes
- relate predictions to the subsequent discoveries of the neutron, neutrino, positron and Higgs boson
- describe quarks as components of subatomic particles
- distinguish between the two types of forces holding the nucleus together: the strong nuclear force and the weak nuclear force
- compare the nature of leptons, hadrons, mesons and baryons
- explain that for every elementary matter particle there exists an antimatter particle of equal mass and opposite charge, and that if a particle and its antiparticle come into contact, they will annihilate each other to create radiation.

Source: VCE Physics Study Design (2016–2021) extracts © VCAA; reproduced by permission.

PRACTICAL WORK AND INVESTIGATIONS

Practical work is a central component of learning and assessment. Experiments and investigations, supported by a **Practical investigation logbook** and **Teacher-led videos**, are included in this topic to provide opportunities to undertake investigations and communicate findings.

Resources

 **Digital documents** Key science skills — VCE Units 1–4 (doc-31856)

Key terms glossary (doc-32186)

Practical investigation logbook (doc-32265)

study

To access key concept summaries and practice exam questions download and print the **studyON: Revision and practice exam question booklet** (sonr-0032).

7.2 The discovery of subatomic particles

KEY CONCEPTS

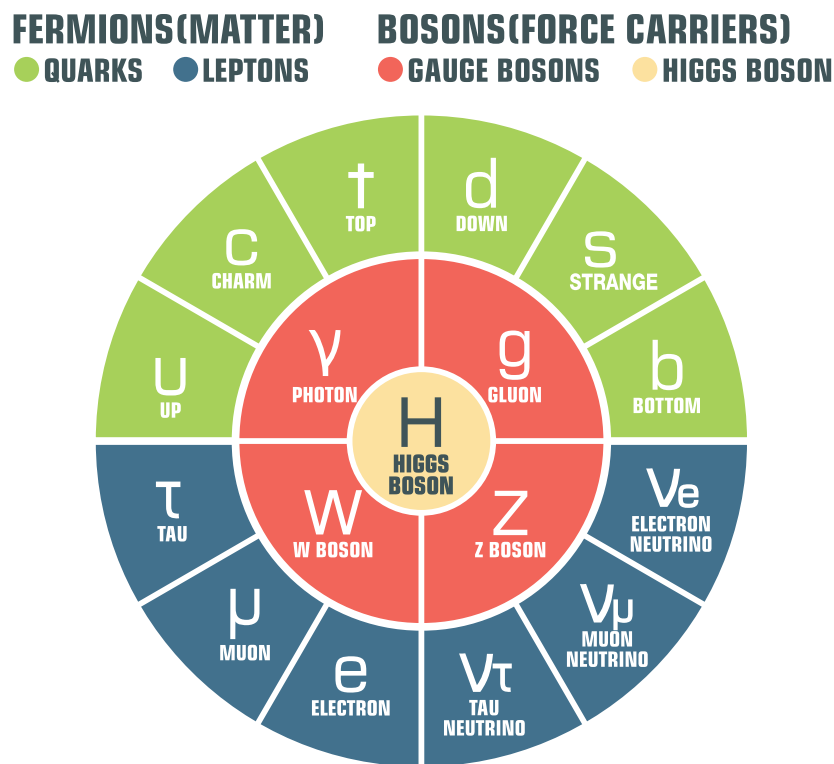
- Relate predictions to the subsequent discoveries of the neutron, neutrino, positron and Higgs boson.
- Describe quarks as components of subatomic particles.
- Distinguish between the two types of forces holding the nucleus together: the strong nuclear force and the weak nuclear force.
- Compare the nature of leptons, hadrons, mesons and baryons.
- Explain that for every elementary matter particle there exists an antimatter particle of equal mass and opposite charge, and that if a particle and its antiparticle come into contact they will annihilate each other to create radiation.

7.2.1 The Standard Model of particle physics

The Standard Model of particle physics describes all known elementary particles of matter and three of the four known fundamental forces that describe their behaviour. There are seventeen particles named in the Standard Model, all of which can be classified into two types of particles: **fermions** and **bosons**.

Fermions describe the fundamental particles that make up all matter, while bosons are the mediators (cause) of interactions between other particles. A fundamental particle is one that is not made up of other smaller particles.

FIGURE 7.2 The Standard Model of particle physics



7.2.2 Gauge bosons

There are four fundamental forces of physics that describe the way particles interact with each other. They are, in order of increasing strength:

- *gravity*. The force of attraction between any two objects with mass, it is the weakest of the four forces and acts over an infinite distance.
- *weak nuclear force* (or *weak interaction*). This force causes radioactive decay. It is much stronger than gravity, but weaker than electromagnetism and the strong force. The weak nuclear force acts over very small distances of magnitude 10^{-18} metres, or distances less than the width of a proton.
- *electromagnetism*. The force that governs electric fields and magnetic fields, it is the second strongest force after the strong nuclear force and acts over an infinite distance.
- *strong nuclear force* (or *strong interaction*). This force is responsible for holding protons and neutrons together in the nucleus by acting between the fundamental particles that make up the proton and neutron. It acts over distances of magnitude 10^{-15} metres, which is about the size of the nucleus.

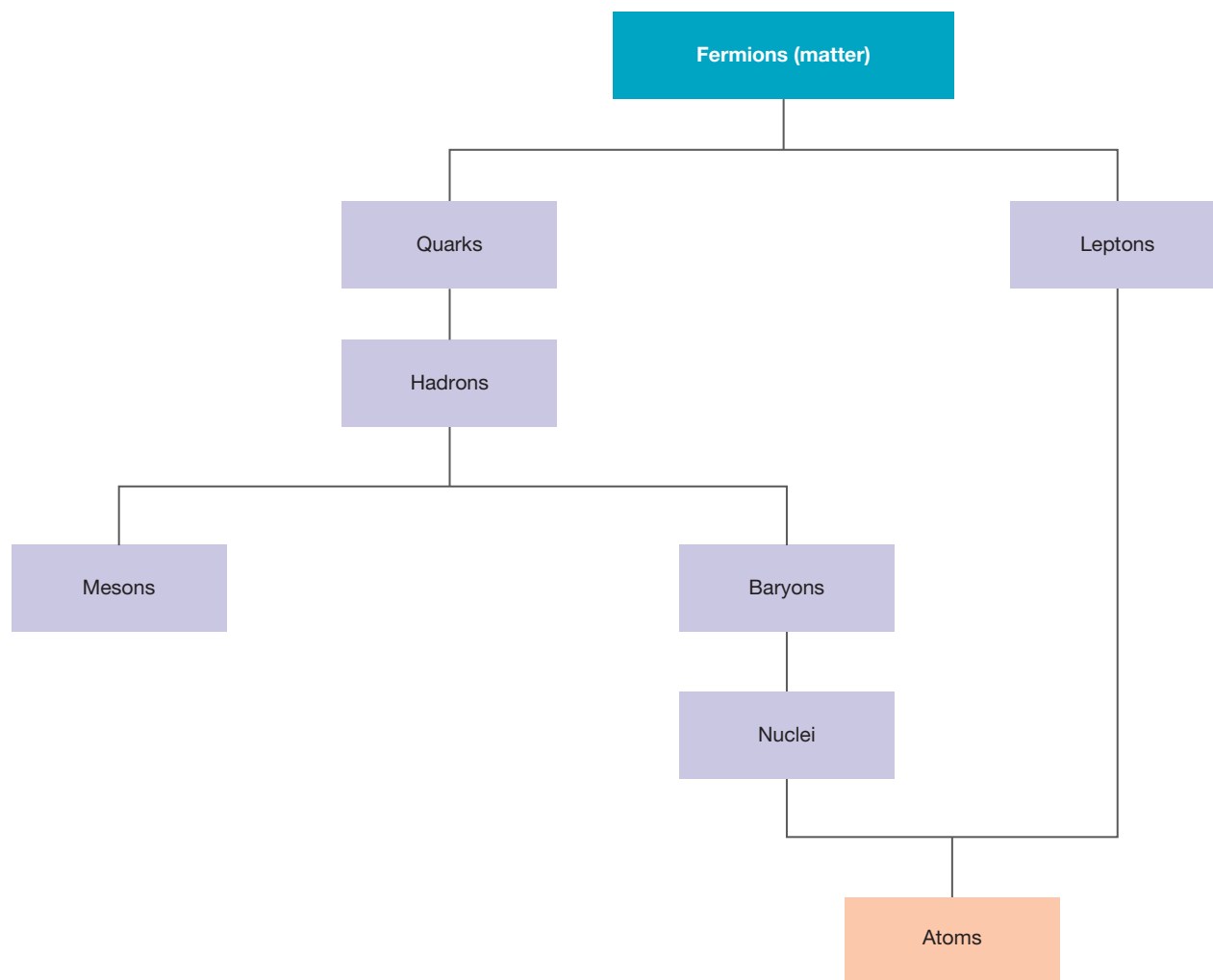
We know that a particle can experience a force due to another particle, even though the two particles are not in direct contact. In the Standard Model, force-carrying particles, called gauge bosons (or bosons), are thought to ‘carry’ forces from one particle to another.

Three of the four fundamental forces are governed by the exchange of bosons. Electromagnetism, the strong nuclear force and the weak nuclear force each have their own boson, so gauge bosons come in three main forms: photons, which carry the electromagnetic force, gluons, which essentially hold quarks together and are therefore considered to carry the strong nuclear force, and the W and Z bosons, which are responsible for the weak nuclear force. As yet, no boson has been found that carries the gravitational force and so gravity is the one force that the Standard Model does not yet explain.

7.2.3 Fermions

The twelve fundamental particles of matter are called fermions, which are defined by their **quantum numbers** (such as charge). Fermions can be classified into two groups: quarks and leptons.

FIGURE 7.3 The families of subatomic particles and their relationship to matter and atoms



Leptons

Leptons are the simplest and lightest of the subatomic particles. The different types of leptons are shown in table 7.1. Leptons interact using the weak nuclear force. They do not experience the strong nuclear force.

Leptons are fundamental particles, that is, they have no internal structure, although muons and tau particles decay into electrons. The neutrinos accompany any interaction of their heavier partner.

TABLE 7.1 Leptons

Name	Symbol	Mass	Charge	First observed	Half-life
Electron	e^-		Negative	1869	Stable
Muon	μ^-	About $200 \times$ mass of electron	Negative	1936	10^{-6} s
Tau	τ	About $277 \times$ mass of electron	Negative	1977	10^{-13} s
Electron neutrino	ν_e	Negligible	Neutral	1956	Stable
Muon neutrino	ν_μ	Negligible	Neutral	1962	Stable
Tau neutrino	ν_τ	Negligible	Neutral	2000	Stable

The electron is found in atoms and determines the chemical properties of elements.

The muon decays to an electron according to the equation: $\mu^- \rightarrow e^- + \bar{\nu}_e + \nu_\mu$. The $\bar{\nu}_e$ particle is an anti-electron neutrino. The bar above the symbol indicates that it is an antiparticle (discussed later).

Note: The neutrino that is produced in beta decay — that is, when a neutron decays into a proton — is actually an anti-electron neutrino.

Muons have a number of industrial uses. They are more penetrating than X-rays and gamma rays and are non-ionising, so they are safe for humans, plants and animals. Their better penetrating power means that, for example, they can be used to investigate cargo containers for shielded nuclear material. Muons have also been used to look for hidden chambers in the pyramids. Muon detectors were used at the Fukushima nuclear complex to determine the location and amount of nuclear fuel still inside the reactors that were damaged by the Japanese tsunami in 2011.

The tau particle was discovered some time later than the muon. The unusual feature of this particle is that it decays into two pions, which are discussed later. The decay equation is $\tau^- \rightarrow \pi^- + \pi^0 + \nu_\tau$. The negative pion, π^- , then decays into an electron, while the neutral pion, π^0 , decays to two gamma rays.

SAMPLE PROBLEM 1

How many different leptons are there in the Standard Model? Name them.

THINK

1. Look up leptons in table 7.1.
2. List the names from table 7.1.

WRITE

There are six leptons in the Standard Model.

The six leptons are:

- electron
- muon
- tau
- electron neutrino
- muon neutrino
- tau neutrino.

PRACTICE PROBLEM 1

Compare the life times of the leptons.

Quarks

We know that all matter is made up of **protons**, **neutrons** and **electrons**, however, protons and neutrons can be broken down further into fundamental particles called **quarks**.

The quark model has six different quarks, each with different masses and a fraction of the charge of the electron. Each quark has its own antiparticle. Quarks have rather unusual names, which are shown in table 7.2 along with their charges and mass.

The top quark has the same mass as a gold atom!

Quarks are the only particles that interact using the strong nuclear force. Leptons do not experience the strong nuclear force. Quarks have never been found on their own, they have only been found bound together with other quarks to form hadrons.

TABLE 7.2 Quarks

Quark	Symbol	Charge	Multiple of proton mass	First observed
Up	u	$+\frac{2}{3}$	0.003	1968
Down	d	$-\frac{1}{3}$	0.006	1968
Charm	c	$+\frac{2}{3}$	1.3	1974
Strange	s	$-\frac{1}{3}$	0.1	1968
Top	t	$+\frac{2}{3}$	184.0	1995
Bottom	b	$-\frac{1}{3}$	4.5	1977

Hadrons

Hadrons are distinctive because they are much heavier than the leptons, but much more importantly they all have an internal structure. Hadrons are made up of different combinations of quarks. Hadrons that are a combination of two quarks are called mesons. The other hadrons are combinations of three quarks and are called baryons.

Mesons

There are over 60 different types of **mesons**. They play a role in nuclear interactions but have very short half-lives, so they are very difficult to detect. Each meson also has an antiparticle. Mesons are composed of one quark and one antiquark. A positive pion (π^+) is made of one up quark and one down antiquark to give a charge of $+1$. While its antiparticle, π^- , is made of one up antiquark and one down quark to give a charge of -1 .

Baryons

Baryons include the proton and neutron as well as about 70 other different particles. Only the proton and neutron are stable, with all other baryons having extremely short half-lives. Each baryon also has its own antiparticle. Baryons have three quarks. A proton is made up of two up quarks and one down quark to give a charge of $+1$. A neutron consists of one up quark and two down quarks to give a charge of zero.

FIGURE 7.4 The quark structure of the neutron and proton

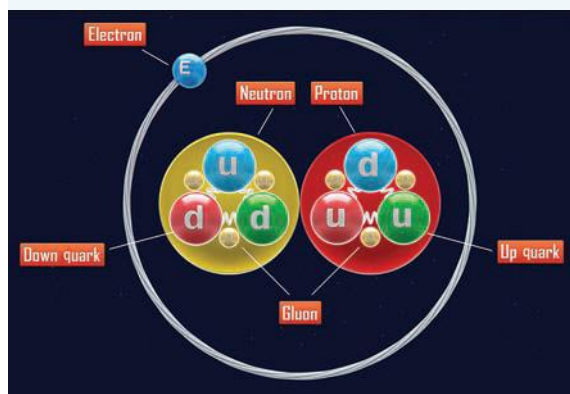
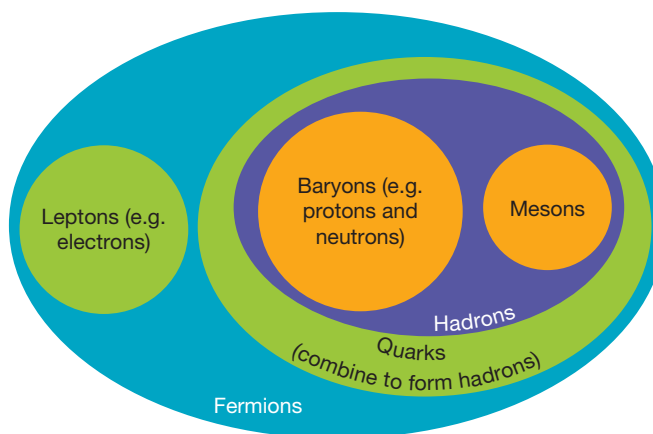


FIGURE 7.5 The different types of fermions



A proton is made up of two up quarks and one down quark to give a charge of $+1$. A neutron consists of one up quark and two down quarks to give a charge of zero.

SAMPLE PROBLEM 2

Particles of matter can be classified as either mesons, baryons or leptons. Which of these is not part of an atom?

THINK

1. Look at figure 7.3, a classification key for subatomic particles. Locate 'Atoms' and determine which is not part of an atom: a meson, baryon or lepton.

WRITE

According to the key, atoms are made up of a combination of nuclei, which in turn are made up of baryons and leptons. Mesons are found on a different branch, therefore, a meson is not part of an atom.

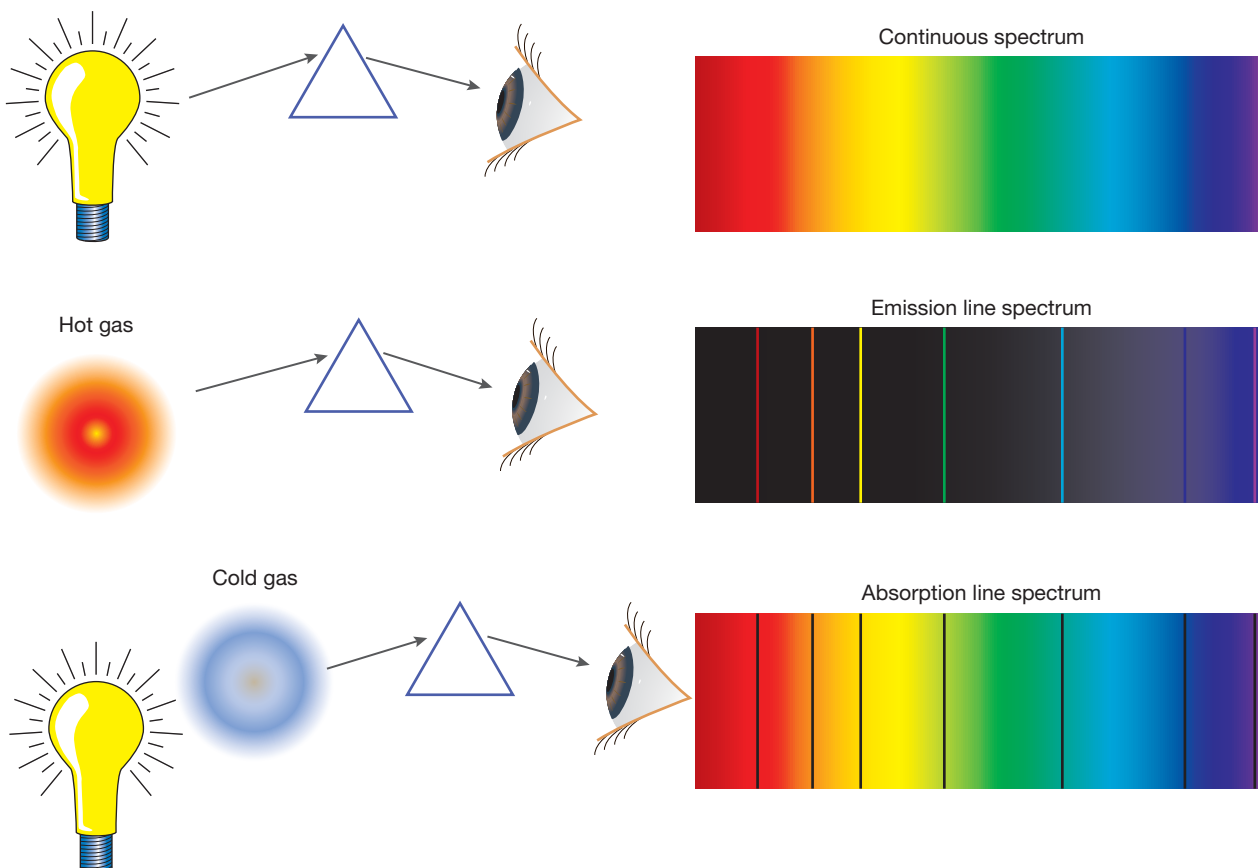
PRACTICE PROBLEM 2

According to figure 7.3, nuclei are made of baryons. What, therefore, are two particles from the baryon family?

Why a quark model?

In the late nineteenth century, when visible light was shone through a gas of atoms of a particular element, a spectra of black lines was observed. Each element produced a unique pattern of these lines, called an absorption pattern (see figure 7.6).

FIGURE 7.6 A continuous spectrum and two different ways of producing an element's fingerprint



In topic 2, the greenhouse effect was explained by describing how H_2O and CO_2 molecules respond to particular infra-red wavelengths of electromagnetic radiation. The lines in the atomic absorption patterns suggested that there was some complexity or structure inside the atom. This structure was discovered early in the twentieth century. Similarly, the absorption patterns for H_2O and CO_2 molecules tell us something about how the molecules are put together.

More information about the internal structure of the nucleus can be determined by the energy of alpha particles emitted through radioactive decay. This energy is specific to the nucleus undergoing decay.

If a system is showing evidence that it can have only certain energy values, then it must have a structure, that is, be made up of smaller particles.

During the 1960s it was discovered that when protons and neutrons were hit by a beam of particles, a type of spectra was evident, much like molecules, atoms and nuclei. This meant that protons and neutrons are made up of even smaller particles. This was the beginning of the quark model.

In 1961, Murray Gell-Mann and Kazuhiko Nishijima developed a classification of all the known subatomic particles that predicted a new type of particle called a quark, which was found a few years later. Then Gell-Mann and George Zweig developed their idea further into the quark model.

SAMPLE PROBLEM 3

Like atoms and nuclei, protons and neutrons are not fundamental particles. They can be explained as a combination of smaller particles called quarks. How do physicists know that atoms, nuclei, protons and neutrons are not fundamental particles?

THINK

1. Identify the observations that physicists have about protons and neutrons.
2. How does this information imply that protons and neutrons are not fundamental particles?

WRITE

In a similar way to atoms and nuclei, a spectrum of allowable energies has been detected for protons and neutrons.

Atoms produce electromagnetic spectra containing particular allowable energies that are interpreted as energy released by electrons as they change state in the atom. If the atom had no structure, but was a fundamental particle, this would be impossible as there would be no electrons or energy states. Similarly with protons and neutrons, the existence of possible energy states within these particles reveals that they have internal structure. They are not fundamental.

As protons and neutrons also have a spectrum of distinct energy states they are not fundamental, but are made up of smaller constituent parts known as quarks.

PRACTICE PROBLEM 3

How many energy states could a fundamental particle be in?

7.2.4 Matter and antimatter

In 1928, Paul Dirac developed a mathematical theory to explain the properties of the electron: its mass, charge, role in beta decay and its energy inside the atom. The calculated values for these properties exactly fitted their measured values, but Dirac's equations suggested there may be two solutions — a negatively charged electron and a positively charged electron, with the same mass but opposite charge. Indeed, he raised the possibility of there being another form of matter, which he called 'antimatter'.

Every particle, whether lepton, hadron or boson has an antiparticle. The best known example is probably the antiparticle of the electron, known as the **positron**. These antiparticles have important practical uses and are a key component of medical scanning through positron emission tomography (PET) scans.

Particles and their antiparticles have the same mass but opposite charge. To indicate an antiparticle of an uncharged particle, a bar is placed above the symbol of the matter particle; for example, a tau neutrino has the symbol ν_τ and the antitau neutrino has the symbol $\bar{\nu}_\tau$. To indicate the antiparticle of a charged particle, the symbol is given the opposite sign; for example, the symbol for the electron is e^- and the symbol for the positron is e^+ .

The electron is a lepton and the positron its antiparticle. Hadrons, such as protons, neutrons and mesons also have antiparticles. If the hadron is charged, its antiparticle has the same mass but opposite charge. The neutron has no charge so the antineutron also has no charge.

Mesons have some interesting examples because they are made from a quark and an antiquark. If the quark and antiquark are of the same type, known as flavour (for example, an up quark and an anti-up quark), then the antiparticle is exactly the same particle!

Bosons, apart from the W are chargeless. These bosons are their own antiparticles. The antiparticle of the W^+ is the W^- , and vice versa.

When a particle and its own antiparticle come together, they annihilate each other, producing photons of energy.

SAMPLE PROBLEM 4

The antiparticle of a proton is an antiproton. It is made from two up antiquarks and a down antiquark. What is the charge of the antiproton? Show that this is consistent with the charges of its component quarks.

 **Teacher-led video:** SP4 (tlvd-0062)

THINK

1. Recall that a charged particle has the opposite charge of its antiparticle.
2. Look up the charges of the up and down quarks and find the charges of the antiquarks.
3. Add the charges of the three antiquarks that make an antiproton.
4. Compare this total with the charge of the antiproton.

WRITE

A proton has a charge of $+1$ so an antiproton has a charge of -1 .

An up quark has a charge of $+\frac{2}{3}$ and a down quark has a charge of $-\frac{1}{3}$. Therefore, an up antiquark has a charge of $-\frac{2}{3}$ and a down antiquark has a charge of $+\frac{1}{3}$.

An antiproton is made of two up antiquarks and one down antiquark. These have a total charge of $-\frac{2}{3} + -\frac{2}{3} + \frac{1}{3} = -1$.

The sum of the antiquark charges is the same as the antiproton charge as expected.

PRACTICE PROBLEM 4

Compare the properties of an antiproton with those of an electron.

7.2.5 Bosons and the strong and weak nuclear forces

The strong force acts between quarks and holds protons and neutrons together to form the different nuclei. The way that this force acts between quarks is through the exchange of massless particles called gluons. The strong force acts over a tiny distance so quarks and hadrons made from them must be very close for gluon exchange to occur. The strong nuclear force is the strongest of the four fundamental forces.

The weak nuclear force is much stronger than gravity but much weaker than electromagnetic force and the strong nuclear force. It acts over only one thousandth of the distance of the strong nuclear force. It is the force that results in beta decay, where protons become neutrons, or neutrons become protons. Other forces do not change particles from one type to another like this. To achieve this change a boson, either a W^+ or a W^- , is exchanged. The weak force acts on all particles involved in beta decay, the nucleon, the electron/positron and the neutrino/antineutrino. The strong nuclear force does not act on leptons such as electrons and neutrinos. A third boson can be exchanged in the weak force. The uncharged Z particle is exchanged when scattering of leptons, like neutrinos, changes their momentum.

SAMPLE PROBLEM 5

How does the strong nuclear force differ from the weak nuclear force in terms of particles it acts on and the distance over which it acts?

 **Teacher-led video:** SP5 (tlvd-0063)

THINK

1. What particles does the strong nuclear force act on?
2. What particles does the weak nuclear force act on?
3. Over what distances do the strong and weak forces act?

WRITE

The strong nuclear force acts on quarks and particles made from quarks — hadrons, including protons and neutrons.

The weak nuclear force acts on leptons such as electrons and neutrinos, as well as quarks. While the strong force holds quarks to each other, the weak force changes properties of the particle. (It can change an up quark to a down and it can change the momentum of a neutrino.)

The strong force acts over a distance of the order of a proton diameter. The weak force acts over a distance only about one-thousandth of this distance.

PRACTICE PROBLEM 5

There is a particle known as a pion. It is a meson made from combinations of pairs of up and down quarks and antiquarks. The half-life of the pion made from an up quark and a down antiquark is 2.6×10^{-8} seconds. They decay into muon and muon neutrinos. What force acts to cause this decay?

7.2.6 Explaining the strong nuclear force

The atomic nucleus is held together by the strong nuclear force due to the exchange of gluons between quarks. The hadrons (such as the proton and neutron) made up of these quarks also experience the strong force.

In the 1930s, Hideki Yukawa was seeking an explanation for the properties of the strong nuclear force that exists between protons and neutrons inside the nucleus. It was known that this force had a very short range, with each proton or neutron attracted only to its near neighbours, not the whole nucleus. Yukawa suggested that a previously unobserved particle acted as ‘glue’ between pairs of protons in the nucleus, as well as between other pairings. To fit the known features of the strong force, he determined the properties of this unobserved particle. He said it should:

- be about 200 times the mass of the electron
- have the same charge size as the electron
- come in two types: positive and negative
- have a very short half-life of about a millionth of a second
- interact very strongly with nuclei.

In 1936 Carl Anderson’s group found such a particle in cosmic ray showers. This particle was named the muon. However, while the muon satisfied the first four of Yukawa’s properties, it became apparent that its interaction with nuclei was very weak, so the muon was not a good candidate to explain the strong nuclear force.

A few years later, Cecil Powell investigated cosmic ray showers at high altitude in the Pyrenees and the Andes. These observations were higher up in the cascade of collisions that cosmic rays set off when they hit the atmosphere. At this altitude, Powell found another particle that better fit the needs of the strong nuclear force. This particle is called the π -meson or pion.

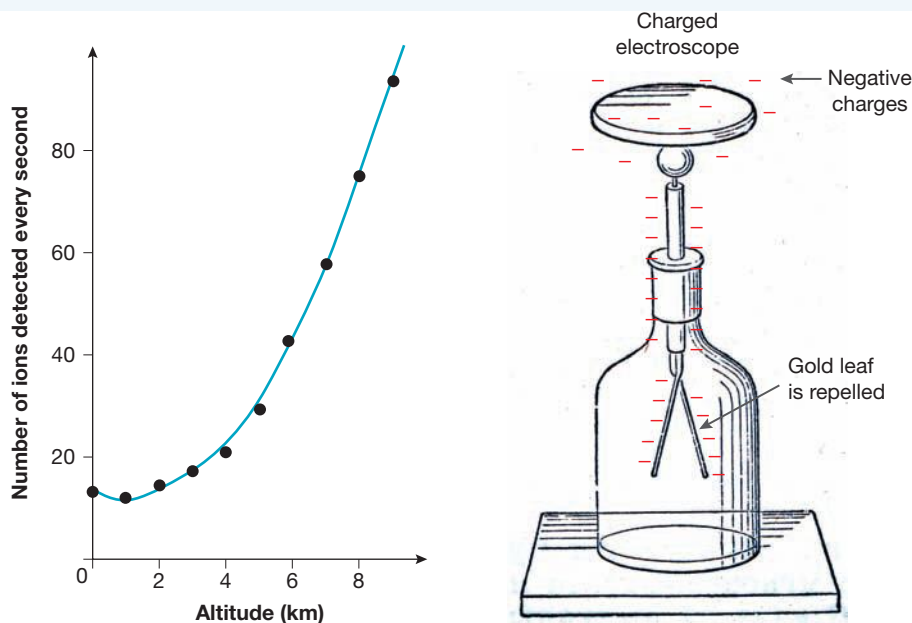
Shortly after Powell’s discovery, the pion was also detected in the laboratory when carbon nuclei were bombarded with high-energy alpha particles. After this time, most new particles were found in laboratories using particle accelerators.

7.2.7 Prediction of new particles

The positron

Natural radioactivity was first discovered when beta particles exposed photographic plates. One of the other technologies used to investigate radioactivity was the gold leaf electroscope. Electroscopes show the presence of electric charge. A charged electroscope slowly loses charge due to the ions in the air produced by radioactive elements in the Earth’s crust. It was thought that this effect would decrease with height above the ground.

FIGURE 7.7 The number of charged particles from cosmic rays varies by altitude above the Earth’s surface.



However, in 1909 it was found that the intensity of radiation was greater on top of the Eiffel Tower. Balloon flights then showed the intensity continued to increase with height, suggesting that the radiation may originate from space. So, the name **cosmic rays** was coined.

Initially cosmic rays were called ‘rays’ because they were thought to be like light. However, even though they are now known to be particles, the name has stuck. Further investigation over the following decades showed that the particles entering the Earth’s atmosphere were mainly protons. The particles seemed to come from beyond the solar system from all points of the sky. Indeed they are now thought to originate in supernovae and the centre of galaxies. They are also extremely fast and energetic. The energy of these protons is 40 million times the energy of the protons in the Large Hadron Collider used to produce the Higgs boson.

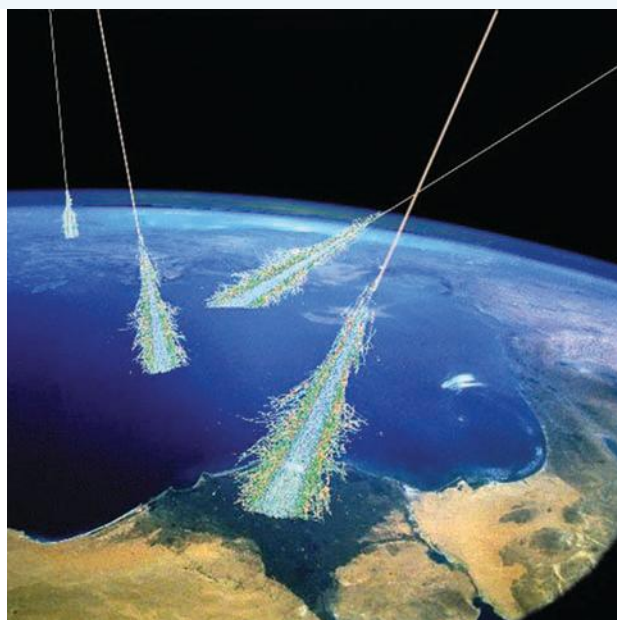
When these protons with their massive energy hit an atom in the upper atmosphere, they cause a cascade of successive collisions that produces a shower of charged particles and gamma rays at the Earth’s surface.

On average, cosmic rays contribute about 16% of your exposure to ionising radiation from natural sources. This exposure increases the more you fly in a plane and the higher you fly.

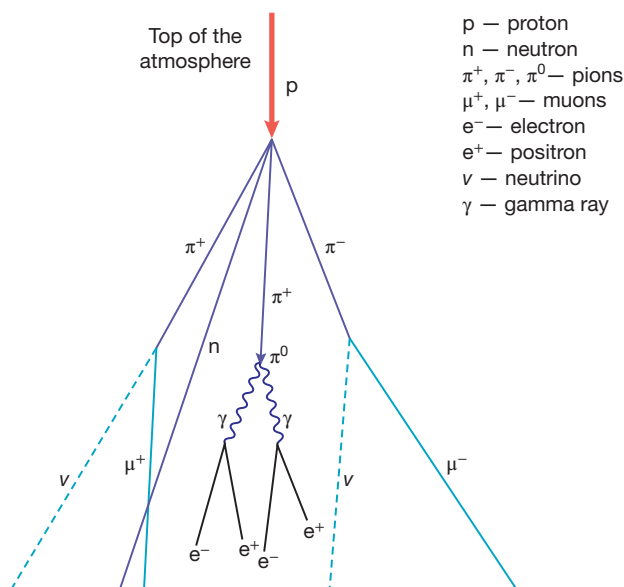
In 1933 Carl Anderson was investigating the charged particles in cosmic ray showers and observed a particle that had the same mass as the electron, but with a positive charge. He had discovered a new particle, the positron.

The chamber Anderson used to detect this charged particle was placed in a strong magnetic field so that a positively charged particle would curve one way and a negatively charged particle would curve the other way. In this experimental set up, an incoming gamma ray collides with a nucleus; the energy of the gamma ray is converted into mass, using $E = mc^2$, but because charge needs to be conserved, two particles of opposite sign are produced.

FIGURE 7.8 Showers of particles form as cosmic rays hit the atmosphere.



Source: NASA



The reverse process is also possible. An electron and a positron, or indeed, any particle and its antiparticle, can collide and annihilate each other, producing two gamma rays.

FIGURE 7.9 A gamma ray produces an electron and a positron. The spiralling is due to the slow loss of energy as the track is created.

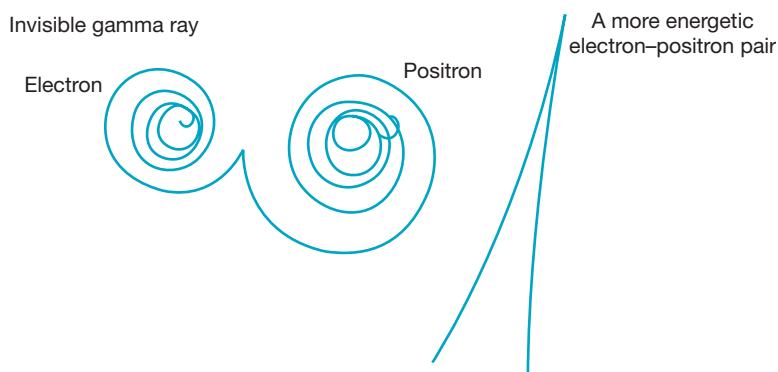
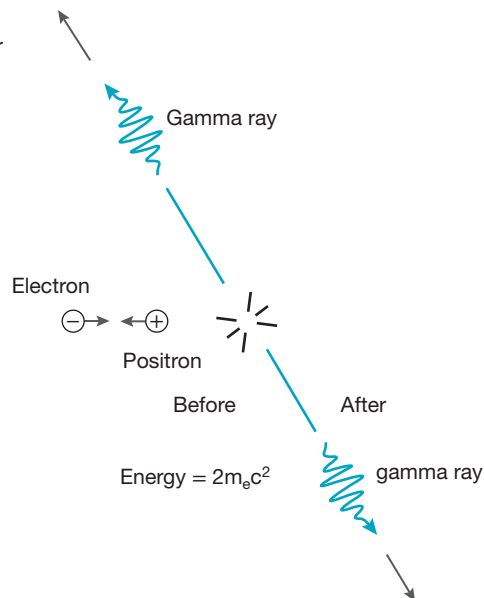


FIGURE 7.10 A particle and antiparticle annihilate each other with their mass, producing two gamma rays.



Resources



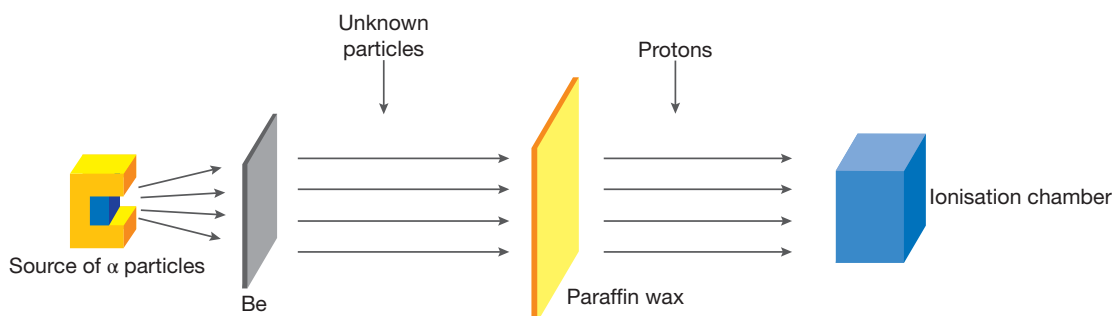
Interactivity Electrons and positrons (int-6394)

The neutron

When Rutherford was developing the concept of the nucleus, it was known that an alpha particle had exactly twice the positive charge of a hydrogen ion, so presumably contained two protons, but was almost exactly four times as heavy. There were a number of explanations for this anomaly. One was that the extra mass was made up of proton–electron pairs, which would effectively have zero charge; another was that there was an as yet unknown neutral particle in the nucleus.

It was only in the 1930s that this neutral particle, called the ‘neutron’, was discovered. In 1930, Walter Bothe and Herbert Becker fired alpha particles at beryllium and detected what they thought was gamma radiation. The husband-and-wife team Frédéric Joliot and Irène Joliot-Curie (daughter of Marie Curie) placed hydrogen-rich paraffin wax in front of this ‘gamma radiation’ and observed the ejection of protons. While they explored the possibility of very high-energy radiation, James Chadwick showed that this was virtually impossible; instead, he demonstrated that a single neutron was ejected when the alpha particle entered the beryllium nucleus, which in turn knocked on a proton in a simple billiard-ball-like collision.

FIGURE 7.11 Discovery of the neutron



The discovery of the neutron now provided an explanation for the existence of isotopes (atoms with the same atomic number but different atomic mass due to different numbers of neutrons).

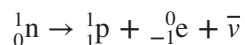
The neutrino

Alpha particles are emitted with particular energies that are unique to the host nucleus, whereas beta particles are emitted with any energy up to a maximum. When examining decay reactions, scientists found that not all of the energy was accounted for. The possible explanations were:

- the Law of Conservation of Energy, one of the foundations of physics, did not apply in nuclear processes
- a second particle, as yet undetected, was emitted. This idea was proposed by Wolfgang Pauli, who said the particle must have no charge, as all the charge was accounted for, and have negligible mass.

Enrico Fermi named the particle ‘neutrino’, from the Italian for ‘little neutral one’. Fermi incorporated Pauli’s suggestion into a theory of β decay that not only built on Dirac’s work but also derived a mathematical relationship between the half-life of a particular decay and the maximum energy of the emitted β particle. This relationship matched the experimental data, which was convincing evidence for the existence of the neutrino, although it was not actually detected until 1956.

The neutrino has the symbol ν , which is the Greek letter *nu*. The antineutrino has the symbol $\bar{\nu}$. The complete β^- decay process is:



Beta decay will be further explored in section 7.4.2.

The Higgs boson

Since the positron was observed in 1932, confirming a prediction from theory, particle after particle that has been predicted has been observed. By the end of 2000, all predicted particles had been observed in experiment except for the Higgs boson. This particle had been predicted in 1964 to solve problems with existing theory. Scientists had developed a theory that made sense of what was known about the particles of matter that made up the known universe. However, it only worked if certain particles had zero mass. Some of those particles were known to have mass so something was missing. Peter Higgs, François Englert and three others proposed that there was a field through space, now known as the Higgs field, that particles with mass interacted with via a particle called the Higgs boson. If the Higgs boson was found, the theory of the Standard Model would match experimental results. To search for this elusive particle, the largest particle accelerator ever built was constructed at CERN on the border of Switzerland and France. More than 100 countries are involved in the Large Hadron Collider, which has cost more than US\$13 billion. In July 2012 scientists announced that this enormous investment had paid off and the final piece in the Standard Model had been observed. Higgs and Englert were awarded the Nobel Prize for Physics in 2013, for the prediction they had made nearly fifty years earlier.

SAMPLE PROBLEM 6

Name four particles whose existence was predicted by scientific theory before they were observed or detected.

THINK

- 1 This topic highlights four particles that were predicted prior to discovery.

WRITE

The neutron, neutrino, positron and Higgs boson were all predicted by scientific theory prior to their detection. If they had been found not to exist, a new theory would have been required as the theory would not have been consistent with observation.

PRACTICE PROBLEM 6

Refer to topic 6. What is another example of a phenomenon that was predicted by theory prior to being observed?

7.2 EXERCISE

To answer questions online and to receive **immediate feedback** and **sample responses** for every question go to your learnON title at www.jacplus.com.au.

1. The Large Hadron Collider used to discover the Higgs boson is an internationally run experiment that has cost billions of dollars. Comment on the importance of scientific theory in its construction.
2. Explain the difference between the terms baryon and hadron.
3. How many quarks does the Standard Model predict? Name them.
4. How many leptons does the Standard Model predict? Name them.
5. Compare the forces holding electrons in an atom with those holding protons and neutrons together in the nucleus.
6. Neutrinos are very difficult to detect and most that hit the Earth pass right through. Protons and electrons do not pass through. Explain the differences.
7. From your knowledge of the neutron, describe an antineutron.
8. What would happen if a neutron and an antineutron came together?
9. Antimatter was discussed in topic 6 when describing matter in the first moments of the universe. Explain why matter appeared for such brief moments before being destroyed in the early universe, and why most of the matter in the form of protons, neutrons and electrons has existed since the first minutes of the universe's existence.
10. Hadrons and quarks were eras of the early universe discussed in topic 6. What were the defining features of those eras?
11. The lambda baryon (Λ) was discovered by researchers at the University of Melbourne in 1950. Its quark composition is uds. What is its charge?

studyon

To answer practice exam questions online and to receive immediate feedback and sample responses for every question go to your learnON title at www.jacplus.com.au.

studyON: Practice exam questions 

Fully worked solutions and sample responses are available in your digital formats.

7.3 Nuclear radiation

KEY CONCEPTS

- Explain nuclear stability with reference to the forces that operate over very small distances.
- Distinguish between the two types of forces holding the nucleus together: the strong nuclear force and the weak nuclear force.
- Describe the radioactive decay of unstable nuclei with reference to half-life.
- Model radioactive decay as random decay with a particular half-life, including mathematical modelling with reference to whole half-lives.

7.3.1 Atoms and isotopes

Nuclear radiation, as the name suggests, is radiation emitted from the nucleus of an atom. In order to explain the mechanisms that release such radiation, it is important to understand a little about the structure of the atom.

Atoms

All matter is made up of atoms. Each atom consists of a tightly packed, positively charged centre, called the **nucleus**, which is surrounded by a ‘cloud’ of negatively charged electrons. The particles in the nucleus are known collectively as **nucleons**, but there are two different types, protons and neutrons. Protons are positively charged, neutrons are chargeless, and both are about 2000 times heavier than the electrons that surround the nucleus.

Scientists name atoms according to the number of protons in the nucleus. For example, all atoms with six protons are called carbon, all atoms with 11 protons are called sodium, and all atoms with 92 protons are called uranium. A substance consisting of atoms that all have the same name is called an **element**. Each element’s name has its own shorthand symbol that scientists use. Carbon has the symbol ‘C’, sodium ‘Na’ and uranium ‘U’. It is very important that the upper or lower case of the letters used in the symbols is kept the same. The names of all the elements, and their symbols, can be found in the periodic table in figure 7.13.

FIGURE 7.12 The structure of a typical atom

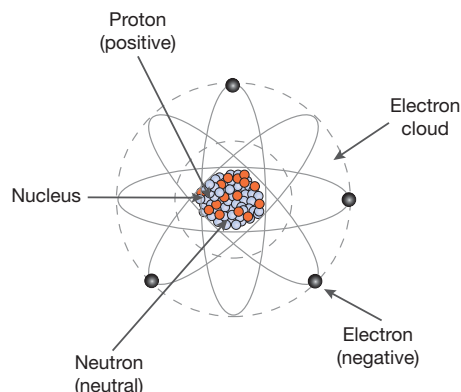


FIGURE 7.13 The periodic table

Group 1																		Group 2																		Group 3																		Group 4																		Group 5																		Group 6																		Group 7																		Group 8																		Group 9																		Group 10																		Group 11																		Group 12																		Group 13																		Group 14																		Group 15																		Group 16																		Group 17																		Group 18																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																	
Period 1																		Period 2																		Period 3																		Period 4																		Period 5																		Period 6																		Period 7																		Period 8																		Period 9																		Period 10																		Period 11																		Period 12																		Period 13																		Period 14																		Period 15																		Period 16																		Period 17																		Period 18																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																	
1 Hydrogen H 1.0																		2 Helium He 4.0																		3 Lithium Li 6.9																		4 Beryllium Be 9.0																		5 Boron B 10.8																		6 Carbon C 12.0																		7 Nitrogen N 14.0																		8 Oxygen O 16.0																		9 Fluorine F 19.0																		10 Neon Ne 20.2																		11 Sodium Na 23.0																		12 Magnesium Mg 24.3																		13 Aluminium Al 27.0																		14 Silicon Si 28.1																		15 Phosphorus P 31.0																		16 Sulfur S 32.1																		17 Chlorine Cl 35.5																		18 Argon Ar 39.9																		19 Potassium K 39.1																		20 Calcium Ca 40.1																		21 Scandium Sc 45.0																		22 Titanium Ti 47.9																		23 Vanadium V 50.9																		24 Chromium Cr 52.0																		25 Manganese Mn 54.9																		26 Iron Fe 55.8																		27 Cobalt Co 58.9																		28 Nickel Ni 58.7																		29 Copper Cu 63.5																		30 Zinc Zn 65.4																		31 Gallium Ga 69.7																		32 Germanium Ge 72.6																		33 Arsenic As 74.9																		34 Selenium Se 79.0																		35 Bromine Br 79.9																		36 Krypton Kr 83.8																		37 Rubidium Rb 85.5																		38 Strontium Sr 87.6																		39 Yttrium Y 88.9																		40 Zirconium Zr 91.2																		41 Niobium Nb 92.9																		42 Molybdenum Mo 96.0																		43 Technetium Tc (98)																		44 Ruthenium Ru 101.1																		45 Rhodium Rh 102.9																		46 Palladium Pd 106.4																		47 Silver Ag 107.9																		48 Cadmium Cd 112.4																		49 Indium In 114.8																		50 Tin Sn 118.7																		51 Antimony Sb 121.8																		52 Tellurium Te 127.6																		53 Iodine I 126.9																		54 Xenon Xe 131.3																		55 Caesium Cs 132.9																		56 Barium Ba 137.3																		57-71 Lanthanoids																		72 Hafnium Hf 178.5																		73 Tantalum Ta 180.9																		74 Tungsten W 183.8																		75 Rhenium Re 186.2																		76 Osmium Os 190.2																		77 Iridium Ir 192.2																		78 Platinum Pt 195.1																		79 Gold Au 197.0																		80 Mercury Hg 200.6																		81 Thallium Tl 204.4																		82 Lead Pb 207.2																		83 Bismuth Bi 209.0																		84 Polonium Po (210)																		85 Astatine At (210)																		86 Radon Rn (222)																		87 Francium Fr (223)																		88 Radium Ra (226)																		89-103 Actinoids																		104 Rutherfordium Rf (261)																		105 Dubnium Db (262)																		106 Seaborgium Sg (266)																		107 Bohrium Bh (264)																		108 Hassium Hs (267)																		109 Meitnerium Mt (268)																		110 Darmstadtium Ds (271)																		111 Roentgenium Rg (272)																		112 Copernicium Cn (285)																		113 Nihonium Nh (280)																		114 Flerovium Fl (289)																		115 Moscovium Mc (289)																		116 Livermorium Lv (292)																		117 Tennessine Ts (294)																		118 Oganesson Og (294)																	
Alkali metal																		Alkaline earth metal																		Transition metal																		Lanthanoids																		Actinoids																		Unknown chemical properties																		Post-transition metal																		Metalloid																		Reactive non-metal																		Halide																		Noble gas																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																															
57 Lanthanum La 138.9																		58 Cerium Ce 140.1																		59 Praseodymium Pr 140.9																		60 Neodymium Nd 144.2																		61 Promethium Pm (145)																		62 Samarium Sm 150.4																		63 Europium Eu 152.0																		64 Gadolinium Gd 157.3																		65 Terbium Tb 158.9																		66 Dysprosium Dy 162.5																		67 Holmium Ho 164.9																		68 Erbium Er 167.3																		69 Thulium Tm 168.9																		70 Ytterbium Yb 173.1																		71 Lutetium Lu 175.0																		89 Actinium Ac (227)																		90 Thorium Th 232.0																		91 Protactinium Pa 231.0																		92 Uranium U 238.0																		93 Neptunium Np (237)																		94 Plutonium Pu (244)																		95 Americium Am (243)																		96 Curium Cm (247)																		97 Berkelium Bk (247)																		98 Californium Cf (251)																		99 Einsteinium Es (252)																		100 Fermium Fm (257)																		101 Mendelevium Md (258)																		102 Nobelium No (259)																		103 Lawrencium Lr (262)																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																									

Isotopes

Not all atoms of the same name (and therefore the same number of protons) have the same number of neutrons. For instance, it is possible to find carbon atoms with six, seven and eight neutrons in the nucleus along with the six protons that make it carbon. These different forms of an element are called **isotopes**. To avoid confusion about which isotope is being referred to, scientists have a few standard ways of writing them. The number of nucleons, or **mass number**, of the particular isotope is used. The isotope of carbon with six protons and six neutrons is written as carbon-12 or ^{12}C , whereas the isotope of carbon with eight

neutrons is written as carbon-14 or ^{14}C . Sometimes the number of protons, or **atomic number**, is written directly underneath the mass number, although this is not necessary (for example, $^{14}_6\text{C}$).

SAMPLE PROBLEM 7

Write the name of the isotope of an atom with 90 protons and 144 neutrons.

THINK

1. What element has 90 protons?
2. What is the mass number of this isotope?
3. Write the name of the isotope.

WRITE

Checking the periodic table, the element thorium (symbol Th) has 90 protons.

$$90 + 144 = 234$$

The isotope of an atom with 90 protons and 144 neutrons is thorium-234 or ^{234}Th .

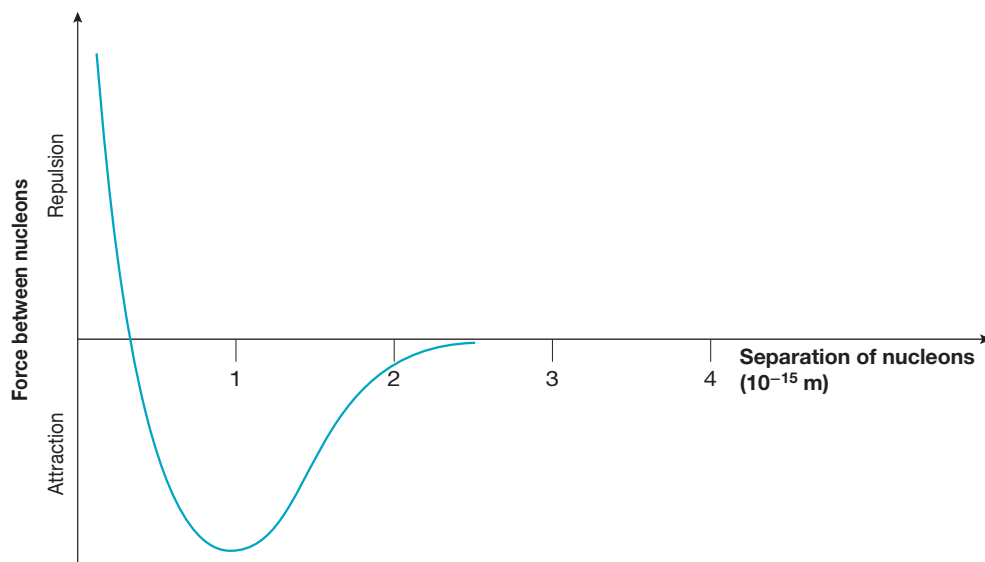
PRACTICE PROBLEM 7

What is the name of the isotope of an atom with 26 protons and 30 neutrons?

What holds the nucleus together?

The force that holds electrons around a nucleus is called an electrostatic force. Electrostatic forces increase as charges move closer together. Electrostatic attraction exists between unlike charges; electrostatic repulsion exists between like charges. So it seems strange that the positive charges inside a nucleus don't repel each other so strongly that the nucleus splits apart. In fact, two protons do repel each other when they are brought together but in the nucleus they are so close to each other that the force of repulsion is overcome by an even stronger force — the strong nuclear force. While the strong nuclear force is a very strong force, it can act over incredibly small distances only. Inside a nucleus, the nucleons are sufficiently close that the pull of the strong nuclear force is much greater than the push of the protons repelling each other, and therefore the nucleus remains intact. Figure 7.14 shows how the strength and sense of the strong nuclear force changes with the separation of the nucleons. Its ability to hold two nucleons together is strongest at around 1×10^{-15} metres but is virtually zero at about 2.5 times this distance.

FIGURE 7.14 How the strong nuclear force between two nucleons varies with the separation of the nucleons



Unstable nuclei

Some nuclei are unstable. Isotopes that contain unstable nuclei are called **radioisotopes**.

The reason that some nuclei are unstable can be explained by considering the interaction. Unstable isotopes can emit various types of radiations of the nucleons with the fundamental forces.

Though the strong nuclear force acts over very short distances only, the electromagnetic force continues to act with decreasing strength as the distance between charged particles increases. This is one reason that many nuclei are unstable. In a large nucleus, the combined effect of all the protons in the nucleus results in an electrostatic repulsion on some protons greater than the strong force holding those protons in the nucleus. This nucleus is unstable and cannot remain like this forever. This explains why the number of neutrons in large atoms is greater than the number of protons; neutrons are chargeless, so do not contribute to the electromagnetic repulsion. This trend is apparent in figure 7.15.

The weak nuclear force and the gravitational force are not significant in determining the stability of nuclei as they are comparatively weak over the distance of nucleon separation.

In order to become more stable, the nucleus in a radioisotope emits different types of nuclear radiation that increase the stability of the nucleus. The different types of radiation will be explained in detail in subtopic 7.4.

FIGURE 7.15 This graph shows which nuclei are stable (yellow) and which are unstable (other).

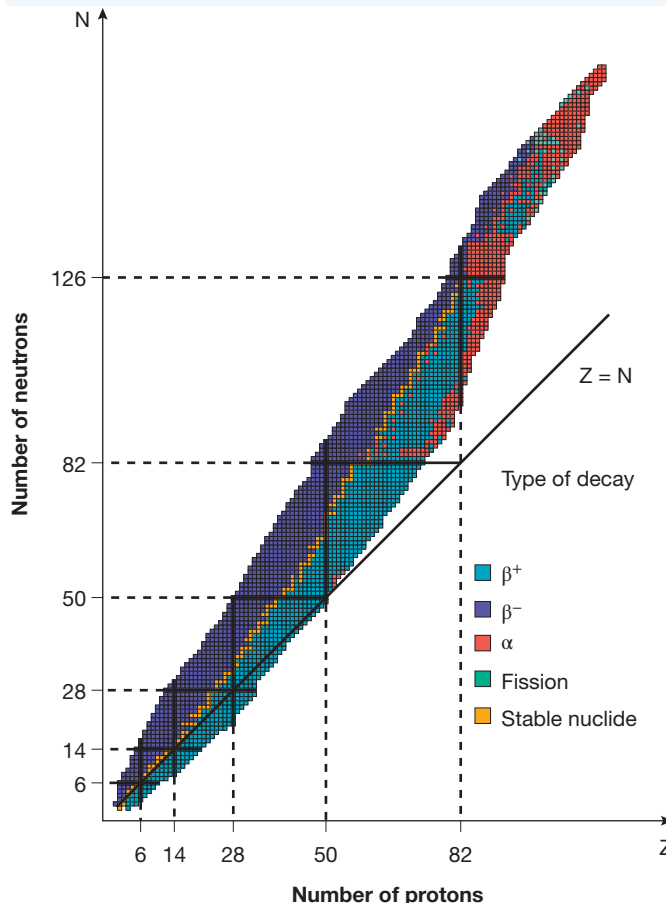


TABLE 7.3 Types of forces, their relative strengths and ranges

Force	Strength	Range	Type
Strong nuclear	1	10^{-15} m (diameter of a nucleus)	Attractive
Electric and magnetic	$\frac{1}{137}$	Infinite	Attractive or repulsive
Weak nuclear	$\frac{1}{1000\,000}$	10^{-18} m (fraction of proton diameter)	Attractive
Gravity	$\frac{1}{10^{38}}$	Infinite	Attractive

SAMPLE PROBLEM 8

The existence of nuclei larger than a single proton depends on forces holding neutrons and protons to together. Describe the nature of this force.

THINK

1. A nucleus larger than a proton includes protons and neutrons that are somehow held together.

WRITE

There is an attractive force called the strong nuclear force that acts between protons and neutrons.

2. Protons repel each other as they have like charge.

The strong nuclear force can only hold a nucleus together when it is stronger than the electromagnetic force pushing the protons apart.

3. Describe the nature of the force.

The force holding protons and neutrons together to form nuclei must be an attractive force that works between neutrons and protons and is stronger than the electromagnetic force at close range.

PRACTICE PROBLEM 8

A helium-3 nucleus has two protons and one neutron. Describe the forces acting within it.

7.3.2 Half-life

It is not possible to predict exactly when a given unstable nucleus will decay. However, we can predict what proportion of a certain number of nuclei will decay in a given time. It is rather like tossing a coin. We can't be sure that a given toss will result in a tail but we can predict that from 1000 tosses about 500 will result in tails. Scientists know that it will take 24 days for half of a group of unstable thorium-234 nuclei to decay to protactinium-234. The time taken for half a group of unstable nuclei to decay is called the **half-life**. Half-lives vary according to the isotope that is decaying. They range from microseconds to thousands of millions of years.

TABLE 7.4 Table of half-lives

Element	Half-life
Indium-115	6×10^{14} years
Potassium-40	1.3×10^9 years
Uranium-235	7.1×10^8 years
Actinium-227	22 years
Thorium-227	18 days
Carbon-11	20 minutes
Thallium-207	4.8 minutes
Magnesium-23	11 seconds
Polonium-212	3×10^{-7} seconds

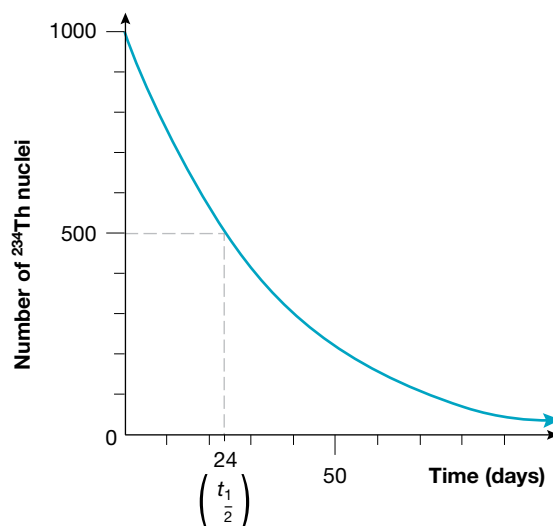
Mathematicians and scientists often use graphs with the same basic shape as the one in figure 7.16. It shows what is known as a **decay curve**. This type of curve often appears in science. It is called exponential decay.

Looking at figure 7.16, in the first few days the number of atoms decaying every day is quite high but towards the end the number is quite low. If there was a Geiger counter near the source at the beginning, it would be clicking quickly but near the end you would wait days for the next click. In fact, a graph of the count rate (the number of clicks per second) will have exactly the same shape and will show the same half-life. The number of decays per second of a radioactive source is a measure of its activity and is measured in becquerels (Bq).

TABLE 7.5 Activities of some everyday items

Item	Activity (Bq)
1 adult human	3000
1 kg coffee	1000
1 kg granite	1000
1 kg coal ash (used in cement)	2000
1 kg superphosphate fertiliser	5000

FIGURE 7.16 Graph showing decay of 1000 thorium-234 nuclei. The time taken for half of the original nuclei (500 nuclei) to remain is called the half-life. It can be seen from this graph that the half-life is 24 days. After the fourth half-life (at time = 96 days) it can be predicted that one-sixteenth of the thorium-234 (about 62 or 63 nuclei) would remain undecayed.



SAMPLE PROBLEM 9

Technetium-99 is often used for medical diagnosis. It has a half-life of 6 hours. A patient has a small amount of the isotope injected into the bloodstream. What fraction of the original amount will remain after:

- 12 hours
- 48 hours?

 **Teacher-led video:** SP9 (tlvd-0056)

THINK

- How many half-lives have passed?
 - How much would be left after halving it that many times?
 - State the solution.
- How many half-lives have passed?
 - How much would be left after halving it that many times?
 - State the solution.

WRITE

a. $\frac{12}{6} = 2$ half-lives

$$\frac{1}{2} \times \frac{1}{2} = \left(\frac{1}{2}\right)^2 = \frac{1}{4}$$

One-quarter would be left after 12 hours.

b. $\frac{48}{6} = 8$ half-lives

$$\left(\frac{1}{2}\right)^8 = \frac{1}{256}$$

$\frac{1}{256}$ would be left after 48 hours.

PRACTICE PROBLEM 9

Cobalt-60 is radioactive with a half-life of 5.27 years. It is produced from cobalt-59 by bombardment with neutrons at a nuclear reactor. It emits a low-energy beta particle followed by two high-energy gamma rays. It is used in the sterilisation of medical equipment, in radiotherapy and in industrial applications. A cobalt-60 source will need to be replaced when its activity decreases to $\frac{1}{16}$ of its initial value. How long will this take?

7.3 EXERCISE

To answer questions online and to receive **immediate feedback** and **sample responses** for every question go to your learnON title at www.jacplus.com.au.

1. Name the isotope that has an atomic number of 11 and contains 12 neutrons.
2. How many protons and neutrons are there in one atom of each of the following isotopes?
 - (a) Hydrogen-2, also known as deuterium
 - (b) Americium-241
 - (c) Europium-164
3. What force acts between a proton and a neutron and under what conditions does it act?
4. The half-life of caesium-134 is 2.06 years. What fraction of caesium is left after 10.3 years?
5. What is meant when an isotope is described to be stable?
6. If the strong nuclear force acts between all nucleons and is much stronger than the electromagnetic force at the distance of two neighbouring nucleons in a nucleus, explain how a nucleus might be unstable.
7. 100 grams of a radioactive isotope is delivered to a hospital. Three hours later there is only 6.25 grams left. What is the half-life of the isotope?
8. Sketch a graph of the decay of the isotope in question 7.
9. Why is half-life used for radioactive isotopes rather than just stating how long it takes to decay?
10. The activity (decays per second) of a radioactive isotope halves with each half-life. Explain why that would be the case.
11. You need 20 grams of a radioactive isotope with a half-life of three hours. How much would you need to buy if it takes 24 hours to deliver it?

studyon

To answer practice exam questions online and to receive immediate feedback and sample responses for every question go to your learnON title at www.jacplus.com.au.

studyON: Practice exam questions 

Fully worked solutions and sample responses are available in your digital formats.

7.4 Types of nuclear radiation

KEY CONCEPTS

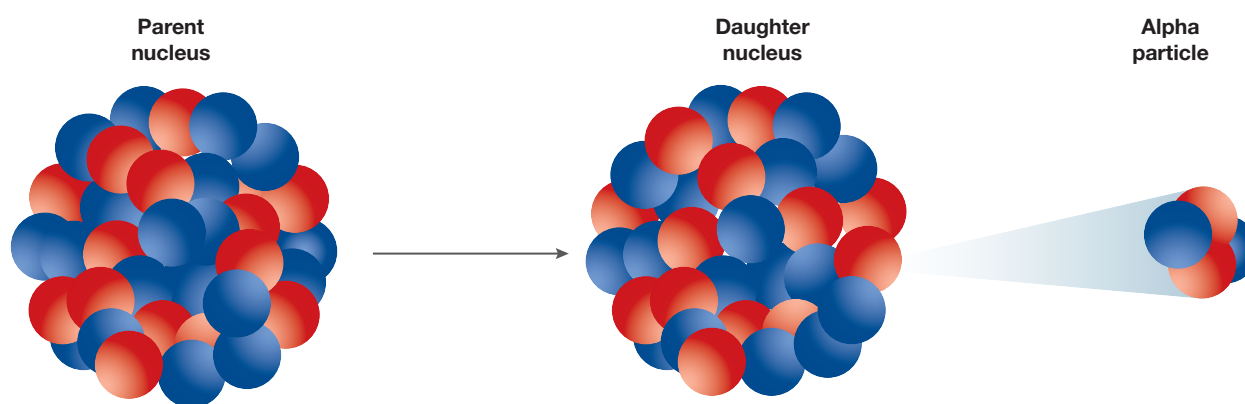
- Apply a simple particle model of the atomic nucleus to explain the origin of α , β^- , β^+ and γ radiation, including changes to the number of nucleons.
- Explain nuclear transformations using decay equations involving α , β^- , β^+ and γ radiation.
- Analyse decay series diagrams with reference to type of decay and stability of isotopes.

Unstable isotopes can emit various types of radiation while ‘striving’ to become more stable. There are three naturally occurring forms of nuclear radiation: α , β and γ (pronounced *alpha*, *beta* and *gamma*). Each type of radiation was named with a different Greek letter because, when the different types of radiation were discovered, scientists did not know what they consisted of. The emissions are described as decay processes because the nucleus changes into a different nucleus and the change is irreversible.

7.4.1 Alpha (α) decay

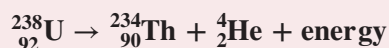
During α decay an unstable nucleus ejects a relatively large particle known as an α **particle**. This actually consists of two protons and two neutrons, and so may be called a helium nucleus. The remainder of the original nucleus, known as the **daughter nucleus**, is now more stable.

FIGURE 7.17 Alpha decay: a nucleus ejects a helium nucleus.



The number of protons in the nucleus determines the elemental name of the atom. The daughter nucleus is therefore of a different element. For example, uranium-238 decays by emitting an α particle. The uranium-238 atom contains 92 protons and 146 neutrons ($238 - 92 = 146$). It emits an α particle, with two protons and two neutrons. The original nucleus is left with four less nucleons: 90 protons ($92 - 2 = 90$) and 144 neutrons ($146 - 2 = 144$). As the daughter nucleus now has 90 protons, it is called thorium and has the symbol Th. This particular isotope of thorium has 234 nucleons (90 protons and 144 neutrons) and is more correctly written as thorium-234.

The information in the previous paragraph can be written much more effectively in symbols. This is called the **decay equation**:



Properties of alpha radiation

The ejected α particle is relatively slow and heavy compared to other forms of nuclear radiation. The particle travels at 5–7% of the speed of light: roughly 2×10^7 metres each second. Every object that moves has a form of energy known as kinetic energy, or energy of motion. Because the α particle is moving, it has kinetic energy. That energy is written into the decay equation.

In addition to having energy, the α particle has an overall charge of +2 because it contains two protons. This charge means the particle can be deflected by electric or magnetic fields — properties that helped scientists determine what an α particle consisted of.

The mass and charge of the alpha particle ensure that it cannot travel more than ten centimetres through the air without interacting with other matter including atoms and molecules. A sheet of paper will stop most alpha particles. For the same reason, its ability to penetrate the skin of animals and humans is extremely limited. However, if an alpha emitting source decays inside the body, it can do significant damage. As a result, alpha emitters are rarely used in nuclear medicine although its lethal properties are being put to work in a targeted way to destroy cancer tissue.

Alpha particles are a strongly ionising form of radiation. As a charged particle it can remove electrons from other atoms it approaches, which can result in chemical changes in body tissue and genetic material.

RADIOACTIVITY IN SMOKE DETECTORS

Some smoke detectors include a sample of the isotope americium-241, an alpha emitter. The alpha particles ionise the air, which sustains a small current between charged plates in the detector. When smoke blocks the access of the alpha particles to the air molecules between the charged plates, the current can no longer flow, which triggers an alarm to go off.

FIGURE 7.18 Smoke alarms are set off when smoke blocks the path of alpha particles

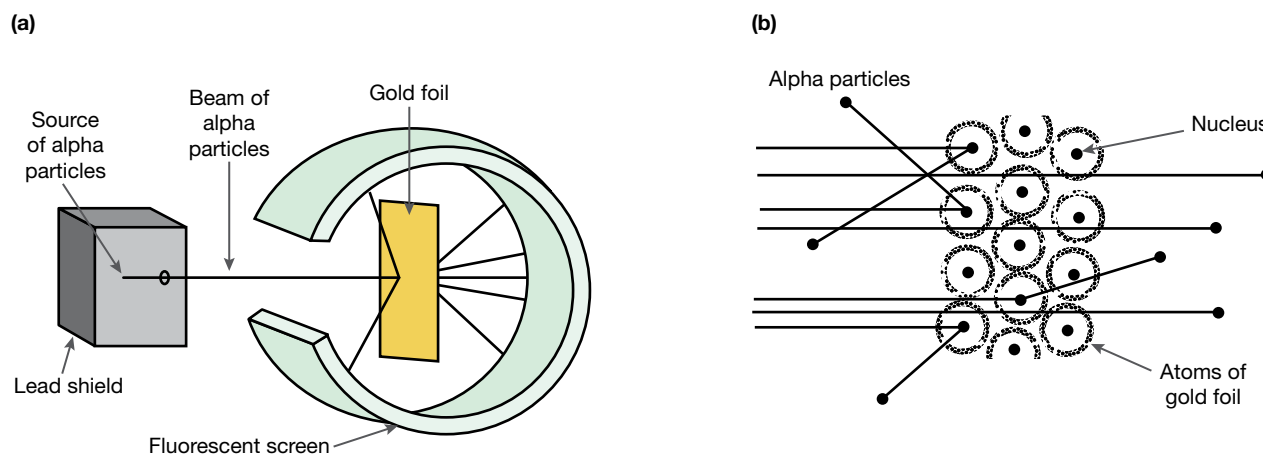


Discovering the nucleus

Ernest Rutherford was one of the central players in the investigation of radioactivity. By 1908, Rutherford and his team had determined that alpha particles were doubly charged helium ions and that they were moving very fast — at about 5% of the speed of light. They quickly realised that these particles would be ideal ‘bullets’ to investigate the structure of the atom.

Two of Rutherford’s younger colleagues, Hans Geiger and Ernest Marsden, fired alpha particles at a very thin foil of gold, about 400 atoms thick, and measured their angle of deflection. Nearly all of the particles either went straight through or suffered a very small deflection, but about 1 in every 8000 came back.

FIGURE 7.19 Geiger and Marsden’s gold foil experiment



The positively charged α particle was repelled and deflected by the electrostatic interaction with the positive charges in the atom. Rutherford calculated that for an α particle to be turned around, these positive charges would need to be concentrated in a very small volume, which he called the ‘nucleus’. He calculated that the radius of such a nucleus would be about 10^{-14} metres, and the radius of an atom was about 10^{-10} metres.

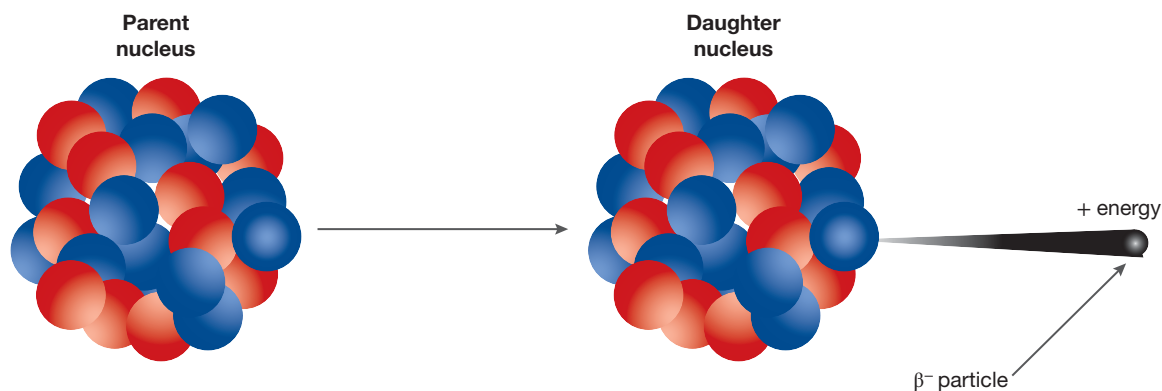
Rutherford’s nuclear model of the atom had nearly all the mass of the atom in the central nucleus and the much lighter electrons ‘orbiting’ around it.

However, this model was incomplete because it did not fully explain the mass of an atom. The neutron was subsequently discovered.

7.4.2 Beta (β) decay

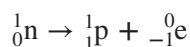
Two types of β decay are possible. The β^- particle is a fast moving electron that is ejected from an unstable nucleus. The β^+ particle is a positively charged particle with the same mass as an electron and is the electron's antiparticle, the positron. Positrons are mostly produced in the atmosphere by cosmic radiation, but some nuclei do decay by β^+ emission.

FIGURE 7.20 β^- decay: a nucleus ejects an electron.



In β^- decay, an electron is emitted from inside the nucleus. Since nuclei do not contain any electrons this might seem strange, but it is in fact true! There is no change whatsoever to the electrons in the shells surrounding the nucleus.

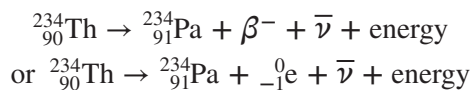
Some very interesting changes take place inside a nucleus to enable it to emit an electron. One of the neutrons in the nucleus transforms into a proton and an electron. The proton remains in the nucleus and the electron is emitted and called a β^- particle:



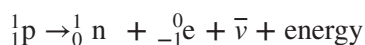
The resulting daughter nucleus has the same number of nucleons as the parent, but one less neutron and one more proton.

An example of β^- decay is the decay of thorium-234. This isotope is the result of the α decay of uranium-238. The nucleus is more stable than it was before the emission of the α particle but could become more stable by emitting a β^- particle. During this second decay, the mass number of the nucleus is unchanged (234). The number of protons, however, increases by one when a neutron changes into a proton and an electron. There are now 91 ($90 + 1$) protons in the nucleus, so the atom must be called protactinium-234. In the next section we will learn about the neutrino. Beta minus decay is accompanied by the emission of another particle called an antineutrino. Beta positive decay is accompanied by the emission of a neutrino. Neutrinos are particles with no charge and nearly zero mass.

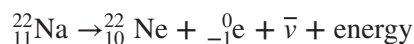
The decay equation is written as:



In β^+ decay, the positron is also emitted from inside the nucleus. In this case, strange as it may seem, the proton changes into a neutron and a positron with the neutron staying in the nucleus:



The resulting nucleus has one less proton but the same number of nucleons. An example of β^+ decay is sodium-22 decaying to neon-22:



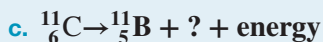
Properties of beta particles

Beta particles are very light when compared to alpha particles. They travel at a large range of speeds — from that of an alpha particle up to 99% of the speed of light. Just like α particles, β particles are deflected by electric and magnetic fields.

The lower charge, mass and higher speed of the beta particle ensures that it can penetrate much further through air and body tissues than alpha particles. They can travel through centimetres of human skin and a metre or two of air. They can be stopped by a few centimetres of water or a few millimetres of aluminium. Beta radiation is useful for precisely measuring the thickness of paper in production and for treating some types of cancers. It is also a form of ionising radiation.

SAMPLE PROBLEM 10

Write down the complete decay equation in each of the following.



 **Teacher-led video:** SP10 (tlvd-0057)

THINK

- a. 1. What is the mass number of the missing particle?
2. What is the atomic number of the missing particle?
3. Determine the missing particles from this information.
4. Write the equation.

WRITE

a. $234 - 230 = 4$

$92 - 90 = 2$

α particle

The number of particles in the nucleus has decreased by 4, while the number of protons has decreased by 2. This implies that an α particle, or helium nucleus, has been released. The full equation is ${}_{92}^{234}\text{U} \rightarrow {}_{90}^{230}\text{Th} + {}_2^4\text{He} + \text{energy}$

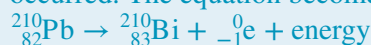
- b. 1. What is the mass number of the missing particle?
2. What is the atomic number of the missing particle?
3. Determine the missing particles from this information.
4. Write the equation.

b. $210 - 210 = 0$

$82 - 83 = -1$

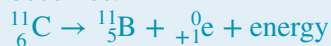
β^- particle

This equation cannot show an α emission, as the mass number remains constant. The atomic number has increased, indicating that a proton has been formed, and therefore β^- decay has occurred. The equation becomes:



- c. 1. What is the mass number of the missing particle? $11 - 11 = 0$
2. What is the atomic number of the missing particle? $6 - 5 = 1$
3. Determine the missing particles from this information. β^+ particle
4. Write the equation.

The mass number stays the same, but there is one less proton, so it must be β^+ decay. The equation becomes:



PRACTICE PROBLEM 10

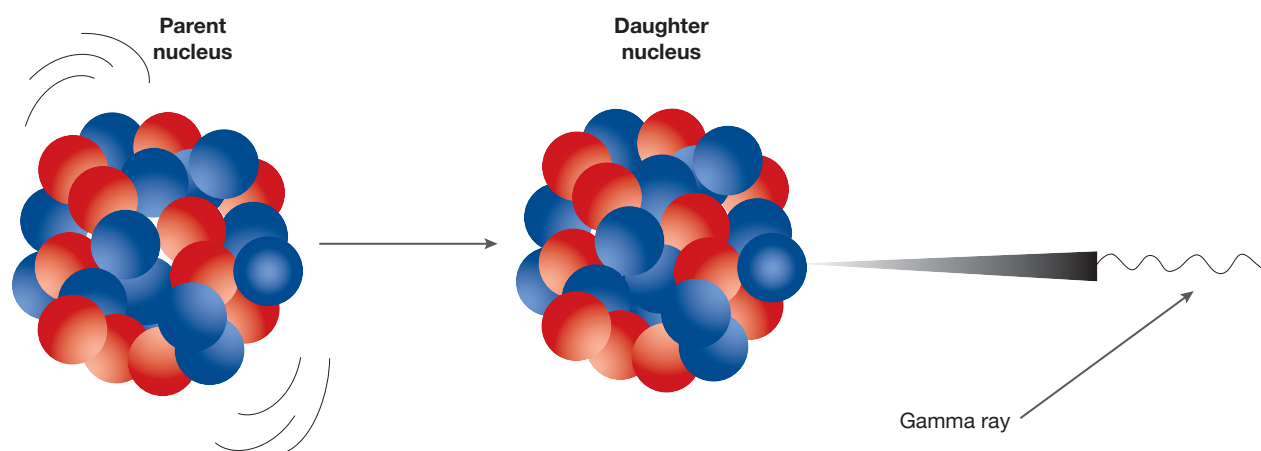
Write the equations for:

- a. the alpha decay of americium-241
- b. the β^- decay of platinum-197
- c. the β^+ decay of magnesium-23.

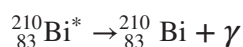
7.4.3 Gamma (γ) decay

This form of radioactive decay is quite different from either α or β decay. During γ decay a small packet of electromagnetic energy called a γ ray, or photon, is emitted, rather than a particle. Gamma emission occurs after another form of nuclear decay has taken place. Following a decay, the arrangement of protons and neutrons in the nucleus may not be ideal and the nucleus may need to release some extra energy to become more stable. Before the release of this energy, the nucleus is known as 'excited'. An **excited nucleus** is denoted by an asterisk (*) after the symbol for the element. The excess energy is emitted as a γ ray.

FIGURE 7.21 Gamma decay: an excited nucleus ejects a photon.



One example of γ decay occurs after lead-210 emits a β^- particle and becomes bismuth-210. The excited daughter nucleus goes on to emit a γ ray:



Properties of gamma radiation

This γ ray is a packet of excess energy. It has no mass and no charge and is not deflected by electric or magnetic fields. Because it is a photon, or packet of electromagnetic energy, it travels at the speed of light.

Gamma radiation is extremely penetrating. A shield of a few centimetres thickness absorbs about 90% of gamma rays. Gamma radiation is ionising like alpha and beta radiation. These properties of gamma radiation make it very useful in medicine. It can be used to trace physiological processes by injecting or swallowing chemical compounds with gamma emitters in the compound. The movement of the compound through the body can be traced with cameras outside the body detecting the gamma rays. A newer technique involves using positron emitters. When the positrons are emitted they meet electrons and both are annihilated, producing gamma rays that can be detected outside the body and an image constructed by computer. This is called positron emission tomography, or PET scans. Gamma rays are also a powerful means of killing cancerous tissue.

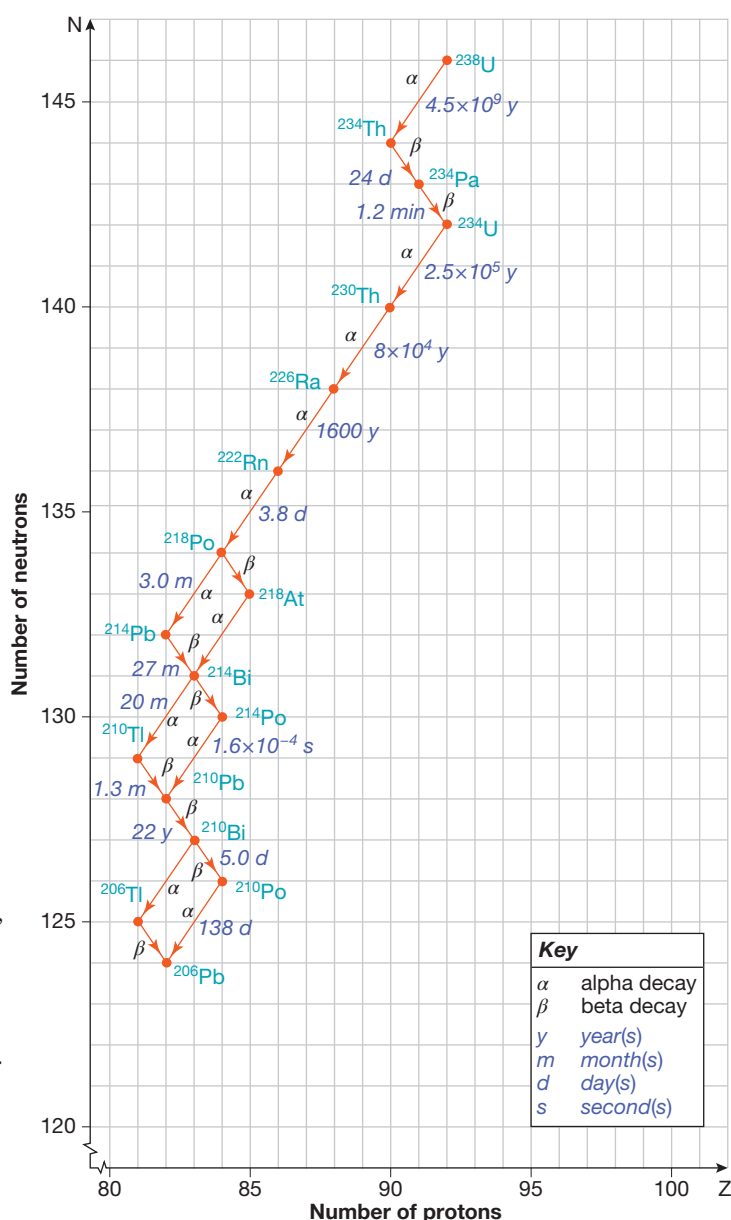
7.4.4 Decay series

In its 'quest' to become stable, an isotope may have to pass through many stages. As a radioactive isotope decays, the daughter nucleus is often radioactive itself. When this isotope decays, the resulting nucleus may also be radioactive. This sequence of radioisotopes is called a **decay chain** or decay series.

Uranium-238 undergoes 14 radioactive decays before it finally becomes the stable isotope lead-206. Two other decay chains, one starting with uranium-235 and another with thorium-232, also end with a stable isotope of lead. Another decay chain once passed through uranium-233, but this chain is almost extinct in nature now due to its shorter half-lives.

Not all naturally occurring radioisotopes are part of a decay series. There are about 10 with atomic numbers less than that of lead, for example, potassium-40. How can there be radioisotopes isolated in the periodic table? A look at the half-lives of potassium-40 and indium-115 reveals the answer (see table 7.4). Their half-lives are so long, greater than the age of the Earth, that they are still decaying from when they were formed in a supernova explosion billions of years ago.

FIGURE 7.22 Radioactive series of uranium-238. The half-life is given beside each decay.



SAMPLE PROBLEM 11

Using the decay series, comment on whether the daughter nucleus is always more stable than its parent.

THINK

1. How can I tell how stable a nucleus is?
2. Do the daughter nuclei always have longer half-lives than the parent nucleus?
3. State the solution.

WRITE

The longer the half-life, the more stable the nucleus.

Often, in a decay chain, the daughter nucleus has a shorter half-life than the parent. For example, uranium-238 has a much longer half-life than its daughter thorium-234.

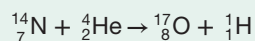
In a decay chain, a nucleus may decay to a less stable nucleus. This, however, is a step towards increased stability as the final nucleus is always stable.

PRACTICE PROBLEM 11

- a. Which is the most stable nucleus in the uranium-238 decay chain apart from lead-206, which is stable?
- b. Why do you think the decay chain starts with a relatively stable nucleus?

Nuclear transformations

Alpha and beta decay are natural examples of nuclear transformations. The numbers of protons and neutrons in the nucleus change during these processes. Artificial nuclear transformations are also possible. These are done either to investigate the structure of the nucleus or to produce specific radioisotopes for use in medicine or industry. The first artificial transformation was made by Ernest Rutherford, who fired alpha particles at nitrogen atoms to produce an isotope of oxygen.



This result raised the intriguing possibility of achieving the alchemist's dream of changing lead into gold. Although prohibitively expensive, it appears to be theoretically possible.

The building of particle accelerators in the early 1930s enabled charged particles such as protons and alpha particles to be fired at atoms as well as alpha particles, but with the advantage that their energy could be pre-set. The limitation of both these particles is that since they are positively charged, they have to be travelling at very high speed to overcome the repulsion of the positively charged nucleus. This problem was overcome with the discovery of the neutron in 1932. The neutron, which has no net charge, can enter the nucleus at any speed. Both protons and neutrons are used today to produce radioisotopes. Particle accelerators firing positive ions produce neutron-deficient radioisotopes such as thallium-201 ($t_{1/2} = 73$ days), which is used to show damaged heart tissue, and zinc-65 ($t_{1/2} = 244$ days), which is used as a tracer to monitor the flow of heavy metals in mining effluent. Neutrons from nuclear reactors produce neutron-rich radioisotopes such as iridium-192 ($t_{1/2} = 74$ days), which is used to locate weaknesses in metal pipes, and iodine-131 ($t_{1/2} = 8$ days), which is used in the diagnosis and treatment of thyroid conditions.

Particle accelerators are also used to produce new elements with atomic numbers greater than that of uranium. The hunt is on for a new stable element. In 2007, calcium-48 ions were fired at californium-249 atoms to produce the element with atomic number 118. Only three atoms were produced and, as the half-life of this isotope is 0.89 milliseconds, they don't exist anymore.

 **Digital documents** eModelling: Numerical model of a decay series (doc-0045)

Investigation 7.1 Radioactive decay (doc-31872)

Investigation 7.2 Background radiation (doc-31873)

 **Teacher-led video** Investigation 7.1: Radioactive decay (tlvd-0817)

 **Video eLesson** Nuclear stability and radiation (eles-2518)

7.4 EXERCISE

To answer questions online and to receive **immediate feedback** and **sample responses** for every question go to your learnON title at www.jacplus.com.au.

1. Write the nuclear equation for the α decay of radon-222.
2. Write the nuclear equation for the β decay of lead-214.
3. Write the nuclear equation for the γ decay of cobalt-60.
4. (a) A particle is missing from the right-hand side of a nuclear equation. The atomic numbers on the left-hand side of a nuclear equation add to 20. The sum of the atomic numbers on the right-hand side of the equation add to 18. What is the atomic number of the missing particle?
(b) The mass numbers of the equation in part (a) add to 50 on the left-hand side. The sum of the mass numbers on the right-hand side of the equation add to 46. What is the mass number of the missing particle?
(c) What is the missing particle?
5. Identify two particles or emissions in nuclear equations that have a mass number and atomic number of zero.
6. Energy is released in nuclear decays other than in the form of gamma rays. What form does this energy take?
7. The atomic number counts the number of protons in the nucleus of an atom. In nuclear equations some particles have atomic numbers but no protons. Given an example and explain what it means.

studyon

To answer practice exam questions online and to receive immediate feedback and sample responses for every question go to your learnON title at www.jacplus.com.au.

studyON: Practice exam questions 

Fully worked solutions and sample responses are available in your digital formats.

7.5 Review

7.5.1 Summary

- There are two types of fundamental particles of matter: quarks and leptons.
- There are six leptons. They are the electron, muon and tau particle, and each has its own neutrino.
- There are six quarks. They all have an electric charge, which is a fraction of the charge size of the electron. Three have a charge of $+\frac{2}{3}$, and three have a charge of $-\frac{1}{3}$. Their masses vary significantly.
- The quarks combine to form particles called hadrons, of which there are two types: mesons and baryons.
- Mesons are composed of one quark and one antiquark. There are many mesons. They can be positively charged, neutral or negatively charged, and have short half-lives.
- Baryons are composed of three quarks. There are a large number of different types of baryons, with a range of masses and charges ranging from $+2$ to -2 .
- Some of the subatomic particles were predicted well before they were detected.
- Nuclear radiation is emitted from the nucleus of unstable atoms (radioisotopes) that are striving to become more stable.

- There are four types of nuclear decay: α , β^- , β^+ and γ radiation.
- α particles are released during α decay. α particles are relatively slow-moving particles that are equivalent to a helium nucleus and can be represented as ${}^4_2\text{He}$. After α decay, the mass number of the daughter nucleus is four less than that of the parent nucleus and the atomic number is two less.
- β^- particles are released in β^- decay. β^- particles are high-speed electrons released from the nucleus when a neutron transforms into a proton, an electron and an antineutrino. After β^- decay, the mass number of the daughter nucleus is the same as that of the parent nucleus, but the atomic number is one more than that of the parent nucleus.
- β^+ particles are released in β^+ decay. β^+ particles are high-speed positrons emitted with a neutrino from the nucleus when a proton transforms into a neutron. The atomic number of the daughter nucleus is one less than the parent nucleus; the mass number remains the same.
- γ radiation is electromagnetic radiation that is emitted when an excited nucleus becomes more stable. γ rays are emitted during α and β decay.
- In all nuclear transformations, atomic and mass numbers are conserved.
- Half-life is the time for half of a group of unstable nuclei to decay. It is different for every isotope. The shorter the half-life of an isotope, the greater the activity — that is, the greater the number of decays per second. Activity decreases over time as less and less of the isotope remains. Activity is measured in becquerels (Bq).
- Isotopes may pass through a sequence of decays in order to become stable. Such a sequence is called a decay chain, or decay series.
- The force that holds nucleons together in a nucleus of an atom is called the strong nuclear force. It acts over a very short distance and is strong enough to overcome the electrostatic force of repulsion that exists between the protons of a nucleus when nucleons are very close together.

on Resources

studyon

To access key concept summaries and practice exam questions download and print the **studyON: Revision and practice exam question booklet** (sonr-0032).

7.5.2 Key terms glossary

An **α particle** is a relatively slow-moving decay product consisting of two protons and two neutrons. It is equivalent to a helium nucleus and so can be written as ${}^4_2\text{He}$. α particles carry a positive charge.

A **γ ray** is the packet of electromagnetic energy released when a nucleus remains unstable after α or β decay. γ rays travel at the speed of light and carry no charge.

The **atomic number** of an atom is the number of protons in its nucleus.

Baryons are hadrons with three quarks.

Cosmic rays are very energetic charged particles that enter our atmosphere. They are mainly protons and originate from beyond the solar system.

A **daughter nucleus** is the nucleus remaining after an atom undergoes radioactive decay. It is more stable than the original nucleus.

A **decay chain** also known as a decay series, is the sequence of stages a radioisotope passes through to become more stable. At each stage, a more stable isotope forms. The chain ends when a stable isotope forms.

A **decay curve** is a graph of the number of nuclei remaining in a substance versus the time elapsed. The half-life of a substance can be determined by looking at the time that corresponds to half of the substance remaining.

A **decay equation** is a representation of a decay reaction. It shows the changes occurring in nuclei and lists the products of the decay reaction.

An **electron** is a negatively charged particle found around the nucleus of an atom.

An **element** is a substance that consists only of atoms of the same name.

An **excited nucleus** is one that does not have an ideal arrangement of protons and neutrons in its nucleus. An excited nucleus emits γ radiation to become more stable.

Hadrons are composite particles made up of either two or three quarks.

A **half-life** is the time taken for half of a group of unstable nuclei to decay.

Isotopes are atoms containing the same number of protons but different numbers of neutrons.

Isotopes of an element are atoms containing the same number of protons but different numbers of neutrons.

Leptons are the simplest and lightest of the subatomic particles. They are fundamental particles with no internal structure.

Mass number describes the total number of nucleons in an atom.

Mesons are hadrons with two quarks.

A **neutron** is a nucleon with no charge.

The collective name for the particles found in the nucleus of an atom is **nucleon**.

The **nucleus** is the solid centre of an atom. Most of the mass of an atom is concentrated in the nucleus.

A **positron** is a positively charged particle with the same mass as an electron.

A **proton** is a positively charged particle in the nucleus of an atom.

Quarks are the fundamental particles that combine to form hadrons.

A **radioisotope** is an unstable isotope.

The **strong nuclear force** is the force that holds nucleons together in a nucleus of an atom. It acts over only very short distances.

The **weak nuclear force** is the force that explains the transformation of neutrons into protons, and vice versa.



Resources



Digital document Key terms glossary (doc-32186)

7.5.3 Practical work and investigations

Investigation 7.1

Radioactive decay

Aim: To analyse the radioactive decay of a source

Digital document: doc-31872

Teacher-led video: tlvd-0817

Investigation 7.2

Background radiation

Aim: To measure the background radiation in the classroom at school

Digital document: doc-31873



Resources



Digital document Practical investigation logbook (doc-32265)

7.5 Exercises

To answer questions online and to receive **immediate feedback** and **sample responses** for every question go to your learnON title at www.jacplus.com.au.

7.5 Exercise 1: Multiple choice questions

- Which of the following shows the quark composition of a proton?
 - Up, up, down
 - Up, down, down
 - Up, up, up
 - Down, down, down
- Which of the following types of particles is not made of quarks?
 - Mesons
 - Baryons
 - Hadrons
 - Leptons
- There are four fundamental forces:
 - gravity
 - electromagnetic force
 - weak nuclear force
 - strong nuclear force.

What is the correct order, from strongest to weakest, at the distance between two nucleons in a nucleus?

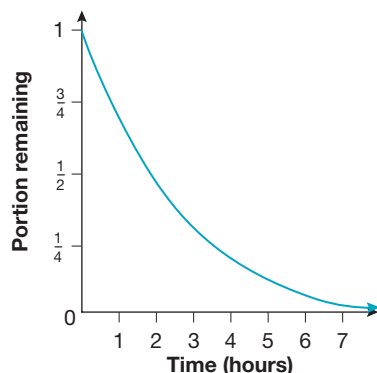
- i, ii, iii, iv
 - iv, iii, ii, i
 - iv, ii, iii, i
 - iv, ii, i, iii
- Which of the following particles was discovered experimentally before being predicted theoretically?
 - Higgs boson
 - Positron
 - Electron
 - Neutron
 - Which of the following forces is *not* significant in the stability of nuclei?
 - Gravity
 - Electromagnetic force
 - Strong nuclear force
 - Weak nuclear force
 - How is the half-life of an isotope best described?
 - Half of the time it would take for the whole sample to decay
 - The time it would take for half of the existing sample to decay
 - The time for the stability of the nucleus to halve
 - A period during which the isotope is not very active
 - Radioisotopes used in nuclear medicine usually have short half-lives. Why is this?
 - They are cheaper.
 - They are more active.
 - The radiation is dangerous to the body so it is good to minimise the time of exposure.
 - The more stable isotopes are more toxic.
 - Alpha decay involves the ejection from the nucleus of which of the following?
 - A tightly bound package of two protons and two neutrons
 - An electron and an antineutrino
 - A positron and a neutrino
 - An energetic photon

9. Cobalt-60 is often used to as a gamma source for sterilising medical equipment. It is made by bombarding stable cobalt-59 with neutrons in nuclear reactors. To answer the following think about the effect on the stability of a relatively small nucleus of adding a neutron.
When cobalt-60 decays, it emits gamma rays and which of the following?
- A. Neutrons
 - B. Alpha particles
 - C. Beta minus particles and antineutrinos
 - D. Beta plus particles and neutrinos
10. In a series of decays, the mass number drops by eight and the atomic number drops by two. Which sequence of decays could result in this transmutation?
- A. An alpha, a beta minus, a beta minus and another alpha
 - B. An alpha, a beta plus, a beta minus and an alpha
 - C. A beta plus, an alpha, a beta minus and an alpha
 - D. An alpha, an alpha, a beta minus and another alpha

7.5 Exercise 2: Short answer questions

1. Design baryons with a charge of:
 - a. +2
 - b. -2
 - c. zero.
2. Some mesons are their own antiparticle. Explain with an example.
3. Why do you think it has taken so long and been so difficult to find neutral particles such as the neutron, neutrino and the Higgs boson?
4. How many protons and neutrons are in the following atoms?
 - a. ${}^{66}_{30}\text{Zn}$
 - b. ${}^{230}_{90}\text{Th}$
 - c. ${}^{45}_{20}\text{Ca}$
 - d. ${}^{31}_{14}\text{Si}$
5. Write the symbols for isotopes containing the following nucleons.
 - a. Two neutrons and two protons
 - b. Seven protons and 13 nucleons
 - c. Ninety-one protons and 143 neutrons
6. Determine the particle, X, that has been released in each of the following decay equations.
 - a. ${}^{14}_6\text{C} \rightarrow {}^{14}_7\text{N} + \text{X} + \text{energy}$
 - b. ${}^{90}_{38}\text{Sr} \rightarrow {}^{90}_{39}\text{Y} + \text{X} + \text{energy}$
 - c. ${}^{238}_{92}\text{U} \rightarrow {}^{234}_{90}\text{Th} + \text{X} + \text{energy}$
7. Write a decay equation to show the following.
 - a. α decay of:
 - i. radium-226
 - ii. polonium-214
 - iii. americium-241.
 - b. β decay of:
 - i. cobalt-60
 - ii. strontium-90
 - iii. phosphorus-32.
8. How many α particles are released by one atom of uranium-238 as it becomes lead-206? How many β particles are released? (*Hint:* Look at the change in the proton number and the change in the nucleon number.) Check your answer by using figure 7.22.

9. What is the half-life of the substance represented in the following graph?



10. Assume the half-life of carbon-14 is 5730 years. If you had 1 gram of carbon-14, how many years would it take for one-eighth of it to remain?

7.5 Exercise 3: Exam practice questions

Question 1 (1 marks)

Atomic nuclei consist of particles that can be classified as which of the following?

- A. Hadrons
- B. Mesons
- C. Baryons
- D. Leptons

Question 2 (3 marks)

PET scans provide doctors with information about how organs are functioning. PET scans use positron emission from sources introduced into the patient's body.

- a. Compare the mass and charge of a positron with those of an electron. 2 marks
- b. The PET scan detects gamma rays rather than positrons. How are these gamma rays produced? 1 mark

Question 3 (3 marks)

- a. Provide an example of a particle whose existence was predicted before it was discovered. 1 mark
- b. How can the existence of an as yet unobserved particle be predicted scientifically? 2 marks

Question 4 (6 mark)

Consider the graph of nuclear stability in figure 7.15. Patterns can be seen where β and α decay occur in relation to the line of stability.

- a. Would adding a proton or a neutron to a stable nucleus make it more likely to undergo β^- decay? 1 mark
- b. Explain why β^- decay is likely to occur in this scenario. 2 marks
- c. Explain why α emission is restricted to very large nuclei by referring to the forces involved in the nucleus. 3 marks

Question 5 (5 marks)

Targeted alpha particle therapy (TAT) is a relatively new treatment for some cancers. One of the radioisotopes used in TAT is actinium-225 ($^{225}_{89}\text{Ac}$), which decays to an isotope of francium (Fr).

- a. Write the decay equation for this. 3 marks
- b. The half-life of actinium-225 is 10 days. What fraction of the dose of actinium-225 administered would remain after 30 days? 2 marks

- c. The daughter nucleus of actinium-225 following α decay is not stable. In fact, a sequence of 4 α decays and 2 β^- decays occurs before stability is reached with an isotope of bismuth. Determine the atomic number and mass number for this isotope of bismuth. Show your working. **2 marks**

7.5 Exercise 4: studyON topic test

Fully worked solutions and sample responses are available in your digital formats.

teachon

Test maker

Create unique tests and exams from our extensive range of questions, including practice exam questions.
Access the assignments section in learnON to begin creating and assigning assessments to students.

8 Energy from the atom

8.1 Overview

Numerous **videos** and **interactivities** are available just where you need them, at the point of learning, in your digital formats, learnON and eBookPLUS at www.jacplus.com.au.

8.1.1 Introduction

The universe can be considered to be made of matter and energy. In this topic we explore how the particles of matter that shape the universe cannot be considered separately from energy. This discovery has led to dangerous weapons and new sources of power for machines and electricity supply. Nuclear power plants harness the energy from matter to create large amounts of energy from very little raw material. It is the hope of many that further developments will provide an almost limitless source of energy with very little pollution. The relationship between mass and energy has supplied a range of light sources for various applications in medicine and many other fields.

FIGURE 8.1 Nuclear power plants use nuclear fission to create roughly 13% of the world's electricity supply.



8.1.2 What you will learn

KEY KNOWLEDGE

After completing this topic you will be able to:

- explain nuclear energy as energy resulting from the conversion of mass: $E = mc^2$
- compare the processes of nuclear fusion and nuclear fission
- explain, using a binding energy curve, why both fusion and fission are reactions that produce energy
- explain light as an electromagnetic wave that is produced by the acceleration of charges
- describe the production of synchrotron radiation by an electron radiating energy at a tangent to its circular path
- model the production of light as a result of electron transitions between energy levels within an atom.

Source: VCE Physics Study Design (2016–2021) extracts © VCAA; reproduced by permission.

PRACTICAL WORK AND INVESTIGATIONS

Practical work is a central component of learning and assessment. Experiments and investigations, supported by a **Practical investigation logbook** and **Teacher-led videos**, are included in this topic to provide opportunities to undertake investigations and communicate findings.

on Resources

-  **Digital documents** Key science skills — VCE Units 1–4 (doc-31856)
Key terms glossary (doc-32266)
Practical investigation logbook (doc-32267)

studyon

To access key concept summaries and practice exam questions download and print the **studyON: Revision and practice exam question booklet** (sonr-0033).

8.2 Energy from mass

KEY CONCEPT

- Explain nuclear energy as energy resulting from the conversion of mass: $E = mc^2$.

The most famous physics equation of all is $E = mc^2$. This is an equation that Albert Einstein derived as a result of his work on relativity. We will now explore what this equation means and how it can be used.

In the previous topic we learnt that some nuclei are unstable. They eventually decay by releasing particles including beta particles, neutrinos, alpha particles and gamma rays. Which particles are released depends on the particular **isotope** involved. Before 1905, scientists would have said that these decays must obey two conservation laws: conservation of mass and conservation of energy.

Conservation of mass states that there is always the same amount of mass in a closed system — one where no mass is entering or leaving. This resulted from early understandings of chemical reactions, where the mass of the products is always the same as the mass of the reactants. Conservation of energy states that there is always the same amount of energy in an isolated system. Energy is never created or destroyed, it is transformed to different forms or transferred from one system to another.

FIGURE 8.2 Albert Einstein



However, in 1905, Albert Einstein stunned the scientific world by showing that these two conservation laws are not strictly correct. He demonstrated that only one conservation law was needed because mass and energy are essentially the same thing. What is conserved is the combination of mass and energy, which is sometimes called mass–energy.

Einstein’s equation was a result of theory. Like the prediction of particles including the neutrino, positron, neutron and Higgs boson, there was no experimental evidence for it at the time and obtaining that evidence was not going to be easy.

$$E = mc^2$$

Where:

E is the energy in joules

m is the mass in kilograms

c is the symbol for the speed of light ($c = 2.997\,924\,58 \times 10^8 \text{ m s}^{-1}$).

Note: The speed of light is usually rounded to $3.00 \times 10^8 \text{ m s}^{-1}$ in calculations.

This equation is a statement that energy and mass are equivalent. If we need to know how much energy a certain mass is equivalent to, we use the equation.

For example, for a mass of 1 kilogram:

$$\begin{aligned} E &= mc^2 \\ &= 1.0 \times (3.00 \times 10^8)^2 \\ &= 9.0 \times 10^{16} \text{ J} \end{aligned}$$

That is a tremendous amount of energy. However, the Sun produces four billion times that every second. Einstein’s $E = mc^2$ calculates that the Sun is losing energy at a rate that is equivalent to 4 billion kilograms every second!

Why do we not see this loss of mass in everyday life when a body radiates energy? Let’s look at the example of an object cooling down, like a hot water bottle in your bed on a winter’s night. The hot water bottle would transfer approximately 100 000 J of energy to your bed as it cools. Using $E = mc^2$:

$$\begin{aligned} E &= mc^2 \\ m &= \frac{E}{c^2} \\ &= \frac{100\,000}{(3.00 \times 10^8)^2} \\ &= 1.1 \times 10^{-12} \text{ kg} \end{aligned}$$

That is one-millionth of one-millionth of a kilogram, far too tiny to notice or measure. As far as typical events are concerned, energy is conserved and mass is conserved. Even the mass lost by the Sun per second is such a tiny percentage of the Sun’s mass that the Sun can continue losing mass at this rate for billions of years.

However, Einstein’s equation has been tested in many ways. In 2008, researchers confirmed that $E = mc^2$ explained the mass of protons and neutrons.

In the previous topic, we learnt that protons comprise two up quarks and one down quark. Similarly, neutrons are made up of two down quarks and one up quark. These quarks are held together by the strong nuclear force, which involves the exchange of a boson called a gluon. However, the mass of a proton or a neutron cannot be determined by adding up the masses of the quarks they contain (gluons are massless).

Most of the mass of the proton and neutron derives from the energies of the quarks within each particle. To account for a proton having a mass of 1.67×10^{-27} kilograms we need to add up the mass of the quarks it contains and the mass equivalent of the energy involved by using $E = mc^2$.

Nuclear decays bring a nucleus to a state of lower energy and greater stability. The nucleus prior to the decay, or decay series, has a greater mass than the nucleus after decay, even when the masses of the particles emitted in the decay are accounted for. In the decay, mass is not conserved. Similarly, if the energies prior to the decay were compared with the energies of all of the particles after the decay, we find some energy that appears to have come from nowhere. The difference in mass (m) is equivalent to the difference in energy (E) as predicted by $E = mc^2$.

For example, consider the alpha decay of uranium-238, shown in table 8.1.

TABLE 8.1 The decay of uranium-238 to thorium-234 and helium-4

	Nucleus	Mass (kg)
Parent	Uranium-238	$3.952\,93 \times 10^{-25}$
Daughter	Thorium-234	$3.886\,39 \times 10^{-25}$
Decay particle	Helium-4	$6.645\,758 \times 10^{-27}$
Mass after decay	He-4 + Th-234	$3.952\,85 \times 10^{-25}$
Change of mass resulting from decay	Mass defect	8.242×10^{-30}

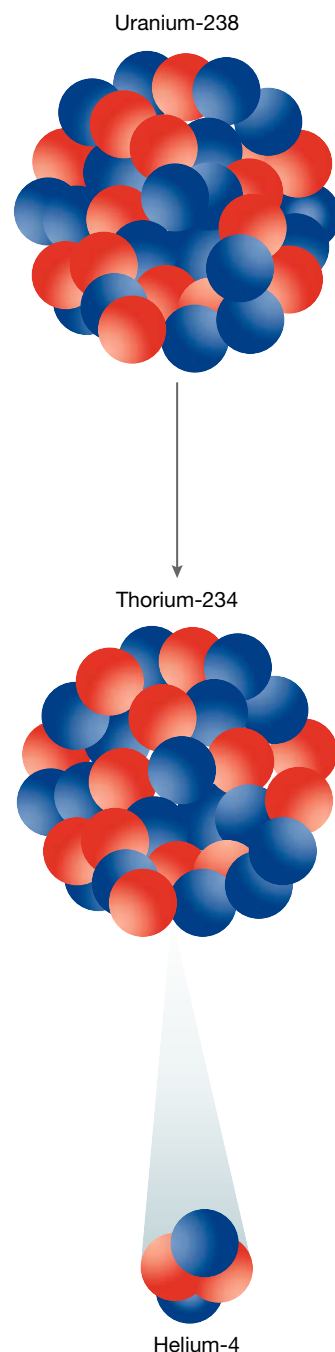
The thorium nucleus and the α particle produced by the decay of uranium-238 have a slightly lower mass than the parent uranium nucleus. This change in mass is called the **mass defect**. Mass is not conserved here. Where is the missing mass?

The mass can be accounted for by applying $E = mc^2$. The mass is equivalent to 7.42×10^{-13} J. This energy is the kinetic energy of the remaining particles, most of it going to the α particle, which moves away from the thorium nucleus at approximately $10\,000\text{ km s}^{-1}$.

Energy is often better expressed in a unit called the electronvolt (eV) when dealing with nuclear physics.

1 eV is the kinetic energy an electron or proton would gain if accelerated across a potential difference of 1 V. $1\text{ eV} = 1.6 \times 10^{-19}\text{ J}$. The energy produced in the α decay of uranium-238 is then $7.42 \times 10^{-13}\text{ J} = 4.63\text{ MeV}$.

FIGURE 8.3 Alpha decay of uranium-238



SAMPLE PROBLEM 1

Calculate the energy released when thorium-232 undergoes alpha decay. Thorium-232 has a mass of $3.853\,08 \times 10^{-25}\text{ kg}$ and radium-228 has a mass of $3.786\,55 \times 10^{-25}\text{ kg}$. An α particle has a mass of $6.64\,648 \times 10^{-27}\text{ kg}$. Give your answer in MeV.

Teacher-led video: SP1 (tlvd-0065)

THINK

1. Determine the mass of the parent nucleus.
2. Determine the mass of the daughter nucleus and the α particle.
3. Determine the change in the mass due to the decay.
4. Determine the equivalent energy.

WRITE

$$m_{\text{parent}} = 3.853\,08 \times 10^{-25} \text{ kg}$$

$$\begin{aligned} m_{\text{products}} &= 3.786\,55 \times 10^{-25} \text{ kg} + 6.64\,648 \times 10^{-27} \text{ kg} \\ &= 3.85\,301 \times 10^{-25} \text{ kg} \end{aligned}$$

$$\begin{aligned} m_{\text{parent}} - m_{\text{products}} &= 3.85\,308 \times 10^{-25} \text{ kg} - 3.85\,301 \times 10^{-25} \text{ kg} \\ &= 7.26 \times 10^{-30} \text{ kg} \end{aligned}$$

$$\begin{aligned} E &= mc^2 \\ &= 7.26 \times 10^{-30} \times (3.00 \times 10^8)^2 \\ &= 6.5 \times 10^{-13} \text{ J} \end{aligned}$$

5. Convert to MeV.

$$\begin{aligned} E &= \frac{6.5 \times 10^{-13}}{1.602\,176 \times 10^{-13}} \text{ MeV} \\ &= 4.1 \text{ MeV} \end{aligned}$$

6. State the solution.

4.1 MeV of energy is released when thorium-232 undergoes alpha decay.

PRACTICE PROBLEM 1

An α particle has a kinetic energy of 4.2 MeV as it leaves a nucleus. Calculate the mass defect of this reaction. (Assume that all the energy released went into the kinetic energy of the α particle.)

8.2 EXERCISE

To answer questions online and to receive **immediate feedback** and **sample responses** for every question go to your learnON title at www.jacplus.com.au.

1. What does the equation $E = mc^2$ express about mass and energy?
2. What is the energy equivalent of 100 grams of mass in joule?
3. A positron and an electron (each of mass $9.1 \times 10^{-31} \text{ kg}$) annihilate each other. How much energy is released?
4. What is the energy content of a 4500 kJ meal in eV?
5. Calculate the mass equivalent of 4500 kJ.

studyon

To answer practice exam questions online and to receive immediate feedback and sample responses for every question go to your learnON title at www.jacplus.com.au.

studyON: Practice exam questions 

Fully worked solutions and sample responses are available in your digital formats.

8.3 Energy from the nucleus

KEY CONCEPTS

- Compare the processes of nuclear fusion and nuclear fission.
- Explain, using a binding energy curve, why both fusion and fission are reactions that produce energy.

8.3.1 Binding energy

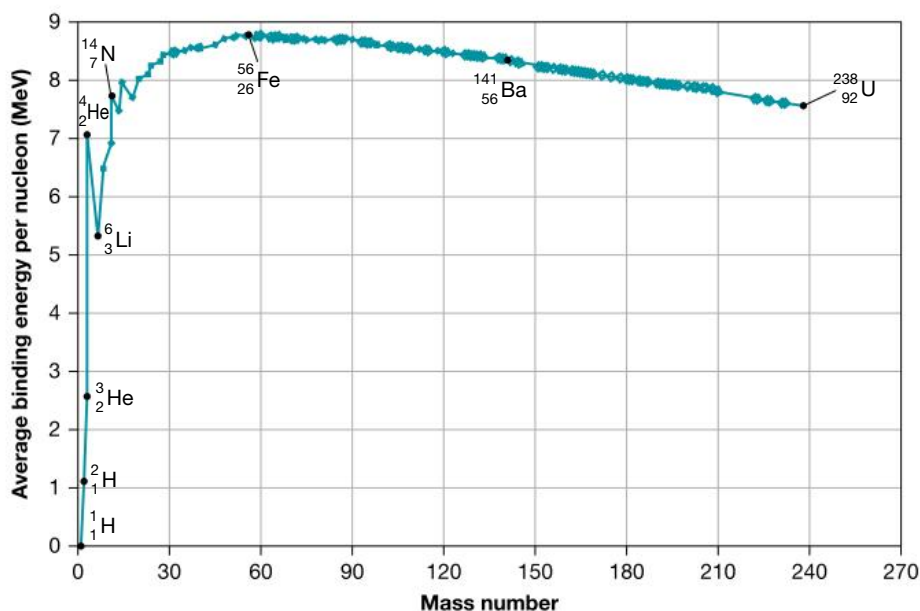
The amount of energy needed to overcome the strong nuclear force and pull apart a nucleus is known as the **binding energy**. This is the amount of energy that has to be added to a nucleus to split it into its individual nucleons — that is, to reverse the binding process. For example, it would take 2.23 MeV of energy to split a ‘heavy’ hydrogen nucleus into a separate proton and neutron.

Each isotope has its own specific binding energy. Nuclei with high binding energies are very stable as it takes a lot of energy to split them into separate protons and neutrons. Nuclei with lower binding energies are easier to split. Of course, it is difficult to supply sufficient energy to cause a nucleus to split totally apart. It is much more common for a nucleus to eject a small fragment, such as an α or β particle, to become more stable.

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

It can be seen from figure 8.4 that iron-56 has the highest binding energy per nucleon. This means it is the most stable of all nuclei. In order to become more stable, other nuclei tend to release some of their energy. Releasing this energy would decrease the amount of energy they contained, and therefore increase the amount of energy that must be added to split them apart.

FIGURE 8.4 This graph of binding energy versus mass number peaks at nickel-62, although the much more common iron-56 is very close behind.



The binding energy is not only the amount of energy required to separate a nucleus into its component parts, but also the amount of energy released when those parts are brought together to form the nucleus; that is, when a proton and a neutron collide to form a ‘heavy’ hydrogen nucleus, 2.23 MeV of energy is released (twice the binding energy per nucleon).

The curve of the graph in figure 8.4 indicates that if two nuclei with low **mass numbers** could be joined together to produce a single nucleus, then a lot of energy would be released. Similarly, if a nucleus with a very high mass number could split into two fragments with greater binding energy per nucleon, then once again a lot of energy would be released. These two possibilities were realised in the 1930s. The released energy can be calculated from Einstein's equation $E = mc^2$, where m is the difference between the total nuclear mass before and after the event, and c is the speed of light.

The joining of two nuclei is **nuclear fusion** and the splitting of a single nucleus is **nuclear fission**.



Resources



Interactivity Making nuclei (int-6393)

8.3.2 Nuclear fission

In 1934, Enrico Fermi investigated the effect of firing neutrons at uranium. The products had half-lives different from that of uranium. He thought that he had made new elements with **atomic numbers** greater than 92. Others repeating the experiment got different half-lives. In 1939, Otto Hahn and Fritz Strassmann chemically analysed the samples and found barium, which has atomic number 56, indicating that the nuclei had split.

Lise Meitner and Otto Frisch called this process 'fission' and showed that neutrons could also initiate fission in thorium and protactinium. Further chemical analysis revealed a range of possible fission reactions, each with a different combination of **fission fragments** including bromine, molybdenum or rubidium (which have atomic numbers around 40) and antimony, caesium or iodine (which have atomic numbers in the 50s). Cloud chamber photographs showing two heavy nuclei flying off in opposite directions confirmed that fission had occurred. Meitner and Frisch also calculated from typical binding energies that the fission of one uranium-235 nucleus would produce about 200 MeV of energy, mainly as kinetic energy of the fission fragments. This is a huge amount of energy to be released by one nucleus, as can be seen when it is compared to the burning of coal in power plants. Each atom of carbon used in coal burning releases only 10 eV of energy — about 20 million times less than the energy released in the fission of uranium-235.

FIGURE 8.5 The first chain reaction in a nuclear reactor was on a squash court at the University of Chicago during World War II.

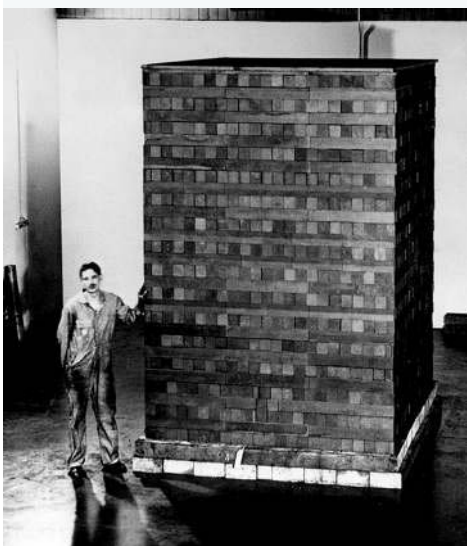
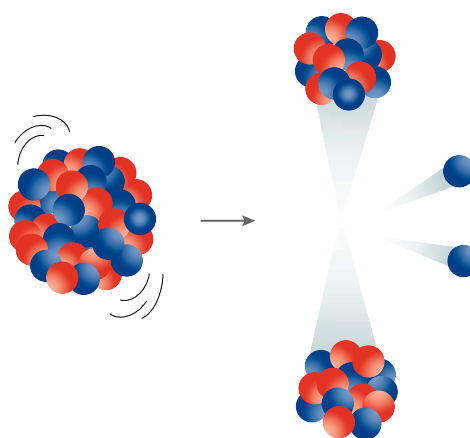


FIGURE 8.6 Nuclear fission reactions involve a large nucleus splitting into two smaller nuclei and a couple of neutrons.



LISE MEITNER (1878–1968)

Lise Meitner was the physicist who coined the term ‘fission’ and, along with her nephew Otto Frisch, explained the splitting of uranium nuclei into barium and lanthanum.

Born in Vienna, Lise was fascinated by the world around her from an early age. A talented student, she wanted to understand the things she observed in nature. Having decided that she would like to pursue her interest in physics and mathematics, Lise engaged a private tutor to prepare her for the university entrance exams, as schools that taught such subjects would not accept girls at that time. She was the second woman to be granted a Doctorate in Physics from the University of Vienna, conferred in 1906.

Lise then moved to the Institute of Experimental Physics in Berlin to work with Otto Hahn. Initially, this proved difficult. Lise was forced to work in a converted workshop as females were not permitted to use the facilities available to male students. As the place of women in the institute became more accepted, Lise was given positions of responsibility, finally being made a professor in 1926. During her time at the institute, Lise made many important contributions to atomic and particle physics, including the co-discovery with Otto Hahn of the radioactive element protactinium.

In 1938 Berlin became a dangerous place for Jews, and Lise moved to Sweden. It was there she and Otto Frisch interpreted the results of experiments conducted by Otto Hahn and Fritz Strassman to come up with the first explanation of the fission process. In doing so, Lise was the first person to use Einstein’s theory of mass–energy equivalence to calculate the energy released during fission.

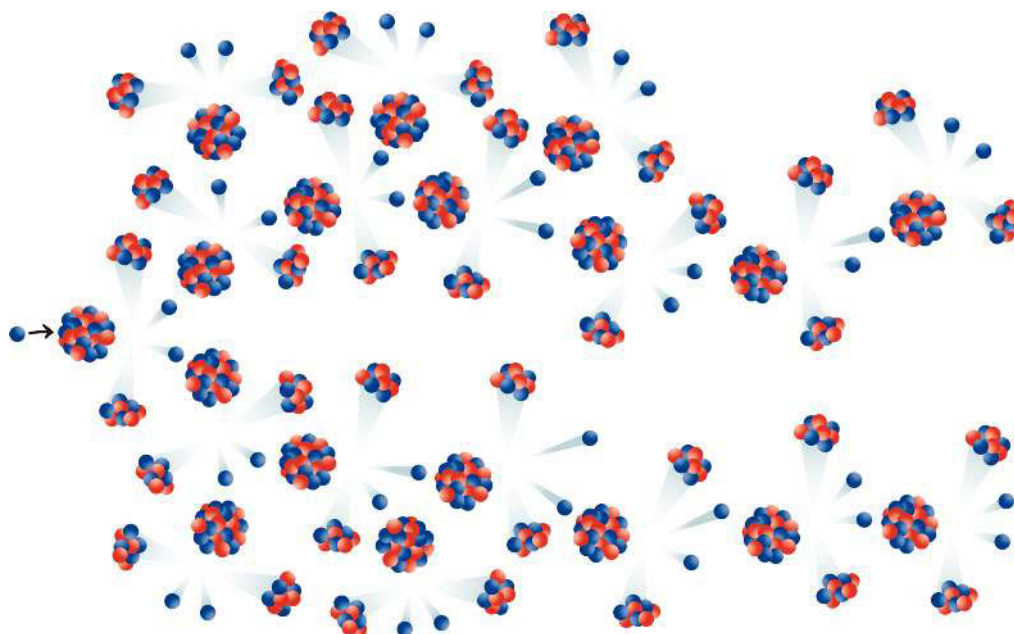
Her international reputation led to an invitation to join the Manhattan Project in 1941 and work on the development of the atomic bomb. Lise objected to the project and declined the offer. She continued to work in Sweden until moving to England in 1960, finally retiring at the age of 82.

FIGURE 8.7 Lise Meitner (1878–1968) was the first to describe how a nucleus could undergo fission.

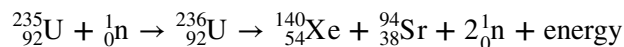
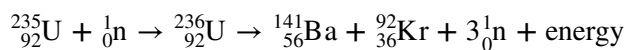
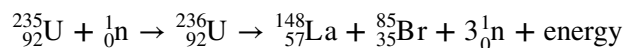


Also in 1939, Frédéric Joliot, Irène Joliot-Curie and their team confirmed that two or three fast neutrons were emitted with each fission reaction. This allowed for the possibility of a chain reaction, where one fission triggers further fissions, which could potentially release enormous amounts of energy.

FIGURE 8.8 The neutrons produced by a fission reaction can go on to produce a chain reaction.



Some possible equations for the fission of uranium-235 set off by the absorption of a neutron are:



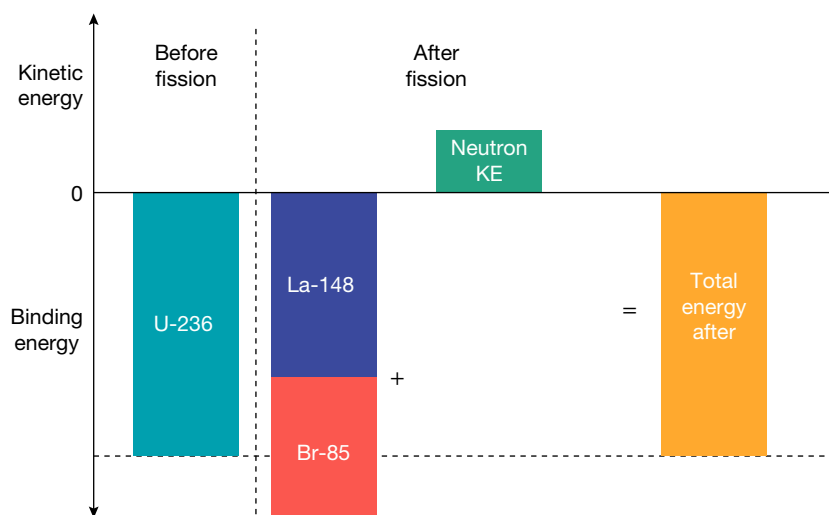
The data in figure 8.4 and Einstein's equation $E = mc^2$ can be used to calculate the amount of energy released in each of these fission reactions.

TABLE 8.2 Masses and binding energies of atoms

Nucleus	Symbol	Mass (kg)	Total binding energy (MeV)
Uranium-236	${}_{92}^{236}\text{U}$	$3.919\,629 \times 10^{-25}$	1790.415 039
Lanthanum-148	${}_{57}^{148}\text{La}$	$2.456\,472 \times 10^{-25}$	1213.125 122
Bromine-85	${}_{35}^{85}\text{Br}$	$1.410\,057 \times 10^{-25}$	737.290 649
Barium-141	${}_{56}^{141}\text{Ba}$	$2.339\,939 \times 10^{-25}$	1173.974 609
Krypton-92	${}_{36}^{92}\text{Kr}$	$1.526\,470 \times 10^{-25}$	783.185 242
Xenon-140	${}_{54}^{140}\text{Xe}$	$2.323\,453 \times 10^{-25}$	1160.734 009
Strontium-94	${}_{38}^{94}\text{Sr}$	$1.559\,501 \times 10^{-25}$	807.816 711
Neutron	${}_0^1\text{n}$	$1.674\,746 \times 10^{-27}$	

Speed of light, c , = $2.997\,924\,58 \times 10^8 \text{ m s}^{-1}$; 1 MeV = $1.602\,176 \times 10^{-13}$ joules

FIGURE 8.9 Graph of energies in a fission reaction. The sum of the binding energies of La-148 and Br-85 is greater than the binding energy of U-236. The difference is released as kinetic energy of the neutrons and the fission fragments. The total energy after fission is the same as the energy before.



SAMPLE PROBLEM 2

Answer the following questions about the fission of uranium-236 producing lanthanum-148 and bromine-85. Use table 8.2 for data on masses and binding energies.

- What is the difference between the binding energy of the uranium-236 nucleus and the sum of the binding energies of the two fission fragments?
- What is the difference between the mass of the uranium-236 nucleus and the sum of the masses of all the fission fragments, including neutrons?
- Use $E = mc^2$ to calculate the energy equivalent of this mass difference in joules and MeV.

 Teacher-led video: SP2 (tlvd-0066)

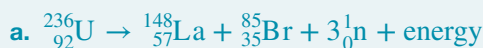
THINK

1. Write out the fission equation.
2. Use table 8.2 to find the binding energy of uranium-236.
3. Use table 8.2 to calculate the sum of the binding energies of the fragments.
4. Calculate the difference between the binding energy of the uranium nucleus and its fission fragments.
5. State the solution.

1. Use table 8.2 to find the mass of uranium-236.
2. Use table 8.2 to find the sum of the masses of the fragments.
3. Calculate the difference between the mass of the uranium nucleus and its fission fragments.
4. State the solution.

1. Use $E = mc^2$ to calculate the energy difference in joules. (The full value for c is used here, but you may use the rounded value.)
2. Convert the energy to MeV.
3. State the solution.

WRITE



Binding energy of uranium-236 = 1790.415 039 MeV

Binding energy of lanthanum-148 = 1213.125 122 MeV

Binding energy of bromine-85 = 737.290 649 MeV

$1213.125\,122 + 737.290\,649 = 1950.415\,771\text{ MeV}$

Energy difference = $1950.415\,771 - 1790.415\,039$
 $= 160.000\,732\text{ MeV}$

The difference between the binding energy of the uranium-236 nucleus and the sum of the binding energies of the two fission fragments is 160.001 MeV.

b. Mass of uranium-236 = $3.919\,629 \times 10^{-25}\text{ kg}$

Mass of lanthanum-148 = $2.456\,472 \times 10^{-25}$

Mass of bromine-85 = $1.410\,057 \times 10^{-25}$

Mass of a neutron = $1.674\,746 \times 10^{-27}$

$2.456\,472 \times 10^{-25} + 1.410\,057 \times 10^{-25} + 3 \times$
 $1.674\,746 \times 10^{-27} = 3.916\,771 \times 10^{-25}\text{ kg}$

Mass difference = $3.919\,629 \times 10^{-25} - 3.916\,771 \times 10^{-25}$
 $= 2.857\,62 \times 10^{-28}\text{ kg}$

The difference between the mass of the uranium-236 nucleus and the sum of the masses of all the fission fragments is $2.857\,62 \times 10^{-28}\text{ kg}$.

c. $E = mc^2$

$= 2.857\,62 \times 10^{-28} \times (2.997\,924\,58 \times 10^8)^2$

$= 2.568\,301 \times 10^{-11}\text{ J}$

$\frac{2.568\,301 \times 10^{-11}}{1.602\,176 \times 10^{-13}} = 160.300\,789\text{ MeV}$

The energy equivalent of this mass difference is $2.568\,301 \times 10^{-11}\text{ J}$ or 160.300 789 MeV.

PRACTICE PROBLEM 2

Answer the following questions about the fission of uranium-236 to barium-141 and krypton-92. Use table 8.2 for data on masses and binding energies.

- What is the difference between the binding energy of the uranium-236 nucleus and the sum of the binding energies of the two fission fragments?
- What is the difference between the mass of the uranium-236 nucleus and the sum of the masses of all the fission fragments, including neutrons?
- Use $E = mc^2$ to calculate the energy equivalent of this mass difference in joules and MeV.



Resources



Weblink Fission animation

8.3.4 Nuclear fusion

Nuclear fusion is the process of joining two smaller nuclei together to form a larger more stable nucleus. This was first observed by Australian physicist Mark Oliphant in 1932 when he was working with Ernest Rutherford. He was searching for other isotopes of hydrogen and helium. Heavy hydrogen (one proton and one neutron) was already known, but Oliphant discovered tritium (one proton and two neutrons) and helium-3 (with only one neutron). In his investigation he fired a fast heavy hydrogen nucleus at a heavy hydrogen target to produce a nucleus of tritium plus an extra neutron. This

fusion reaction was to become the basis of the hydrogen bomb, but Oliphant was interested only in the structure of the nucleus and did not realise the energy implications. For fusion to occur more extensively, high temperatures and pressures are needed, such as those that exist inside the Sun or in a fission bomb explosion.

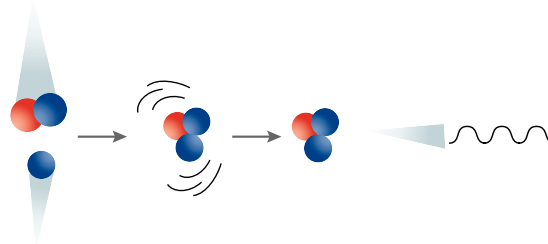
The Sun's core has a temperature of more than 15 million K, just perfect for fusion to occur! Inside the Sun, hydrogen nuclei fuse together to form helium. As helium is more stable than hydrogen, the excess nuclear energy is released. This energy is emitted from the nuclei as γ radiation, and is eventually received on Earth as light and heat.

Fusion reactions also take place in other stars. Stars that are bigger than the Sun have such severe conditions that larger, more stable nuclei such as silicon and magnesium can be produced from the fusion of smaller nuclei. A star about 30 times more massive than the Sun would be needed to produce conditions that would enable the formation of iron by fusing smaller nuclei.

Our Sun

The chain of events occurring in the Sun is quite complex. The major component of the Sun is ${}^1_1\text{H}$; that is, nuclei consisting of only one proton and no neutrons. When collisions occur between ${}^1_1\text{H}$ nuclei, they have a chance of fusing together but a change needs to occur for this pairing of positively charged particles to become a stable nucleus. One of the protons is changed into a neutron (in much the same way as a neutron is changed into a proton and an electron during β^- decay). This forms a ${}^2_1\text{H}$ nucleus. The by-products of this process are a positron and a neutrino.

FIGURE 8.10 Nuclear fusion of hydrogen-2 and a proton. The resulting nucleus is in an excited state, which releases a gamma ray.



Positrons are also produced when some artificially produced isotopes undergo radioactive decay. As we learnt previously, positrons are the antiparticle of the electrons; they have the same mass but carry a positive charge. When a positron and an electron collide, they immediately annihilate each other. The only thing that remains of either is a γ ray. Neutrinos are produced when protons change into neutrons, and vice versa. They have no charge, are considered massless and travel at close to the speed of light. Fifty trillion neutrinos from the Sun pass through the human body every second.

When a ${}^1_1\text{H}$ nucleus and a ${}^1_1\text{H}$ nucleus collide, in the conditions found in the centre of the Sun, they form a more stable ${}^2_1\text{H}$ nucleus and release the extra energy as a γ ray. If two ${}^3_2\text{He}$ nuclei collide, they complete the process of turning hydrogen into helium. The collision results in the formation of a ${}^4_2\text{He}$ nucleus and two ${}^1_1\text{H}$ nuclei. Again, energy is released. The energy released during nuclear reactions inside the Sun provides energy for life on Earth.

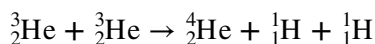
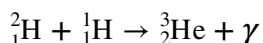
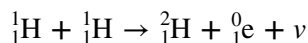
FIGURE 8.11 Our sun is powered by fusion of small nuclei.



FORMATION OF LARGER ATOMS

Most of the atoms that make up your body (and the rest of the atoms in the Earth) were originally produced in a star. Fusion in stars produced most of the atoms other than hydrogen and helium. Those nuclei with atomic numbers up to that of iron were produced in regular stars. However, when large stars stop producing energy from fusion of elements up to iron, they implode, or collapse in on themselves. This causes conditions in which even larger atoms will fuse to produce very heavy elements such as gold, lead and uranium. These stars explode as supernovas, spreading the elements they have made out into space. The Earth was formed from a cloud consisting of remnants of old supernovas. Other atoms form from radioactive decay processes as described in the previous topic, and from high energy collisions of cosmic rays.

The main sequence of nuclear equations that occur in the Sun to convert hydrogen to helium is:



The binding energy can be used to determine the amount of energy released in a fusion reaction.

The difference between the binding energies of the reactants and the products is equivalent to the mass defect.

SAMPLE PROBLEM 3

In the final nuclear equations that occur in the Sun, shown above, two helium-3 nuclei collide to produce a helium-4 nucleus and two hydrogen-1 nuclei, that is, two protons.

Use the data in the following table to calculate the:

- difference between the binding energy of the helium-4 nucleus and sum of the binding energies of the two helium-3 nuclei

- b. difference between the sum of masses of the helium-4 nucleus and the two protons, and mass of two helium-3 nuclei
- c. energy equivalent of this mass difference in joules and MeV.

Particle	Symbol	Mass (kg)	Total binding energy (MeV)
Helium-3	${}^3_2\text{He}$	$5.006\,942 \times 10^{-27}$	7.864 501
Helium-4	${}^4_2\text{He}$	$6.645\,758 \times 10^{-27}$	28.295 673
Proton	${}_1^1\text{p or } {}_1^1\text{H}$	$1.673\,351 \times 10^{-27}$	

THINK

- a. 1. Use the table to find the binding energy of the helium-4 nucleus.
2. Use the table to find the binding energy of the helium-3 nuclei.
3. Calculate the difference in binding energies.
4. State the solution.
- b. 1. Use the table to find the mass of the reactants.
2. Use the table to find the mass of the products.
3. Calculate the difference in mass.
4. State the solution.
- c. 1. Use $E = mc^2$ to calculate the energy difference in joules.
2. Convert the energy to MeV.
3. State the solution.

WRITE

- a. Binding energy of helium-4 nucleus = 28.295 673 MeV

$$\begin{aligned}\text{Binding energy of two helium-3 nuclei} &= 2 \times 7.864\,501 \\ &= 15.729\,002 \text{ MeV}\end{aligned}$$

$$\begin{aligned}\text{Difference} &= 28.295\,673 - 15.729\,002 \\ &= 12.566\,671 \text{ MeV}\end{aligned}$$

The difference between the binding energy of the helium-4 nucleus and sum of the binding energies of the two helium-3 nuclei is 12.566 671 MeV.

$$\begin{aligned}\text{b. Mass before fusion} &= 2 \times 5.006\,942 \times 10^{-27} \\ &= 1.001\,388 \times 10^{-26} \text{ kg}\end{aligned}$$

$$\begin{aligned}\text{Mass after fusion} &= 6.645\,758 \times 10^{-27} + \\ &\quad (2 \times 1.674\,746 \times 10^{-27}) \\ &= 9.995\,25 \times 10^{-27} \text{ kg}\end{aligned}$$

$$\begin{aligned}\text{Mass difference} &= 10.013\,88 \times 10^{-27} - 9.995\,25 \times 10^{-27} \\ &= 1.863 \times 10^{-29} \text{ kg}\end{aligned}$$

The difference between the sum of masses of the helium-4 nucleus and the two protons, and mass of two helium-3 nuclei is $1.863 \times 10^{-29} \text{ kg}$.

$$\begin{aligned}\text{c. } E &= mc^2 \\ &= 1.863 \times 10^{-29} \times (2.997\,924\,58 \times 10^8)^2 \\ &= 1.674\,381 \times 10^{-12} \text{ J}\end{aligned}$$

$$\frac{1.674\,381 \times 10^{-12}}{1.602\,176 \times 10^{-13}} = 10.45 \text{ MeV}$$

The energy equivalent of this mass difference is $1.674 \times 10^{-12} \text{ J}$ or 10.45 MeV.

PRACTICE PROBLEM 3

A fusion reaction in the Sun of hydrogen-1 and hydrogen-2 produces helium-3. Use the data in the following table to calculate the:

- difference between the binding energy of the helium-3 nucleus and sum of the binding energies of the hydrogen-1 and hydrogen-2 nuclei
- difference between the masses of the helium-3 nucleus and the sum of the masses of the hydrogen-1 and hydrogen-2 nuclei
- energy equivalent of this mass difference in joules and MeV.

Particle	Symbol	Mass (kg)	Total binding energy (MeV)
Helium-3	${}^3_2\text{He}$	$5.006\,942 \times 10^{-27}$	7.864 501
Hydrogen-2	${}^2_1\text{H}$	$3.344\,132 \times 10^{-27}$	2.224 573
Proton	${}^1_1\text{p}$ or ${}^1_1\text{H}$	$1.673\,351 \times 10^{-27}$	



Resources

- Digital document** Investigation 8.1 Chain reaction of dominoes (doc-32621)
- Teacher-led video** Investigation 8.1 Chain reaction of dominoes (tlvd-0845)
- Weblink** Fusion animation

8.3 EXERCISE

To answer questions online and to receive **immediate feedback** and **sample responses** for every question go to your learnON title at www.jacplus.com.au.

- Define the terms 'fusion' and 'fission'.
- Which of these reactions occurs in our Sun?
- Explain why splitting uranium-235 nuclei releases energy, but joining hydrogen atoms also releases energy.
- Use the graph of binding energy per nucleon (see figure 8.4) to estimate the amount of energy released when a uranium-235 nucleus is split into barium-141 and krypton-92. Think carefully about the number of significant figures in your answer. How well does your answer agree with the measured value of 200 MeV?
- Why is energy released in the process of fusing two small nuclei together?
- What aspect of the binding energy per nucleon curve shows that fusion of light elements releases more energy than fission of heavy ones?
- When two light elements fuse to form a single heavier one, is the product lighter or heavier than the sum of the masses of the two light atoms? Explain.
- When uranium-236 undergoes fission to form two lighter nuclei plus some neutrons, is the mass of the uranium-236 greater than, equal to or less than the sum of the masses of the two nuclei plus the neutrons? Explain.

studyON

To answer practice exam questions online and to receive immediate feedback and sample responses for every question go to your learnON title at www.jacplus.com.au.

studyON: Practice exam questions

Fully worked solutions and sample responses are available in your digital formats.

8.4 Energy from accelerating charges

KEY CONCEPTS

- Explain light as an electromagnetic wave that is produced by the acceleration of charges.
- Describe the production of synchrotron radiation by an electron radiating energy at a tangent to its circular path.
- Model the production of light as a result of electron transitions between energy levels within an atom.

8.4.1 Matter and light

The word ‘light’ is often used as a shorthand collective for all the different types of electromagnetic radiation from radio waves to gamma rays, including infra-red, visible, ultraviolet and X-rays. It is used here in that context.

So far in this text, matter has produced light in a variety of different ways. The glow of hot objects, such as the Sun, was explained by collisions between the outer electrons of atoms. The electrons’ collisions with each other caused a change in direction or speed, or often both. This acceleration of the electron produced light. If the temperature was high and the accelerations sudden, then the object glowed. The same situation applies when electrons are free from their atoms or free in space.

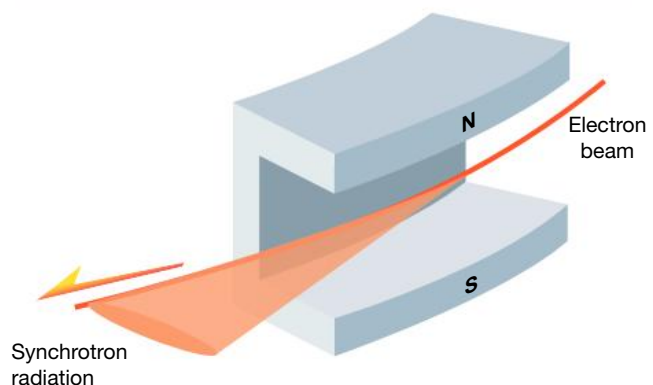
A common example of where electromagnetic waves are produced is the mobile phone. A mobile phone turns the sound signal of the person speaking into it into an electrical signal. This electrical signal moves electrons back and forth in the antenna. The antenna is a conductor inside the mobile phone. The electrons moving back and forth along the antenna produce electromagnetic waves in the radio wave portion of the electromagnetic spectrum, that move outwards from the mobile phone at the speed of light. They are received by another antenna on a mobile phone tower in the neighbourhood. The electrons in the antenna experience a force in the presence of the electromagnetic waves causing them to move up and down the antenna, turning the radio wave signal back into an electrical signal. In this way the signals can be spread around the world. Antennas work in both directions, turning electrical signals into radio waves or radio waves into electrical signals, depending on whether they are transmitting or receiving a signal.

In particle accelerators such as the Large Hadron Collider at CERN in Switzerland and the Australian Synchrotron, charged particles are accelerated by electric fields to speeds close to the speed of light, then deflected into a circular path by magnetic fields. The circular path means a constantly changing direction, so the particles are continually being accelerated and consequently giving off radiation. At CERN, this radiation and loss of energy is an unavoidable nuisance as the researchers using it want very fast particles, such as protons, to smash into each other.

FIGURE 8.12 Hundreds of mobile phone towers around the state receive and transmit radio waves from mobile phones.



FIGURE 8.13 Synchrotron radiation is emitted along the tangent of the circular path.



However, at the Australian Synchrotron scientists use electrons accelerated to almost the speed of light. When electrons reach this speed, the radiation comes off in a very narrow beam along the tangent to the circular path. The radiation beam is also very intense and includes all the wavelengths across a large range. The beams at the Australian Synchrotron have a variety of uses including scientific research such as investigating the structure of proteins, medical uses such as high resolution imaging and cancer radiation therapy, as well as the analysis of mineral samples, forensic analysis and the investigation of advanced materials.

The name **synchrotron radiation** comes from the fact that it was first observed in 1946 when the first synchrotron was built. Since then this type of radiation has been observed in galaxies, when electrons travelling at the speed of light spiral through an intense magnetic field.

FIGURE 8.14 The Australian Synchrotron in Clayton Victoria produces intense beams of synchrotron radiation that are used to analyse the composition and structure of materials, right down to the atomic scale.



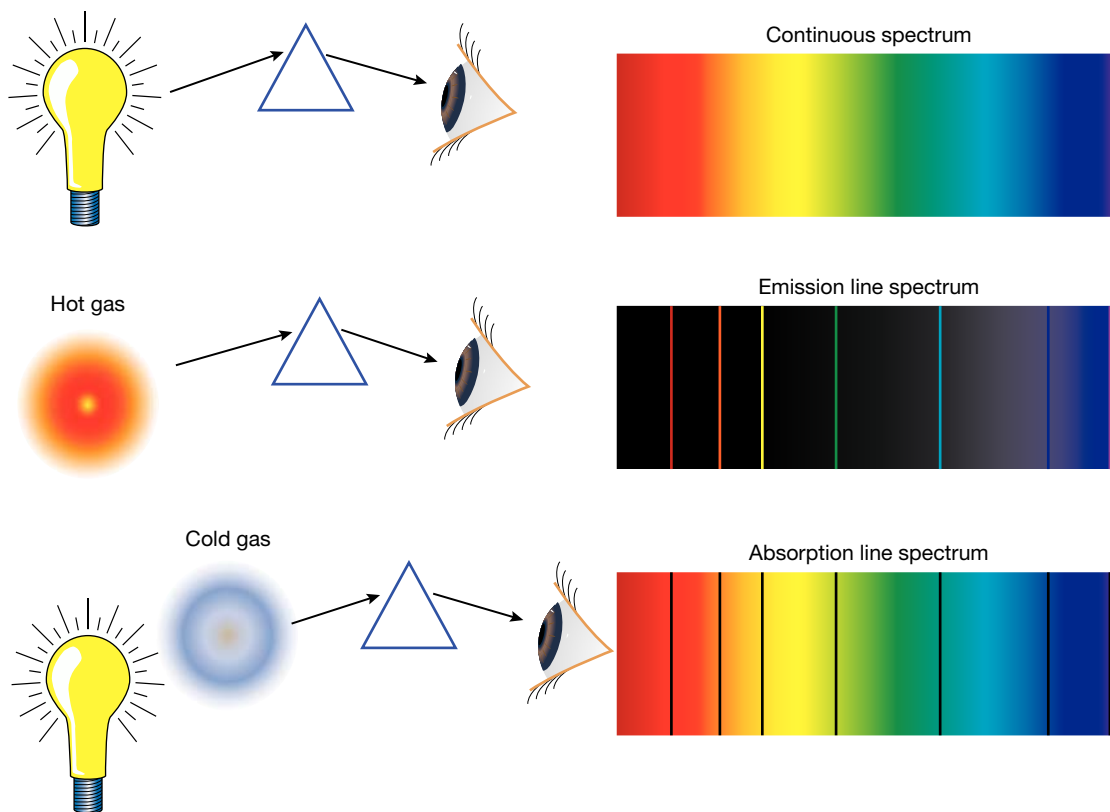
Source: ANSTO

8.4.2 Light from atoms

Electrons within atoms are also able to produce light and electromagnetic radiation from other parts of the spectrum. They can do this because there are different energy states that the electrons within atoms can take. This model of the electrons in atoms differs from the common one that imagines electrons as circling the nucleus like planets revolving around the Sun. This planetary model of the atom cannot work because of synchrotron radiation. Those charged electrons orbiting the nucleus would radiate energy, which is not observed. Also, as the electrons radiated energy they would lose energy, spiralling into the nucleus. This does not happen.

Instead, we need to think of electrons in atoms very differently. An example of the evidence for electron behaviour can be seen in the spectra from different materials. Figure 8.15 shows a typical absorption spectrum, where light is shone through a gas and specific colours are absorbed. The figure also shows an emission spectrum, where a gas is heated to a high temperature and gives a characteristic colour. The inverse of one pattern is almost identical to the other.

FIGURE 8.15 A continuous spectrum and two different ways of producing an element's fingerprint



Each line has a specific wavelength and frequency. Consequently, the light of that colour in the spectrum has a specific energy. Each line of light in the emission spectrum has come from an electron inside the atom that has jumped from one energy level down to a lower one. The difference in energy between the two levels is emitted as light energy. The existence of several lines tells us about the different energy levels that electrons in this atom can have and gives a picture of the structure inside the atom.

These emission and absorption spectra are unique to each element.

Each arrow in figure 8.16 shows possible energy transitions for electrons in hydrogen. The electron would normally be in level $n = 1$, known as the ground state, but collision with another charged particle or a photon could give the electron enough energy to enter one of the higher energy states. When this happens, it is only a matter of time before the electron gives up that additional energy in the form of a photon of light. Photons are packets of energy that make up light waves and all parts of the electromagnetic spectrum. The higher the energy of the photon, the further its light is towards the gamma end of the spectrum. Lower energy photons are towards the radio end of the spectrum. The colour of the light depends on the size of the energy transition. The arrows in figure 8.16 show energy transitions that would result in an emission spectrum. Only photons of energies that correspond to the changes in energy levels can occur, so the light emitted from excited hydrogen gas has very specific energies. Most of these lines have energies outside the visible spectrum of light, but the Balmer series are in the visible spectrum.

This feature of gases is used to great effect in lighting. Gas discharge tubes like fluorescent tubes that probably light up your Physics classroom contain a gas at low pressure. The gas in fluorescent tubes is mercury vapour. When a high voltage is put across the ends of the tube, a current of electrons flows through the tube. These electrons hit electrons in the mercury atoms, giving them energy to rise to a higher energy level. When the electron falls back to its ground state it emits light of a particular frequency. With mercury, this tends to be light in the ultraviolet part of the spectrum. The glass tube is covered with a material that absorbs the ultraviolet light and re-emits it in the visible part of the spectrum. The different frequencies of this light can be viewed by observing the fluorescent tubes through a spectroscope.

FIGURE 8.16 Electron transitions for the hydrogen atom

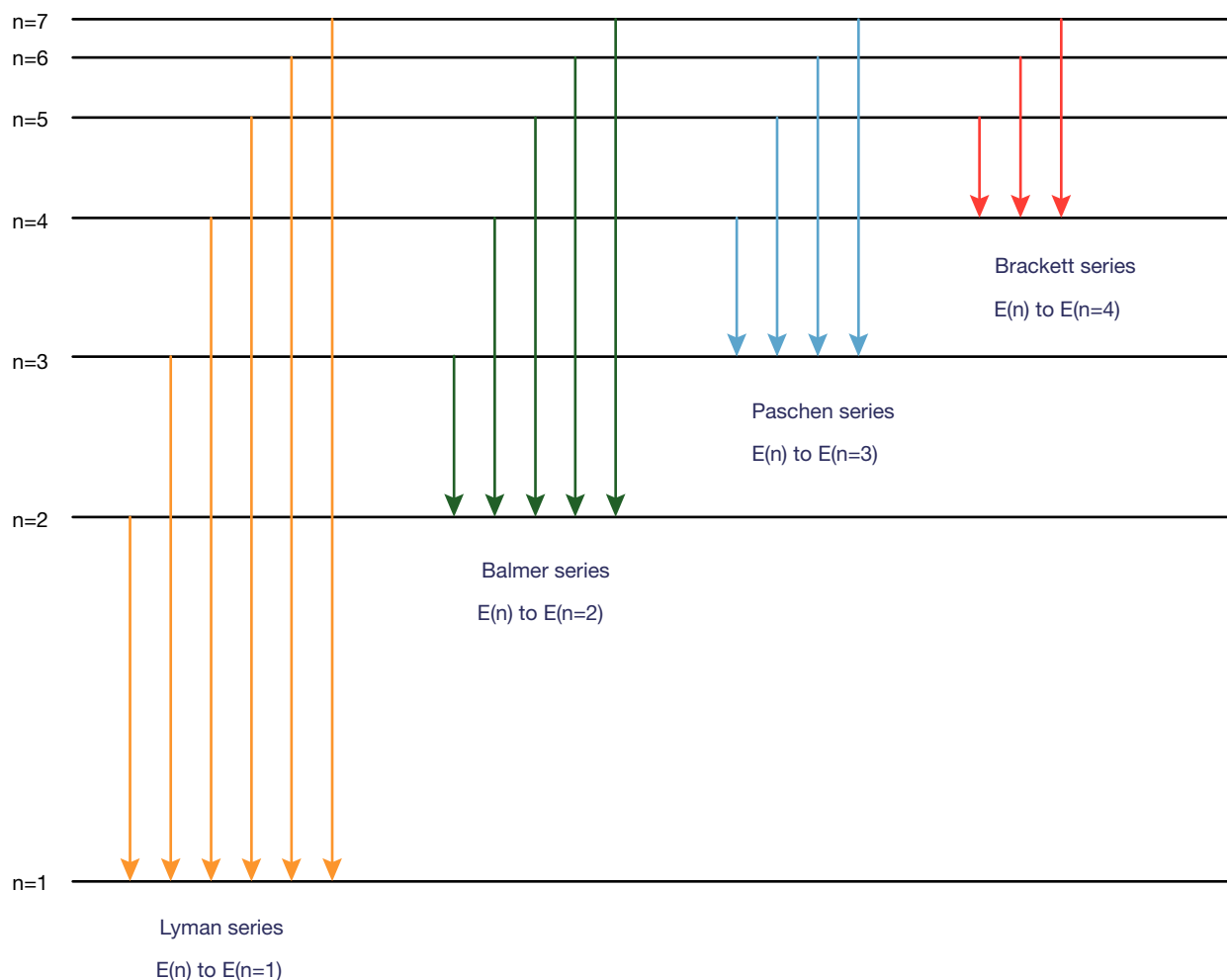
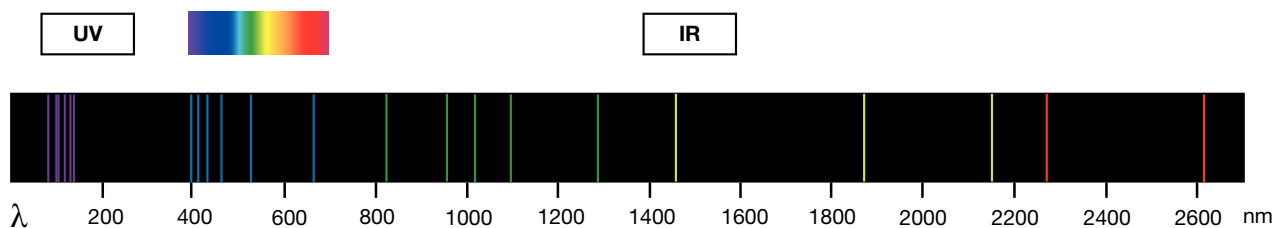


FIGURE 8.17 The emission spectrum of hydrogen



Other gas discharge tubes are used in advertising, with different gases used in the tubes, like neon, to produce light of different colours.

Liquids and solids produce spectra that resemble a continuous spectrum due to the proximity of the atoms resulting in the energy levels that have little energy difference between them. Electrons in these 'bands' can take on a nearly continuous range of energies. As a result, glowing solids, like the filament in an incandescent light bulb, produce a continuous spectrum.

FIGURE 8.18 The skipping girl sign in Richmond is a Melbourne landmark using tubes of different gases to produce the effect of a girl skipping.



SAMPLE PROBLEM 4

Identify three processes in which electrons produce electromagnetic radiation.

THINK

- 1 Recall three processes in which electrons produce electromagnetic radiation.

WRITE

Any three of the following:

- Electrons in atoms in a hot metal move between energy levels and emit electromagnetic radiation.
- Electrons moving in circles in a synchrotron produce intense electromagnetic radiation tangent to the path.
- Electrons passing through a gas at high voltage excite the electrons in the gas, which then emit electromagnetic radiation as they return to ground state.
- Electrons accelerate in an antenna.

PRACTICE PROBLEM 4

Explain why electrons cannot move around the nucleus like planets around the Sun.

-  **Digital documents** Investigation 8.2 The spectrum of hydrogen (doc-31903)
Investigation 8.3 Spectroscopes (doc-32622)
-  **Teacher-led video** Investigation 8.3 Spectroscopes (tlvd-0254)

8.4 EXERCISE

To answer questions online and to receive **immediate feedback** and **sample responses** for every question go to your learnON title at www.jacplus.com.au.

1. What situation leads to the production of synchrotron radiation?
2. Electrons are said to exist in energy levels in atoms. What is some evidence for this claim?
3. What is the source of electromagnetic radiation?
4. What can you say about the electrons in the transmitter's antenna at a radio station of frequency 621 kHz, compared with one of frequency 774 kHz?
5. Compare the energy levels of electromagnetic radiation emitted from the nucleus (gamma rays) with that emitted by the electrons in atoms.

studyon

To answer practice exam questions online and to receive immediate feedback and sample responses for every question go to your learnON title at www.jacplus.com.au.

studyON: Practice exam questions 

Fully worked solutions and sample responses are available in your digital formats.

8.5 Review

8.5.1 Summary

- Mass and energy are equivalent and related by the equation $E = mc^2$.
- The nuclei of different atoms have varying degrees of stability. The binding energy of a nucleus is the energy required to completely separate a nucleus into individual nucleons. Therefore, the binding energy is a measure of the stability of a nucleus. Iron-56 is commonly thought to be the most stable of all nuclei, however, the rarer iron-58 and nickel-62 have a slightly higher binding energy per nucleon.
- In order for a nucleus to become more stable, it emits energy called nuclear energy. The amount of energy released corresponds to the difference between the mass of the particles before and after the release of energy, according to $E = mc^2$.
- Fusion reactions generally occur between small nuclei which form nuclei that are smaller than iron. Fusion occurs in our Sun, where hydrogen nuclei are converted into helium nuclei, resulting in large amounts of energy being released.
- Fission reactions occur when a large nucleus is split into smaller, more stable fission fragments that have higher binding energy per nucleon.
- Electromagnetic radiation is produced when electric charges are accelerated.
- Electric charges can be accelerated in a number ways to produce electromagnetic radiation.
- Very fast electrons moving in a circular path produce synchrotron radiation.
- Electrons moving between energy levels inside an atom produce light in parts of the electromagnetic spectrum determined by the difference between the energy levels.

8.5.2 Key terms

The number of protons in a nucleus is called the **atomic number** of the atom.

The **binding energy** of a nucleus is the energy that is required to split a nucleus into individual nucleons.

Fission fragments are the products from a nucleus that undergoes fission. The fission fragments are smaller than the original nucleus.

Atoms containing the same number of protons but different numbers of neutrons are called **isotopes** of an element.

The **mass defect** is the difference in the mass of the products and reactants in a nuclear reaction.

Mass number describes the total number of nucleons in an atom.

Nuclear fission is the process of splitting a large nucleus to form two smaller, more stable nuclei.

Nuclear fusion is the process of joining together two nuclei to form a larger, more stable nucleus.

Synchrotron radiation is the electromagnetic radiation produced when electric charges move in circular motion. It is radiated at a tangent to the curve.

8.5.3 Practical work and investigations

Investigation 8.1

Chain reaction of dominoes

Aim: To model controlled and uncontrolled chain reaction in nuclear fission using dominoes

Digital document: doc-32621

Teacher-led video: tlvd-0845



Investigation 8.2

The spectrum of hydrogen

Aim: To observe the spectral lines of hydrogen, measure their wavelengths and compare these values with the theoretical values

Digital document: doc-31903

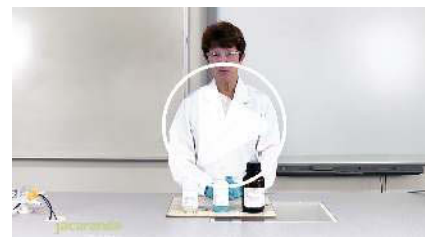
Investigation 8.3

Spectroscopes

Aim: To use a spectroscope to observe the spectrum of a light source

Digital document: doc-32622

Teacher-led video: tlvd-0254





8.5 Exercises

To answer questions online and to receive **immediate feedback** and **sample responses** for every question go to your learnON title at www.jacplus.com.au.

8.5 Exercise 1: Multiple choice questions

- What does the equation $E = mc^2$ describe?
 - The equivalence of mass and energy
 - That energy is much more significant than mass by a factor of c^2
 - That energy has mass
 - That the speed of light is constant
- When does fission occur?
 - Two small nuclei merge.
 - A small nucleus splits.
 - Two large nuclei merge.
 - A large nucleus splits.
- The products of fission have which of the following?
 - Greater binding energy per nucleon than the original nucleus
 - Less binding energy per nucleon than the original nucleus
 - Equal binding energy per nucleon as the original nucleus
 - It depends on the nucleus.
- What do current commercial nuclear plants run on?
 - Fusion
 - Fission
 - Alpha decay
 - A mixture of fusion and fission
- Electromagnetic radiation is *not* produced by accelerating which of the following?
 - Protons
 - Electrons
 - Neutrons
 - Positrons
- Which of the following is a source of the Sun's energy?
 - Fission of uranium-235
 - Fusion of carbon
 - Exothermic chemical reactions
 - Fusion of protons
- Which of the following is *not* a product of the fusion of protons?
 - Electron
 - Positron
 - Antimatter
 - Neutrino
- Radio waves from a radio station are produced by which of the following?
 - Synchrotron
 - Electrons moving between energy levels
 - Electrons moving back and forth along an antenna
 - Electrons moving in energy bands in the metal of an antenna

9. Which of the following is one of the conditions required for a nucleus to undergo fission?
 - A. The binding energy per nucleon must be less in the products than the parent nucleus.
 - B. The binding energy per nucleon must be greater in the products than the parent nucleus.
 - C. The mass of the products must be greater than the mass of the parent nucleus.
 - D. The nucleus must be smaller than that of iron-56.
10. Which of the following is *not* a unit of energy?
 - A. eV
 - B. MeV
 - C. J
 - D. kW

8.5 Exercise 2: Short answer questions

1. Why might different elements produce different absorption and emission spectra?
2. A gas absorbs some wavelengths of light to produce an absorption spectrum, but the light is very quickly re-emitted. Why doesn't the re-emitted light fill in the dark line?
3. The emission spectra shown in figure 8.17 is for hydrogen, which has only one electron. Why do you think there are so many lines in the spectrum?
4. Why are neutrons good at initiating nuclear reactions?
5. In what form does the energy released from a nuclear fusion reaction appear?
6. What conditions are required before two protons will fuse to form a single nucleus? Why are these conditions required?
7. Einstein's theories suggested that energy and mass are not conserved.
 - a. Describe what he found.
 - b. Describe an example of where it can be observed that mass and energy are not conserved.
 - c. Why is the problem with the laws of conservation of mass so difficult to observe?

8.5 Exercise 3: Exam practice questions

Use table 8.3 to answer the questions that follow.

TABLE 8.3 Masses and binding energies

Nucleus	Symbol	Mass (kg)	Total binding energy (MeV)
Plutonium-240	${}^{240}_{94}\text{Pu}$	$3.985\,755 \times 10^{-25}$	1813.454 956
Strontium-90	${}^{90}_{38}\text{Sr}$	$1.492\,791 \times 10^{-25}$	782.631 470
Barium-147	${}^{147}_{56}\text{Ba}$	$2.439\,632 \times 10^{-25}$	1204.158 203
Uranium-234	${}^{234}_{92}\text{U}$	$3.885\,920 \times 10^{-25}$	1778.572 388
Zirconium-95	${}^{95}_{40}\text{Zr}$	$1.575\,810 \times 10^{-25}$	821.139 160
Tellurium-136	${}^{136}_{52}\text{Te}$	$2.256\,760 \times 10^{-25}$	1131.440 918
Neutron	${}_0^1\text{n}$	$1.674\,746 \times 10^{-27}$	
Proton	${}_1^1\text{p}$ or ${}_1^1\text{H}$	$1.673\,351 \times 10^{-27}$	
Hydrogen-2	${}_1^2\text{H}$ or ${}_1^2\text{D}$	$3.344\,132 \times 10^{-27}$	2.224 573
Hydrogen-3	${}_1^3\text{H}$ or ${}_1^3\text{T}$	$5.007\,725 \times 10^{-27}$	8.481 821
Helium-4	${}_2^4\text{He}$	$6.645\,758 \times 10^{-27}$	28.295 673
Lithium-6	${}_3^6\text{Li}$	$9.987\,263 \times 10^{-27}$	31.994 564

Question 1 (6 marks)

A plutonium-239 nucleus absorbs a neutron to become plutonium-240, which splits to form strontium-90, barium-147 and three neutrons.

- a. What is the difference between the binding energy of the plutonium-240 nucleus and the sum of the binding energies of the two fission fragments? **2 marks**
- b. What is the difference between the mass of the plutonium-240 nucleus and the sum of the masses of all the fission fragments, including neutrons? **2 marks**
- c. Use $E = mc^2$ to calculate the energy equivalent of this mass difference in joules and MeV. **2 marks**

Question 2 (6 marks)

A uranium-233 nucleus absorbs a neutron to become uranium-234, which splits to form zirconium-95, tellurium-136 and three neutrons.

- a. What is the difference between the binding energy of the uranium-234 nucleus and the sum of the binding energies of the two fission fragments? **2 marks**
- b. What is the difference between the mass of the uranium-234 nucleus and the sum of the masses of all the fission fragments, including neutrons? **2 marks**
- c. Use $E = mc^2$ to calculate the energy equivalent of this mass difference in joules and MeV. **2 marks**

Question 3 (9 marks)

A fusion reactor could not feasibly use the same reactions as the Sun. A reactor on Earth would have to use a different reaction, preferably a one-step reaction with only two reactants. Three *possible* reactions for a terrestrial fusion reactor are as follows.

- a. ${}^2_1\text{H} + {}^3_1\text{H} \rightarrow {}^4_2\text{He} + {}^1_0\text{n}$
- b. ${}^2_1\text{H} + {}^2_1\text{H} \rightarrow {}^3_1\text{H} + {}^1_1\text{H}$
- c. ${}^2_1\text{H} + {}^6_3\text{Li} \rightarrow 2{}^4_2\text{He}$

Using data from table 8.3, calculate the:

- i. difference between the binding energy of the products and the sum of the binding energies of the reactants **3 marks**
- ii. difference between the sum of masses of the products and of the reactants **3 marks**
- iii. energy equivalent of this mass difference in joules and MeV. **3 marks**

Question 4 (3 marks)

Compare the processes of fission and fusion.

Question 5 (2 marks)

List two reasons fusion would be a preferable way of generating power to fission.

8.5 Exercise 4: studyON topic test

Fully worked solutions and sample responses are available in your digital formats.

teach

Test maker

Create unique tests and exams from our extensive range of questions, including practice exam questions. Access the assignments section in learnON to begin creating and assigning assessments to students.

UNIT 1 | AREA OF STUDY 3 REVIEW

AREA OF STUDY 3

What is matter and how is it formed?

OUTCOME 3

Explain the origins of atoms, the nature of subatomic particles and how energy can be produced by atoms.

PRACTICE EXAMINATION

STRUCTURE OF PRACTICE EXAMINATION		
Section	Number of questions	Number of marks
A	20	20
B	4	20
Total		40

Duration: 50 minutes

Information:

- This practice examination consists of two parts. You must answer all question sections.
- Pens, pencils, highlighters, erasers, rulers and a scientific calculator are permitted.
- You may use the VCAA Physics formula sheet for this task.



Resources



Weblink VCAA Physics formula sheet

SECTION A — Multiple choice questions

All correct answers are worth 1 mark each; an incorrect answer is worth 0.

1. Which of the following phenomena does Hubble's Law refer to?
 - A. The red shift that is observed in distant galaxies, due to the expansion of the universe
 - B. That the more distant a galaxy is from us, the faster it is moving away from us
 - C. That the red shift of distant galaxies is due to the Doppler effect
 - D. The limit to the maximum possible speed that distant galaxies are receding from us
2. The currently accepted theory of the Big Bang origin of the universe is *not* supported by which of the following observation?
 - A. The cosmic microwave background is the temperature the universe cooled to after the Big Bang.
 - B. Distant galaxies are observed to be red shifted as they are receding from us.
 - C. The further a galaxy is from us, the more red shifted it is.
 - D. Distant galaxies are all red shifted by the same amount.

3. The light from a star near the Sun within the Milky Way galaxy is blue shifted. Which of the following best describes the current explanation for this change in wavelength?
 - A. The star is moving away from us.
 - B. The star is moving towards us.
 - C. The space between the star and the Sun is contracting.
 - D. The star is being drawn towards the centre of the Milky Way away from the Sun.
4. The Voyager 1 probe is the furthest human-made object from our solar system. It is travelling at a speed of approximately 17 km s^{-1} . What is the distance it will travel in one year, in metres?
 - A. $2.2 \times 10^8 \text{ m}$
 - B. $5.4 \times 10^8 \text{ m}$
 - C. $2.2 \times 10^{11} \text{ m}$
 - D. $5.4 \times 10^{11} \text{ m}$
5. The Hubble constant (H) could be used to estimate the age of the universe. Using the best observational data, Edwin Hubble estimated the constant to have a value $1.6 \times 10^{-17} \text{ s}^{-1}$. Which of the following is the best estimate of the age of the universe?
 - A. $1.6 \times 10^{16} \text{ s}^{-1}$
 - B. $6.3 \times 10^{16} \text{ s}^{-1}$
 - C. $1.6 \times 10^{17} \text{ s}^{-1}$
 - D. $6.3 \times 10^{17} \text{ s}^{-1}$
6. Which of the following best describes the reason for the ratio of protons to neutrons in the early universe as 7:1?
 - A. There was insufficient matter to form neutrons.
 - B. Seven is the ideal ratio for the protons to fuse with neutrons to form helium nuclei.
 - C. The universe cooled to a point that protons do not interact with electrons with sufficient energy.
 - D. There were too many protons that interfered with neutron formation.
7. According to the current theory of matter, which of the following groups of particles comprise the basic particles that form all other matter?
 - A. Protons, neutrons and electrons with their antiparticles
 - B. Hadrons and leptons with their antiparticles
 - C. Baryons and mesons with their antiparticles
 - D. Quarks and leptons with their antiparticles
8. An isotope of hydrogen is tritium. A neutrally charged atom of tritium comprises a proton and two neutrons. How many quark and leptons make up this atom?
 - A. 3 quarks and 1 leptons
 - B. 6 quarks and 3 leptons
 - C. 3 quarks and 3 leptons
 - D. 9 quarks and 1 leptons
9. Which of the following *cannot* be classified as a fermion?
 - A. A beta particle
 - B. A hydrogen nucleus
 - C. A quark
 - D. A gamma ray
10. Which of the following does *not* describe the hadron family of particles?
 - A. They include the positron.
 - B. They include baryons and mesons.
 - C. They are composed of two or three quarks.
 - D. They have an internal structure.

Use the following information to answer questions 11 and 12.

Study the following table of quarks.

Type	Charge	Type	Charge
Up (u)	$+\frac{2}{3}$	Charm (c)	$+\frac{2}{3}$
Down (d)	$-\frac{1}{3}$	Bottom (b)	$-\frac{1}{3}$
Strange (s)	$-\frac{1}{3}$	Top (t)	$+\frac{2}{3}$

11. Which of the following best describes the charge of the combination of a charm quark and an antibottom quark?
- A. $-\frac{1}{3}$
 B. $+\frac{1}{3}$
 C. -1
 D. $+1$
12. This combination of quarks results in what sort of particle?
- A. Baryon
 B. Lepton
 C. Meson
 D. Neutrino

Use the following information to answer questions 13 and 14.

When a matter particle and an antimatter particle collide, they annihilate each other and all matter and antimatter is transformed into energy in the form of electromagnetic radiation.

Mass of electron: 9.1×10^{-31} kg

Mass of proton: 1.67×10^{-27} kg

Speed of light: 3.0×10^8 m s⁻¹

13. Using the data provided, what is the best estimate of the energy released when an electron and a positron meet, at rest?
- A. 1.6×10^{-13} J
 B. 8.2×10^{-14} J
 C. 5.5×10^{-22} J
 D. 2.7×10^{-22} J
14. When a proton and an antiproton meet, at rest, the energy released is 3.0×10^{-10} J. What is the approximate equivalent amount of this energy in MeV?
- A. 1.9 MeV
 B. 19 MeV
 C. 190 MeV
 D. 1900 MeV
15. How many protons and neutrons are there in an alpha particle ${}^4_2\alpha$?
- A. 4 protons and 2 neutrons
 B. 2 protons and 4 neutrons
 C. 2 protons and 2 neutrons
 D. 2 protons and 6 neutrons

Use the following information to answer questions 16 and 17.

Strontium-90, $^{90}_{38}\text{Sr}$, is a beta emitter with a half-life of 29 years.

16. Element X is the daughter element of strontium-90. Which of the following best describes the nucleus of X following the beta decay of strontium-90?
 - A. $^{90}_{39}\text{X}$
 - B. $^{86}_{36}\text{X}$
 - C. $^{90}_{38}\text{X}$
 - D. $^{86}_{39}\text{X}$
17. A chemical mixture from the last century contains strontium-90. A sample of it has been analysed and it is found that there is only 12.5% of the original amount of strontium-90 left. How old is this chemical mixture?
 - A. 29 years old
 - B. 58 years old
 - C. 87 years old
 - D. 116 years old
18. The binding energy per nucleon for the deuteron ^2_1H (or D) is 1.11 MeV. Which of the following best describes the binding energy of this nucleus?
 - A. 0.556 MeV
 - B. 1.11 MeV
 - C. 2.22 MeV
 - D. 3.33 MeV
19. Helium fusion occurs in stars where three nuclei of helium fuse to form a carbon nucleus. This process releases 1.16×10^{-12} J of energy per carbon nucleus formed. What is the best estimate of the amount of mass lost for each carbon nucleus formed?
 - A. 3.9×10^{-21} kg
 - B. 1.3×10^{-29} kg
 - C. 3.9×10^{-29} kg
 - D. 1.3×10^{-21} kg
20. A radioactive source has 240 000 active nuclei initially. After 32 hours, there are 15 000 active nuclei remaining. Which of the following best describes the half-life of this source?
 - A. 2 hours
 - B. 4 hours
 - C. 6 hours
 - D. 8 hours

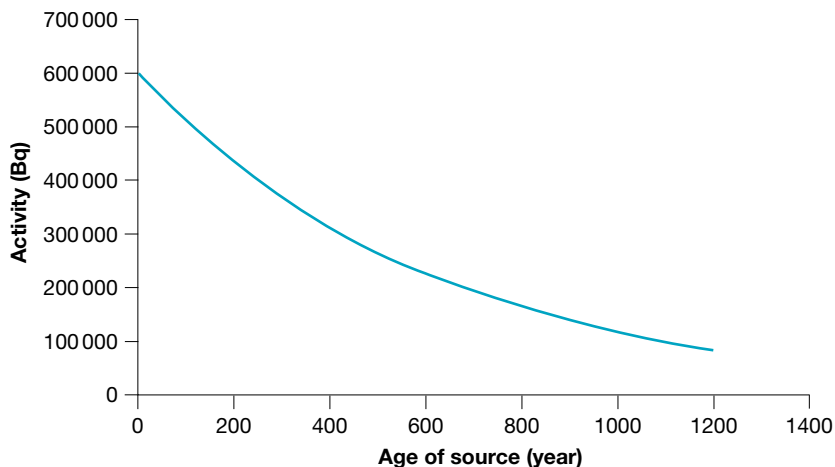
SECTION B — Short answer questions

Question 1 (6 marks)

- a. Within a second of the Big Bang, protons and neutrons were formed in equal amounts as the protons interacted with electrons to form neutrons, which decayed in turn to form protons and electrons. Explain why within the next few minutes the ratio of neutrons to protons dropped to 1:7. **2 marks**
- b. Within minutes of the Big Bang, nearly all the neutrons had fused to form helium-4, resulting in helium-4 making up 25% of the mass in the universe. Provide a detailed explanation of how the mass of helium-4 is 25% that of the universe. **3 marks**
- c. It took a further 380 000 years before neutral atoms were formed and the universe became transparent to electromagnetic radiation. What was the condition that led to the formation of neutral atoms? **1 mark**

Question 2 (5 marks)

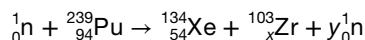
Americium-241, $^{241}_{95}\text{Am}$, is an alpha emitter that is commonly used in smoke detectors. The following graph shows the activity curve of a sample of americium-241. This sample had an initial strength of $6.0 \times 10^5 \text{ Bq}$.



- Use the graph to estimate the half-life of americium-241. Outline the two points on the graph that you used to arrive at your estimate. **2 marks**
- Describe what is meant by the term alpha decay (which occurs to an alpha emitter). **1 mark**
- Americium-241 radioactively decays and its daughter element is neptunium, Np. Write the full decay equation of americium. **2 marks**

Question 3 (6 marks)

Plutonium-239 is a fissile radioisotope which undergoes a fission reaction according to the following equation:



- What is the value of x in the equation? **2 marks**
- How many neutrons, y , were produced in each reaction event? **2 marks**
- Each reaction event results in a mass deficit of $3.1 \times 10^{-28} \text{ kg}$. What is the amount of energy produced per reaction event, expressed in MeV? **2 marks**

Question 4 (3 marks)

Particle colliders have been used to create hadrons to study and discern the physics of the early universe. One such hadron is found to be made up of three quarks, with a charge of $+2$.

- Is the hadron a meson or a baryon? **1 mark**
- Two of the quarks are known to be up quarks. Which of the following quarks might be the third quark? Justify your response. **2 marks**

Type	Charge	Type	Charge
Up (u)	$+\frac{2}{3}$	Charm (c)	$+\frac{2}{3}$
Down (d)	$-\frac{1}{3}$	Bottom (b)	$-\frac{1}{3}$
Strange (s)	$-\frac{1}{3}$	Top (t)	$+\frac{2}{3}$

ASSESSMENT TASK – A MODELLING ACTIVITY

In this task, you will be required to explain the origins of atoms, the nature of subatomic particles and how energy can be produced by atoms.

- A scientific calculator is permitted for this task.
- Access to a spreadsheet program such as Excel will assist.

Total time: One lesson to complete the simulation;
50 minutes for the completion of the three listed tasks
(5 minutes reading and 45 minutes writing)

Total marks: 35 marks

A MODELLING ACTIVITY FOR RADIOACTIVE SAMPLES

The radioactive decay of a single nucleus is a random event. However, for a large enough population of identical radioactive nuclei, the half-life can be found for the sample. Even a small radioactive sample contains many billions of nuclei. Thus, the overall pattern of decay will appear quite ordered with the source getting less intense over time.

Dice, when thrown, have a probability of landing with a 6 face up equal to $\frac{1}{6}$. Like radioactive material, the outcome of each die, or nucleus, is unpredictable but a large sample will follow an ordered statistical behaviour.

In this experimental assessment task you will produce a radioactive decay curve by simulating the radioactive decay process using dice. You will analyse this curve to determine the 'half-life' of your set of dice. The analogy is simple. Each trial corresponds to a set interval of time. If a die falls with 6 face up it is said to have decayed. If not, it is deemed to be still radioactive in the sense that it has not decayed. By recording the number of dice remaining at the end of each successive trial you will trace the 'radioactive decay' of the sample of dice.

Materials

A box of dice, appropriate table (either by paper or on a digital spreadsheet) and graph paper

Method

Firstly, count how many dice you have to start with; a good number would be 50 dice.

Create a table similar to the following. The first row has been done assuming there were 50 dice to begin with. This table could be completed in a spreadsheet.

Number of trial n	Number of dice remaining in sample
0	50
1	
2	

1. Toss all the dice randomly.
2. Count the number of 6s in the sample and remove them from the sample. Record the number of dice left after the first trial where $n = 1$.
3. Toss all the remaining dice and count the number of 6s. Again remove them from the sample and record the number of dice left after the second trial, this time $n = 2$.
4. Repeat this process a further 13 times making a total of 15 trials.
5. If all the dice have been removed before the 15th trial, record the dice remaining in the last trials as 0.
6. Now perform the process another two times to obtain three independent simulations in total. You will need to make two more columns for your simulation data.



Results and discussion

Task 1

Create a spreadsheet or a table with column B recording the change in the sample size for trials 0 to 15 in your first simulation.

In columns C and D record the results of your second and third simulations.

In column E obtain the sum of each of the rows in each of the other three simulations to get the total results for your three simulations.

Task 2

Plot a graph of the total number of dice remaining (summed over three trials (column E)) versus the number of trials, 1 through 15. Draw a curve of best fit.

Task 3

Answer the following questions related to this investigation.

1. If there are 100 dice and they are tossed, what fraction on average would you expect to land with 6 face up?
2. Consequently, from 100 dice how many would you expect to be removed?
3. How many dice would be left if those dice were removed?
4. From those remaining after the first toss, repeat steps 1, 2 and 3 each time calculating the number of dice left after those with a face up value of 6 have been removed. Repeat this until there are less than 50 dice remaining.
5. Use this sequence of numbers (called a geometric sequence) to estimate the half-life.
6. Use your graph of your simulation to estimate the half-life for your population of dice? Ensure you show this on your graph and identify the result you obtained.
7. Describe how you used your graph to estimate this half-life.
8. What is meant by the half-life of a radioactive material?
9. What happens to the decay rate — that is, the number of atoms decaying — after each half-life. Explain.
10. 1 kilogram of Tc-99 (technetium-99) contains approximately 6.0×10^{24} atoms. The half-life of Tc-99 is 6 hours and it is a beta-emitter. What does the term beta-emitter mean?
11. How long would it take for the Tc-99 sample to be reduced to a mass of:
 - (a) 500 grams (3.0×10^{24} atoms)
 - (b) 125 grams (1.5×10^{24} atoms)?
12. Tim has 2 kilograms of Tc-99. It takes 6 hours for the sample to be reduced to 1 kilogram. Tim states that every 6 hours, 1 kilogram will decay, so after 12 hours no sample will be left. Explain why the statement made by Tim is incorrect.
13. Compare the processes of nuclear fusion and nuclear fission. Explain why both fusion and fission are processes that can produce energy.
14. The process of nuclear fusion was fundamental during the development of the universe. Explain how this process lead to the formation of atoms, with specific reference to atoms and subatomic particles present during the formation of the universe and early nucleogenesis.
15. There are two types of forces holding the nucleus together: the strong nuclear force and the weak nuclear force. Describe these two forces and identify which is responsible for the decay simulated in this investigation.



Resources



Digital document School-assessed coursework (doc-32275)

UNIT 2

WHAT DO EXPERIMENTS REVEAL ABOUT THE PHYSICAL WORLD?

In this unit, you will explore the power of conducting experiments and investigations to understand and develop models and theories. This unit allows you to investigate motion, exploring the effects of balanced and unbalanced forces both theoretically and practically. You will conduct further research in an area of interest, selecting from one of 12 options. This will allow for an in-depth application of physics, focusing on topics such as astrophysics, medical physics and sports science. You will also conduct a practical investigation related to the knowledge and skills developed across Units 1 and 2.



AREA OF STUDY	OUTCOME	TOPICS
1. How can motion be described and explained?	Investigate, analyse and mathematically model the motion of particles and bodies.	9. Analysing motion 10. Forces in action 11. Energy and motion
2. OPTIONS: Observation of the physical world	Twelve options are available for selection in Area of Study 2. Each option is based on a different observation of the physical world. Students are required to apply and explain concepts for the one option selected.	Topics 12–23
3. Practical investigation	Design and undertake an investigation of a physics question related to the scientific inquiry processes of data collection and analysis, and draw conclusions based on evidence from collected data.	24. Practical investigation

Source: VCE Physics Study Design (2016–2021) extracts © VCAA; reproduced by permission.

9 Analysing motion

9.1 Overview

Numerous **videos** and **interactivities** are available just where you need them, at the point of learning, in your digital formats, learnON and eBookPLUS at www.jacplus.com.au.

9.1.1 Introduction

The study of the motion of objects relies upon an accepted and reliable means for describing and analysing motion. In this topic you will explore the key quantities used to describe motion, their characteristics and interrelationships. By the end of this topic you should be able to distinguish between scalar and vector quantities. You will be able to describe motion in terms of position, displacement, speed, velocity and acceleration. You will analyse motion using the most suitable method, including numerical calculations, estimations, algebraic analysis and graphical analysis. This area of study is often broadly referred to as kinematics. The skills developed through this topic provide the foundation for studies of the role of forces and energy in the understanding motion in the topics that follow.

FIGURE 9.1 When driving a vehicle, the driver needs to be aware of their movements in terms of position, speed, direction and acceleration.



9.1.2 What you will learn

KEY KNOWLEDGE

After completing this topic, you will be able to:

- identify parameters of motion as vectors or scalars
- analyse graphically, numerically and algebraically, straight-line motion under constant acceleration:

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

- graphically analyse non-uniform motion in a straight line.

Source: VCE Physics Study Design (2016–2021) extracts © VCAA; reproduced by permission.

PRACTICAL WORK AND INVESTIGATIONS

Practical work is a central component of learning and assessment. Experiments and investigations, supported by a **Practical investigation logbook** and **Teacher-led videos**, are included in this topic to provide opportunities to undertake investigations and communicate findings.

on Resources

 **Digital documents** Key science skills — VCE Units 1–4 (doc-31856)

Key terms glossary (doc-32266)

Practical investigation logbook (doc-32267)

studyon

To access key concept summaries and practice exam questions download and print the **studyON: Revision and practice exam question booklet** (sonr-0034).

9.2 Describing movement

KEY CONCEPTS

- Identify parameters of motion as vectors or scalars.
- Analyse numerically and algebraically, straight-line motion under constant acceleration.

The study of the way in which an object moves is the starting point for developing an understanding of the nature of forces and their relationship with motion.

9.2.1 Distance and displacement

Distance is a measure of the length of the path taken during the change in position of an object. Distance is a **scalar** quantity. It does not specify a direction.

Displacement is a measure of the change in position of an object. Displacement is a **vector** quantity. In order to describe a displacement fully, a direction must be specified as well as a magnitude. The path taken by the fly in figure 9.2 as it escapes the swatter illustrates the difference between distance and displacement. The displacement of the fly is 60 centimetres to the right, while the distance travelled is well over 1 metre.

In a 100-metre sprint, the runners travel in a straight line, therefore the magnitude of the displacement is the same as the distance. However, it is the displacement that fully describes the change in position of the runner because it specifies the direction.

FIGURE 9.2 Distance and displacement are different quantities.



FIGURE 9.3 Runners in the 100-metre sprint travel in a straight line.



The displacement of an object that has moved from position $\vec{x}_1$ to position $\vec{x}_2$ is expressed as:

$$\begin{aligned}\text{displacement} &= \text{change in position} \\ &= \text{final position} - \text{initial position} \\ \Delta\vec{x} &= \vec{x}_2 - \vec{x}_1\end{aligned}$$

Displacement can also be represented by the symbols $\vec{x}$ or $\vec{s}$. (Vectors can be represented using either bold text or a right arrow.)

SAMPLE PROBLEM 1

A hare and a tortoise decide to have a race along a straight 100-metre stretch of highway. They both head due north. However, at the 80-metre mark, the hare realises that he dropped his phone at the 20-metre mark. He dashes back, grabs his phone and resumes the race, arriving at the finishing line at the same time as the tortoise. (It was a very fast tortoise!)

- What was the displacement of the hare during the entire race?
- What was the distance travelled by the hare during the race?
- What was the distance travelled by the tortoise during the race?
- What was the displacement of the hare during his return to collect his phone?

 **Teacher-led video:** SP1 (tlvd-0069)

THINK

- Recall the relationship $\Delta x = x_2 - x_1$.
- Identify the variables. Using the start as the reference point, the displacement was 100 m north. In symbols, this calculation can be done by denoting north as positive and south as negative.
- Substitute into the relationship to find Δx .
- State the solution.

WRITE

$$\begin{aligned}\text{a. } \Delta x &= x_2 - x_1 \\ x_1 &= 0, \quad x_2 = 100 \text{ m north}\end{aligned}$$

$$\begin{aligned}\Delta x &= 100 - 0 \\ &= 100 \text{ m north}\end{aligned}$$

The displacement of the hare is 100 metres north.



b. 1. The distance is the length of the path taken.

2. State the solution.

c. 1. The distance travelled by the tortoise is the length of the path taken.

2. State the solution.

d. 1. Recall the relationship $\Delta x = x_2 - x_1$.

2. The hare returns from a position 80 m north of the reference point (or start) back to a position 20 m north of the reference point.

3. State the solution.

b. The hare travels a total distance of 80 m (before noticing his phone) + 60 m (running back to the 20 m mark) + 80 m (from the 20 m mark to the finishing line).

$$\begin{aligned}\text{Distance} &= 80 + 60 + 80 \\ &= 220 \text{ m}\end{aligned}$$

The total distance that the hare travels is 220 metres.

c. Length of the path taken = 100 m

The tortoise travels a total distance of 100 metres.

$$\begin{aligned}\text{d. } \Delta x &= x_2 - x_1 \\ &= 20 \text{ m} - 80 \text{ m} \\ &= -60 \text{ m}\end{aligned}$$

The displacement is 60 metres south.

PRACTICE PROBLEM 1

A cyclist rides 4 kilometres due west from home, then turns right to ride a further 4 kilometres due north. She stops, turns back and rides home along the same route.

a. What distance did she travel during the entire ride?

b. What was her displacement at the instant that she turned back?

c. What was her displacement from the instant she commenced her return journey until she arrived home?

9.2.2 Speed

Speed is a measure of the rate at which an object moves over a distance. When you calculate the speed of a moving object, you need to measure the distance travelled over a time interval.

The average speed of an object can be calculated by dividing the distance travelled by the time taken:

$$\text{average speed} = \frac{\text{distance travelled}}{\text{time interval}}$$

The speed obtained using this formula is the average speed during the time interval. Speed is a scalar quantity as it does not include direction. The unit of speed is m s^{-1} if SI units are used for distance and time. However, it is often more convenient to use other units such as cm s^{-1} or km h^{-1} .

SNAIL'S PACE

A snail would lose a race with a giant tortoise! A giant tortoise can reach a top speed of 0.37 km h^{-1} . However, its 'cruising' speed is about 0.27 km h^{-1} . The world's fastest snail covers ground at the breathtaking speed of about 0.05 km h^{-1} . However, the common garden snail is more likely to move at a speed of about 0.02 km h^{-1} . Both of these creatures are slow compared with light, which travels through the air at 1080 million km h^{-1} , and sound, which travels through the air (at sea level) at about 1200 km h^{-1} .

How long would it take the snail, giant tortoise, light and sound respectively to travel once around the equator, a distance of 40 074 km?



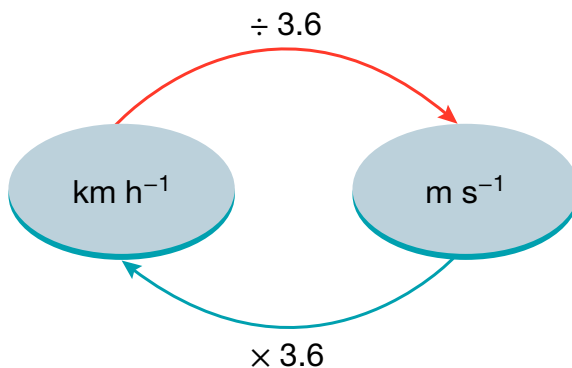
9.2.3 Converting units of speed

It is often necessary to convert units that are not derived from SI units (such as km h^{-1}) to and from units that are derived SI units, such as m s^{-1} .

TABLE 9.1 Converting units of speed

To convert 60 km h^{-1} to m s^{-1}	To convert 30 m s^{-1} to km h^{-1}
$\begin{aligned} &\frac{60 \text{ km}}{1 \text{ h}} \\ &= \frac{60\,000 \text{ m}}{3600 \text{ s}} \\ &= 16.7 \text{ m s}^{-1} \end{aligned}$	$\begin{aligned} &\frac{30 \text{ m}}{1 \text{ s}} \\ &= \frac{0.030 \text{ km}}{\frac{1}{3600} \text{ h}} \\ &= \frac{3600 \times 0.030 \text{ km}}{1 \text{ h}} \\ &= 108 \text{ km h}^{-1} \end{aligned}$
The speed in km h^{-1} has been multiplied by $\frac{1000}{3600}$, or divided by 3.6.	The speed in m s^{-1} has been multiplied by $\frac{3600}{1000}$, that is, by 3.6.

To quickly convert between speeds in m s^{-1} and km h^{-1} you can simply multiply or divide by 3.6 depending on which way you are converting.



SAMPLE PROBLEM 2

A plane carrying passengers from Melbourne to Perth flies at an average speed of 250 m s^{-1} . The flight takes 3 hours. Use this information to determine the approximate distance by air between Melbourne and Perth.

THINK

1. Recall the relationship and rearrange to find distance.
2. Identify the values, and convert into the similar units.
Note: Alternatively, the distance could be calculated in metres and converted to kilometres. Multiply the time interval by 3600 to convert h to s.
- 3 Substitute into the relationship to find distance.
- 4 State the solution.

WRITE

$$\text{Average speed} = \frac{\text{distance travelled}}{\text{time interval}}$$

$$\text{Distance travelled} = \text{average speed} \times \text{time interval}$$

$$\text{Time interval} = 3 \text{ h}$$

$$\begin{aligned}\text{Average speed} &= 250 \text{ m s}^{-1} \quad (\times 3.6 \text{ to convert to km h}^{-1}) \\ &= 900 \text{ km h}^{-1}\end{aligned}$$

$$\begin{aligned}\text{Distance travelled} &= 900 \text{ km h}^{-1} \times 3 \text{ h} \\ &= 2700 \text{ km}\end{aligned}$$

The approximate distance by air between Melbourne and Perth is 2700 kilometres.

PRACTICE PROBLEM 2

A car takes 8 hours to travel from Canberra to Ballarat at an average speed of 25 m s^{-1} . What is the road distance from Canberra to Ballarat?

9.2.4 Velocity

In everyday language, the word *velocity* is often used to mean the same thing as speed. In fact, velocity is not the same quantity as speed; **velocity** is a measure of the rate of displacement, or rate of change in position, of an object. Because displacement is a vector quantity, velocity is also a vector quantity. The velocity has the same direction as the displacement. The symbol $\mathbf{v}$ is used to denote velocity. (Unfortunately, the symbol v is often used to represent speed as well, which can be confusing.) To make a distinction between vectors and scalars, this text mostly displays vector symbols in bold. When bold can't be used to distinguish a vector (for example, in the following pink box or when writing by hand), it is common practice to place a vector symbol above ($\vec{v}$) or below ($\underline{v}$) vector quantities.

The average velocity of an object, $\vec{v}_{\text{av}}$, during a time interval t can be expressed as:

$$\vec{v}_{\text{av}} = \frac{\Delta \vec{x}}{\Delta t}$$

where $\Delta \vec{x}$ represents the displacement (change in position).

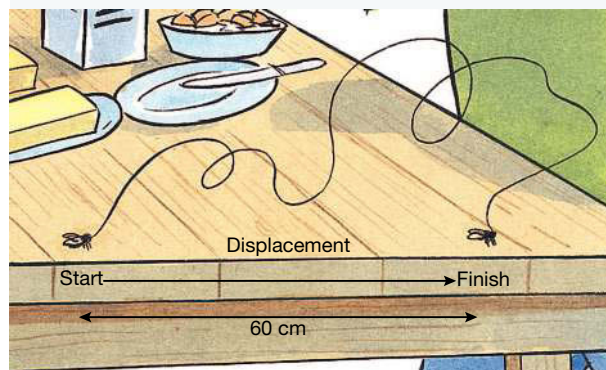
For motion in a straight line in one direction, the magnitude of the velocity is the same as the speed. The motion of the fly in figure 9.4 illustrates the difference between velocity and speed. If the fly takes 2 seconds to complete its flight, its average velocity is:

$$\begin{aligned} v_{av} &= \frac{\Delta x}{\Delta t} \\ &= \frac{60 \text{ cm to the right}}{2 \text{ s}} \\ &= 60 \text{ cm s}^{-1} \text{ to the right} \end{aligned}$$

The path taken by the fly is about 180 cm. Its average speed is:

$$\begin{aligned} \text{average speed} &= \frac{\text{distance travelled}}{\text{time travelled}} \\ &= \frac{180 \text{ cm}}{2 \text{ s}} \\ &= 90 \text{ cm s}^{-1} \end{aligned}$$

FIGURE 9.4 When motion is not in a straight line, in one direction, velocity is different to speed.



on Resources

 **Digital document** Investigation 9.1 Going home (doc-31874)

SAMPLE PROBLEM 3

Calculate the (a) average speed and (b) average velocity of the hare in Sample problem 1 if it takes 20 seconds to complete the race.

THINK

- a. 1. Recall the relationship.
2. Identify the values.
3. Substitute into the relationship to find the average speed.
4. State the solution.
- b. 1. Recall the relationship.
2. Identify the values.
3. Substitute into the relationship to find v_{av} .
4. State the solution.

WRITE

a. Average speed = $\frac{\text{distance travelled}}{\text{time interval}}$

Distance travelled = 220 m

Time interval = 20 s

$$\begin{aligned} \text{Average speed} &= \frac{220 \text{ m}}{20 \text{ s}} \\ &= 11 \text{ m s}^{-1} \end{aligned}$$

The average speed of the hare is 11 m s^{-1} .

b. Average velocity: $v_{av} = \frac{\Delta x}{\Delta t}$

Displacement = 100 m north

Time interval = 20 s

$$\begin{aligned} v_{av} &= \frac{100 \text{ m north}}{20 \text{ s}} \\ &= 5.0 \text{ m s}^{-1} \text{ north} \end{aligned}$$

The average velocity of the hare is 5 m s^{-1} north.

PRACTICE PROBLEM 3

During the final 4.2-kilometre run stage of a triathlon, a participant runs 2.8 kilometres east, then changes direction to run a further 1.4 kilometres in the opposite direction, completing the stage in 20 minutes. What was the participant's:

- a. average speed
- b. average velocity?

Express both answers in m s^{-1} to two significant figures.

9.2.5 Instantaneous speed and velocity

Neither the average speed nor the average velocity provide information about movement at any particular instant of time. For example, when Jamaican athlete Usain Bolt broke the 100-metre world record in 2009 with a time of 9.58 seconds, his average speed was 10.4 m s^{-1} . However, he was not travelling at that speed throughout his run. He would have taken a short time to reach his maximum speed and would not have been able to maintain it throughout the run. His maximum speed would have been much more than 10.4 m s^{-1} .

FIGURE 9.5 During his 100-metre world record in 2009, Usain Bolt's average speed was 10.4 m s^{-1} .



The speed at any particular instant of time is called the **instantaneous speed**. The velocity at any particular instant of time is, not surprisingly, called the **instantaneous velocity**. If an object moves with a constant velocity during a time interval, its instantaneous velocity throughout the interval is the same as its average velocity.

9.2.6 Acceleration

When the velocity of an object changes, it is helpful to describe it in terms of the rate at which the velocity is changing. In everyday language, the word *accelerate* is used to mean ‘speed up’. The word *decelerate* is used to mean ‘slow down’. However, if you wish to describe motion precisely, these words are not adequate. The rate at which an object changes its velocity is called its **acceleration**. Acceleration is a vector quantity.

A car starting from rest and reaching a velocity of 60 km h^{-1} north in 5 seconds has an average acceleration of 12 km h^{-1} per second or $12 (\text{km h}^{-1})\text{s}^{-1}$ north. This is expressed in words as 12 km per hour per second. In simple terms, it means that the car increases its speed in a northerly direction by an average of 12 km h^{-1} each second.

The average acceleration of an object, $\vec{a}_{\text{av}}$, can be expressed as:

$$\vec{a}_{\text{av}} = \frac{\Delta \vec{v}}{\Delta t}$$

The change in velocity during the time interval Δt can be expressed as:

$$\Delta \vec{v} = \text{final velocity} - \text{initial velocity}$$

This is commonly also written as:

$$\Delta \vec{v} = \vec{v} - \vec{u}$$

The direction of the average acceleration is the same as the direction of the change in velocity.

SAMPLE PROBLEM 4

Spiro leaves home on his bicycle to post a letter. He starts from rest and reaches a speed of 10 m s^{-1} in 4 seconds. He then cycles at a constant speed in a straight line to a letterbox. He brakes at the letterbox, coming to a stop in 2 seconds, posts the letter and returns home at a constant speed of 8 m s^{-1} . On reaching home he brakes, coming to rest in 2 seconds. The direction away from home towards the letterbox is assigned as positive.

- What is Spiro’s average acceleration before he reaches his ‘cruising speed’ of 10 m s^{-1} on the way to the letterbox?
- What is Spiro’s average acceleration as he brakes at the letterbox?
- What is Spiro’s average acceleration as he brakes when arriving home?
- During which two parts of the trip is Spiro’s acceleration negative?
- Does a positive acceleration always mean that the speed is increasing? Explain.

 **Teacher-led video:** SP4 (tlvd-0072)

THINK

- Recall the relationship.
- Identify the values.
- Substitute into the relationship to find the average acceleration.

WRITE

a. Average acceleration: $a_{\text{av}} = \frac{\Delta v}{\Delta t}$

$$\Delta v = 10 \text{ m s}^{-1}$$
$$\Delta t = 4 \text{ s}$$
$$\text{Average acceleration} = \frac{10 \text{ m s}^{-1}}{4 \text{ s}}$$
$$= 2.5 \text{ m s}^{-2}$$



4. State the solution.

b. 1. Recall the relationship.

2. Identify the values.

3. Substitute into the relationship to find the average acceleration.

4. State the solution.

c. 1. Recall the relationship.

2. Identify the values.

3. Substitute into the relationship to find the average acceleration.

4. State the solution.

d. 1. Recall the positive and negative directions.

2. Acceleration is negative when the velocity in the direction towards the house is increasing.

e. 1. Recall the definition of acceleration.

2. As speed does not take into account direction, an increasing speed does not necessarily equate to a positive acceleration.

Spiro's average acceleration on his journey to cruising speed is 2.5 m s^{-2} towards the letterbox.

b. Average acceleration: $a_{\text{av}} = \frac{\Delta v}{\Delta t}$

$$\Delta v = -10 \text{ m s}^{-1}$$

$$\Delta t = 2 \text{ s}$$

$$\begin{aligned}\text{Average acceleration} &= \frac{-10 \text{ m s}^{-1}}{2 \text{ s}} \\ &= -5 \text{ m s}^{-2}\end{aligned}$$

Spiro's average acceleration when braking at the letterbox is 5 m s^{-2} away from the letterbox.

c. Average acceleration: $a_{\text{av}} = \frac{\Delta v}{\Delta t}$

$$\Delta v = 8 \text{ m s}^{-1}$$

$$\Delta t = 2 \text{ s}$$

$$\begin{aligned}\text{Average acceleration} &= \frac{8 \text{ m s}^{-1}}{2 \text{ s}} \\ &= 4 \text{ m s}^{-2}\end{aligned}$$

Spiro's average acceleration when braking at the end of his journey is 4 m s^{-2} towards the letterbox.

d. Positive direction is away from the house, negative direction is towards the house.

The two sections of the trip where acceleration is negative are braking at the letterbox and accelerating back towards home from the letterbox.

e. Acceleration is equal to change in velocity.

A decreasing speed in the negative direction is a positive change in velocity, and hence a positive acceleration.

PRACTICE PROBLEM 4

- a. A cheetah (the fastest land animal) takes 2 seconds to reach its maximum speed of 30 m s^{-1} . What is the magnitude of its average acceleration?
- b. A drag-racing car reaches a speed of 420 km h^{-1} from a standing start in 6 seconds. What is its average acceleration in:
- $\text{km h}^{-1} \text{ s}^{-1}$
 - m s^{-2} ?

CHANGING DIRECTION

A non-zero acceleration does not always result from a change in speed. Consider a car travelling at 60 km h^{-1} in a northerly direction turning right and continuing in an easterly direction at the same speed. Assume that the complete turn takes 10 seconds. The average acceleration during the time interval of 10 seconds is given by:

$$a_{av} = \frac{\Delta v}{\Delta t}$$

The change in velocity must be determined first. Thus:

$$\begin{aligned}\Delta v &= v - u \\ &= v + -u\end{aligned}$$

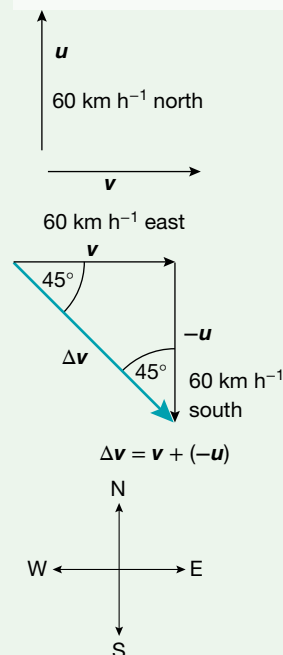
The vectors v and $-u$ are added together to give the resulting change in velocity.

The magnitude of the change in velocity is calculated using Pythagoras' theorem or trigonometric ratios to be 85 km h^{-1} . Alternatively, the vectors can be added using a scale drawing and then measuring the magnitude and direction of the sum. The direction of the change in velocity can be seen in figure 9.6 to be south-east.

$$\begin{aligned}a_{av} &= \frac{\Delta v}{\Delta t} \\ &= \frac{85 \text{ km h}^{-1} \text{ south-east}}{10 \text{ s}} \\ &= 8.5 \text{ km h}^{-1} \text{ s}^{-1} \text{ south-east}\end{aligned}$$

In fact, the direction of the average acceleration is the same as the direction of the average net force on the car during the 10-second interval. The steering wheel is used to turn the wheels to cause the net force to be in this direction.

FIGURE 9.6 A change in acceleration can occur even if there is no change in speed.



9.2 EXERCISE

To answer questions online and to receive **immediate feedback** and **sample responses** for every question go to your learnON title at www.jacplus.com.au.

- State whether each of the following is a vector quantity or a scalar quantity.
 - Distance
 - Displacement
 - Speed
 - Velocity
 - Acceleration
- The speed limit on Melbourne's suburban freeways is 100 km h^{-1} . Express this speed in m s^{-1} .
- Leisel Jones's average speed while swimming a 100-metre breaststroke race is about 1.5 m s^{-1} . Calculate what her average speed would be in km h^{-1} .
- The speed limit on US freeways is 55 miles per hour. One mile is approximately 1.6 km. Express this speed in:
 - km h^{-1}
 - m s^{-1} .
- A jogger heads due north from his home and runs 400 metres along a straight footpath before realising he has forgotten his sunscreen and runs straight back to get it.
 - What distance has the jogger travelled by the time he gets back home?
 - What was the displacement of the jogger when he started to run back home?
 - What was his displacement when he arrived back home to pick up the sunscreen?

6. The world records for some women's track events (as at early 2019) are listed in the table 9.2.

TABLE 9.2 World records for women's track events

Athlete	Event	Time
Florence Griffith Joyner (USA)	100 m	10.49 s
Florence Griffith Joyner (USA)	200 m	21.34 s
Marita Koch (German Democratic Republic)	400 m	47.60 s
Jarmilia Kratochvilova (Czechoslovakia)	800 m	1 min 53.28 s
Genzebe Dibaba (Ethiopia)	1 500 m	3 min 50.07 s
Wang Junxia (China)	3 000 m	8 min 06.11 s
Tirunesh Dibaba (Ethiopia)	5 000 m	14 min 11.15 s
Almaz Ayana (Ethiopia)	10 000 m	29 min 17.45 s

- (a) Calculate the average speed (to three significant figures) of each of the athletes listed in the table.
- (b) Why is there so little difference between the average speeds of the world-record holders of the 100-metre and 200-metre events despite the doubling of the distance?
- (c) How long would it take Genzebe Dibaba to complete the marathon if she could maintain her average speed during the 1500-metre event for the entire 42.2 km course? (The world record for the women's marathon, set on 13 April 2003, is 2 h 15 min 25 s.)
- (d) Which of the athletes in table 9.2 has an average speed that is the same as the magnitude of her average velocity? Explain.
7. (a) A jogger takes 30 minutes to cover a distance of 5 km. What is the jogger's average speed in:
- km h⁻¹
 - m s⁻¹?
- (b) How long does it take for a car travelling 60 km h⁻¹ to cover a distance of 200 metres?
8. In 2018, cyclist Chloe Dygert, of the USA, set a world record of 3 min, 20.060 seconds for the 3000-metre pursuit.
- What was her average speed?
 - How long would it take her to cycle from Melbourne to Bendigo, a distance of 151 km, if she could maintain her 3000-metre pursuit average speed for the whole distance?
 - How long does it take a car to travel from Melbourne to Bendigo if its average speed is 80 km h⁻¹?
 - A car travels from Melbourne to Bendigo and back to Melbourne in 4 hours.
 - What is its average speed?
 - What is its average velocity?
9. Once upon a time, a giant tortoise had a bet with a hare that she could beat him in a foot race over a distance of 1 kilometre. The giant tortoise can reach a speed of about 7.5 cm s⁻¹. The hare can run as fast as 20 m s⁻¹. Both animals ran at their maximum speeds during the race. However, the hare was a rather arrogant creature and decided to have a little nap along the way. How long did the hare sleep if the result was a tie?
10. An unfit Year 11 student arrives at school late and attempts to run from the front gate of the school to the physics laboratory. He runs the first 120 metres at an average speed of 6 m s⁻¹, the next 120 metres at an average speed of 4 m s⁻¹ and the final 120 metres at an average speed of 2 m s⁻¹. What was the student's average speed during his attempt to arrive at his class on time?
11. While on holidays, a physics teacher drives her old Volkswagen from Melbourne to Wodonga, a distance of 300 kilometres. Her average speed was 80 km h⁻¹. She trades in her old Volkswagen and purchases a brand-new Toyota Prius. She proudly drives her new car back home to Melbourne at an average speed of 100 km h⁻¹. Calculate the average speed for the entire journey and explain any difference between the predicted and calculated average speed.

12. Determine (i) the change in speed and (ii) the change in velocity of each of the following situations.
- The driver of a car heading north along a freeway at 100 km h^{-1} slows down to 60 km h^{-1} as the traffic gets heavier.
 - A fielder catches a cricket ball travelling towards him at 20 m s^{-1} .
 - A tennis ball travelling at 25 m s^{-1} is returned directly back to the server at a speed of 30 m s^{-1} .
13. A car travelling east at a speed of 10 m s^{-1} turns left to head south at the same speed. Has the car undergone an acceleration? Explain your answer with the aid of a diagram.
14. Estimate the acceleration of a car in m s^{-2} as it resumes its journey through the suburbs after stopping at traffic lights.
15. Use the data in table 9.2 (question 5) to help you estimate the average acceleration of a world-class 100-metre sprinter at the beginning of a race.

studyon

To answer practice exam questions online and to receive immediate feedback and sample responses for every question go to your learnON title at www.jacplus.com.au.

studyON: Practice exam questions online only

Fully worked solutions and sample responses are available in your digital formats.

9.3 Analysing motion graphically

KEY CONCEPTS

- Analyse graphically, numerically and algebraically, straight-line motion under constant acceleration.
- Graphically analyse non-uniform motion in a straight line.

The motion of an object often varies with time. To help analyse the motion of objects it can be very useful to construct graphs of the characteristics of that motion against time.

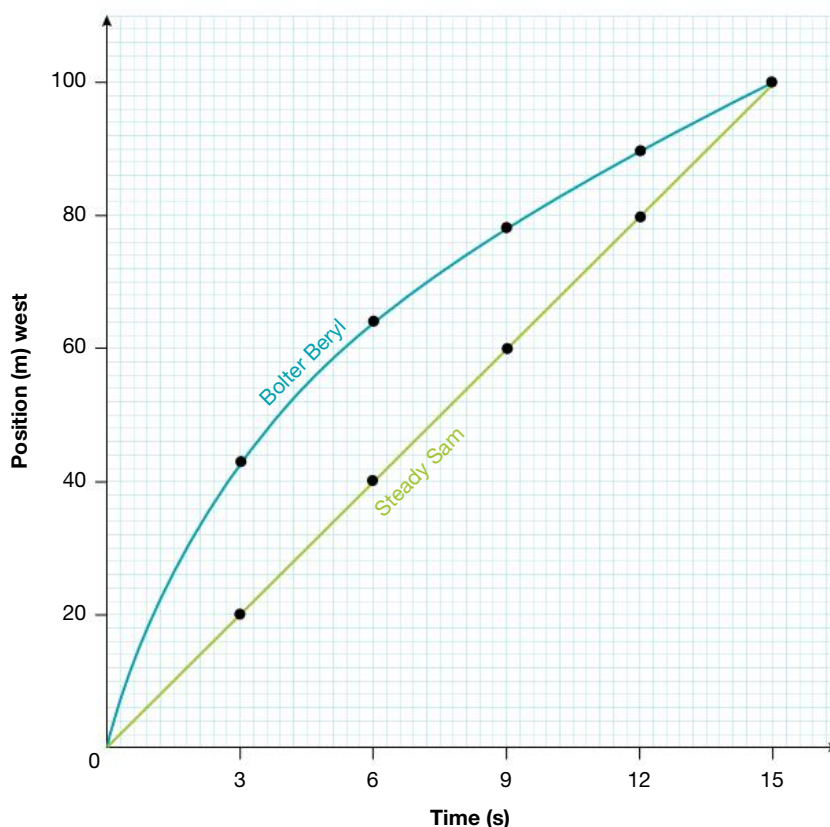
9.3.1 Position-versus-time graphs

Bolter Beryl and Steady Sam decide to race each other on foot over a distance of 100 metres. They run due west. Timekeepers are instructed to record the position of each runner after each 3-second interval.

TABLE 9.3 The progress of Bolter Beryl and Steady Sam

Position (distance from starting line) in metres		
Time (seconds)	Bolter Beryl	Steady Sam
0.0	0	0
3.0	43	20
6.0	64	40
9.0	78	60
12.0	90	80
15.0	100	100

FIGURE 9.7 The position-versus-time graph of the race provides valuable information about the motion of the two runners.



The points indicating Bolter Beryl's position after each 3-second interval are joined with a smooth curve. It is reasonable to assume that her velocity changes gradually throughout the race.

A number of observations can be made from the graph of position versus time.

- Both runners reach the finish at the same time. The result is a dead heat. Bolter Beryl and Steady Sam each have the same average speed and the same average velocity.
- Steady Sam, who has an exceptional talent for steady movement, maintains a constant velocity throughout the race. In fact, his instantaneous velocity at every instant throughout the race is the same as his average velocity. Steady Sam's average velocity and instantaneous velocity are both equal to the gradient of the position-versus-time graph since:

$$\begin{aligned}
 v_{\text{av}} &= \frac{\Delta x}{\Delta t} \\
 v_{\text{av}} &= \frac{100 \text{ m west}}{15 \text{ s}} \\
 v_{\text{av}} &= \frac{\text{rise}}{\text{run}} \\
 v_{\text{av}} &= \text{gradient}
 \end{aligned}$$

Steady Sam's velocity throughout the race is 6.7 m s^{-1} west.

- Bolter Beryl, in her usual style, makes a flying start; however, after her initial 'burst', her instantaneous velocity decreases throughout the race as she tires. Her average velocity is also 6.7 m s^{-1} west.

A more detailed description of Bolter Beryl's motion can be given by calculating her average velocity during each 3-second interval of the race (see table 9.4).

TABLE 9.4 Bolter Beryl's changing velocity

Time interval (s)	Displacement $\Delta \vec{x}$ (m west)	Average velocity during interval $\vec{v}_{av} = \frac{\Delta \vec{x}}{\Delta t}$ (m s^{-1} west)
0.0–3.0	$43 - 0 = 43$	14.0
3.0–6.0	$64 - 43 = 21$	7.0
6.0–9.0	$78 - 64 = 14$	4.7
9.0–12.0	$90 - 78 = 12$	4.0
12.0–15.0	$100 - 90 = 10$	3.3

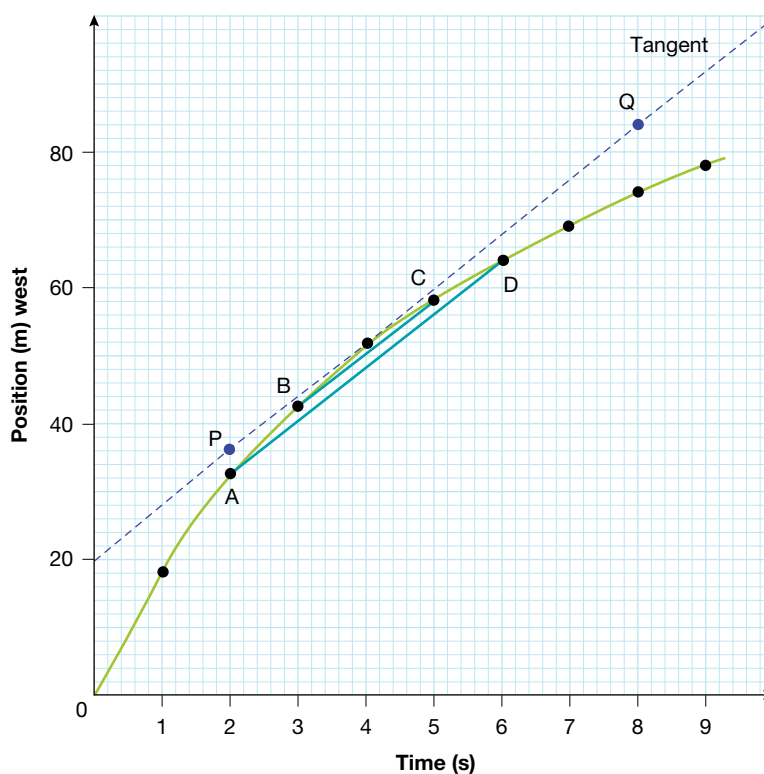
The average velocity during each interval is the same as the gradient of the straight line joining the data points representing the beginning and end of the interval. An even more detailed description of Bolter Beryl's run could be obtained if the race was divided into, say, 100 time intervals. The average velocity during each time interval (and the gradient of the line joining the data points defining it) would be a very good estimate of the instantaneous velocity in the middle of the interval. In fact, if the race is progressively divided into smaller and smaller time intervals, the average velocity during each interval would become closer and closer to the instantaneous velocity in the middle of the interval.

The gradient of the tangent of a *position-versus-time* graph gives the *instantaneous velocity* of the object.

Figure 9.8 shows how this process of using smaller time intervals can be used to find Bolter Beryl's instantaneous velocity at an instant 4 seconds from the start of the race.

Bolter Beryl's instantaneous velocity is not the same as the average velocity during the 3-second to 6-second time interval shown in table 9.4. However, it can be estimated by drawing the line AD and finding its gradient. The gradient of the line BC would provide an even better estimate of the instantaneous velocity. If you continue this process of decreasing the time interval used to estimate the instantaneous velocity, you will eventually obtain a line which is a tangent to the curve. The gradient of the tangent to the curve is equal to the instantaneous velocity at the instant represented by the point at which it meets the curve.

The gradient of the tangent to the curve at 4 seconds in figure 9.8 can be determined by using the points P and Q.

FIGURE 9.8 The first 9 seconds of Bolter Beryl's run

$$\begin{aligned}
 \text{gradient} &= \frac{\text{rise}}{\text{run}} \\
 &= \frac{(84 - 36) \text{ m}}{(8 - 2) \text{ s}} \\
 &= \frac{48 \text{ m}}{6 \text{ s}} \\
 &= 8 \text{ m s}^{-1}
 \end{aligned}$$

Bolter Beryl's instantaneous velocity at 4 seconds from the start of the race is therefore 8 m s^{-1} west.

Just as the gradient of a position-versus-time graph can be used to determine the velocity of an object, a graph of distance versus time can be used to determine its speed. Because Bolter Beryl and Steady Sam were running in a straight line and in one direction only, their distance from the starting point is the magnitude of their change in position. Their speed is equal to the magnitude of their velocity.

The *gradient of the tangent of a distance-versus-time graph* gives the *instantaneous speed of the object*.

on Resources

 **Digital document** eModelling: Numerical model of motion 1: finding speed from position-time data (doc-0048)

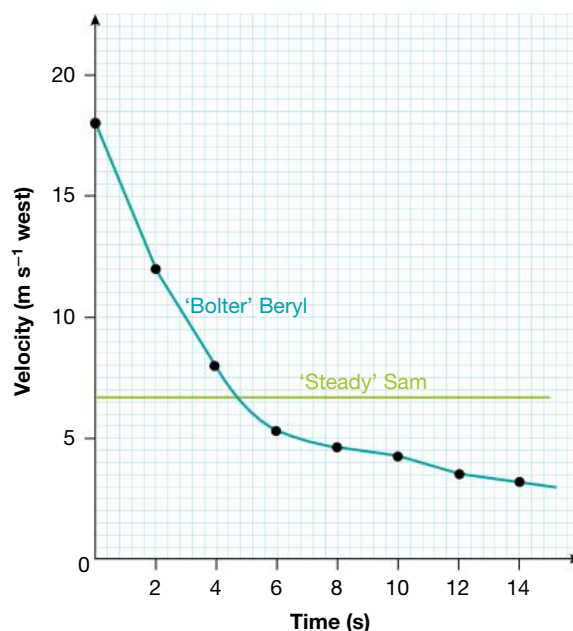
9.3.2 Velocity-versus-time graphs

The race between Bolter Beryl and Steady Sam described by the position-versus-time graph in figure 9.7 can also be described by a graph of velocity versus time. Steady Sam's velocity is 6.7 m s^{-1} due west throughout the race. The curve describing Bolter Beryl's motion can be plotted by determining the instantaneous velocity at various times during the race. This can be done by drawing tangents at a number of points on the position-versus-time graph in figure 9.7. Table 9.5 shows the data obtained using this method. The velocity-versus-time graph in figure 9.9 describes the motion of Bolter Beryl and Steady Sam.

TABLE 9.5 Beryl's velocity during the race

Time (s)	Velocity (m s^{-1} west)
0.0	18.0
2.0	12.0
4.0	8.0
6.0	5.4
8.0	4.7
10.0	4.2
12.0	3.5
14.0	3.1

FIGURE 9.9 Velocity-versus-time graph for the race



The velocity-versus-time graph confirms what you already knew by looking at the position-versus-time graph, namely that:

- Steady Sam's velocity is constant and equal to his average velocity
- the magnitude of Bolter Beryl's velocity is decreasing throughout the race.

The velocity-versus-time graph allows you to estimate the velocity of each runner at any time. It provides a much clearer picture of the way that Bolter Beryl's velocity changes during the race, namely that:

- the magnitude of her velocity decreases rapidly at first, but less rapidly towards the end of the race
- for most of the duration of the race, she is running more slowly than Sam. In fact Bolter Beryl's speed (the magnitude of her velocity) drops below that of Steady Sam's after only 4.7 seconds.

Displacement from a velocity-versus-time graph

In the absence of a position-versus-time graph, a velocity-versus-time graph provides useful information about the change in position, or displacement, of an object. Steady Sam's constant velocity, the same as his average velocity, makes it very easy to determine his displacement during the race.

$$\begin{aligned}\Delta x &= v_{\text{av}} \Delta t \quad \left(\text{since } v_{\text{av}} = \frac{\Delta x}{\Delta t} \right) \\ \Delta x &= 6.7 \text{ m s}^{-1} \text{ west} \times 15 \text{ s} \\ \Delta x &= 100 \text{ m west}\end{aligned}$$

This displacement is equal to the area of the rectangle under the graph depicting Steady Sam's motion.

$$\begin{aligned}\text{area} &= \text{length} \times \text{width} \\ &= 15 \text{ s} \times 6.7 \text{ m s}^{-1} \text{ west} \\ &= 100 \text{ m west}\end{aligned}$$

Because the race was a dead heat, Bolter Beryl's average velocity was also 6.7 m s^{-1} . Her displacement during the race can be calculated in the same way as Steady Sam's.

$$\begin{aligned}\Delta x &= v_{\text{av}} \Delta t \\ &= 6.7 \text{ m s}^{-1} \times 15 \text{ s} \\ &= 100 \text{ m west}\end{aligned}$$

However, Bolter Beryl's displacement can also be found by calculating the area under the velocity-versus-time graph depicting her motion. This can be done by 'counting squares' or by dividing the area under the graph into rectangles and triangles. The area under Beryl's velocity-versus-time graph is, not surprisingly, 100 metres.

In fact, the area under any part of the velocity-versus-time graph is equal to the displacement during the interval represented by that part.

The area under a velocity-versus-time graph gives the displacement (or change in position) of the object during that time interval. To determine the position of the object you must know its starting position.

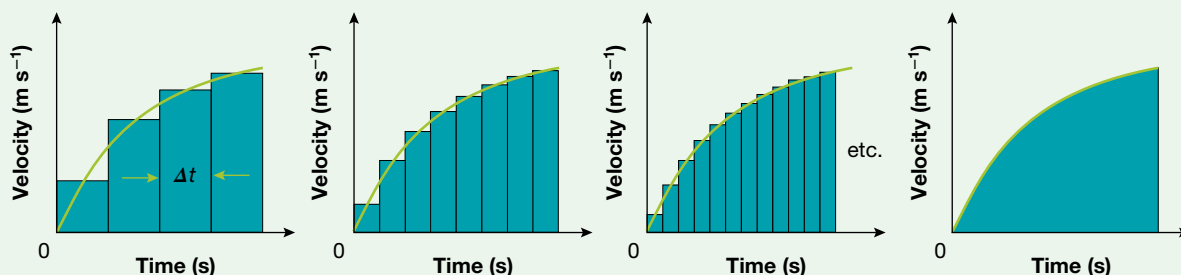
Note: If the velocity-versus-time graph is in the negative velocity range, you can get a negative value for the area. Although this may seem counterintuitive, it indicates a negative displacement.

The area under a speed-versus-time graph gives the distance travelled by the object during that time interval.

CALCULATING THE AREA UNDER A GRAPH WITH TIME INTERVALS

When an object travels with a constant velocity, it is obvious that the displacement of the object is equal to the area under a velocity-versus-time graph of its motion. However, it is not so obvious when the motion is not constant. The graphs below describe the motion of an object that has an increasing velocity. The motion of the object can be approximated by dividing it into time intervals of Δt and assuming that the velocity during each time interval is constant. The approximate displacement during each time interval is equal to $\Delta x = v_{av} \Delta t$, which is the same as the area under each rectangle. The approximate total displacement is therefore equal to the total area of the rectangles.

FIGURE 9.10 By dividing the velocity-versus-time graph into rectangles representing small time intervals, the displacement can be estimated.



To better approximate the displacement, the graph can be divided into smaller time intervals. The total area of the rectangles is approximately equal to the displacement. By dividing the graph into even smaller time intervals, even better estimates of the displacement can be made. In fact, by continuing the process of dividing the graph into smaller and smaller time intervals, it can be seen that the displacement is, in fact, equal to the area under the graph.

SAMPLE PROBLEM 5

At what time in the race between Bolter Beryl and Steady Sam did Bolter Beryl's speed drop below Steady Sam's speed? What is Steady Sam's displacement at this point in time?

THINK

1. See the velocity-versus-time graph (figure 9.9) to determine when Bolter Beryl's speed dropped below Steady Sam's.
2. Determine Steady Sam's displacement by calculating the area under the graph.

WRITE

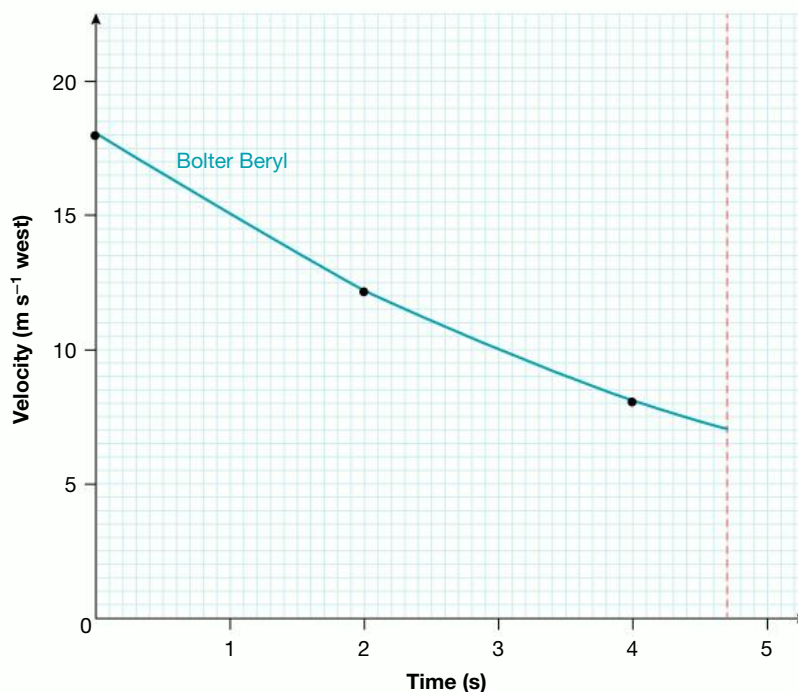
The time at which Bolter Beryl's speed dropped below Steady Sam's is approximately 4.7 seconds.

$$\begin{aligned}\text{Area under the graph} &= 4.7 \times 6.7 \\ &= 31 \text{ m}\end{aligned}$$

Steady Sam's displacement was 31 metres at 4.7 seconds.

PRACTICE PROBLEM 5

The following graph is of a section of figure 9.9 showing the first 4.7 seconds of Bolter Beryl's motion.



- Estimate Bolter Beryl's displacement after 2 seconds.
- At 4.7 seconds into the race, determine how far ahead Bolter Beryl was of Steady Sam (whose velocity was a constant 6.7 m s⁻¹).

Acceleration from a velocity-versus-time graph

The graph in figure 9.11 describes the motion of an elevator as it moves from the ground floor to the top floor and back down again. The elevator stops briefly at the top floor to pick up a passenger. For convenience, any upward displacement from the ground floor is defined as positive. The graph has been divided into seven sections labelled A to G.

Finding the acceleration

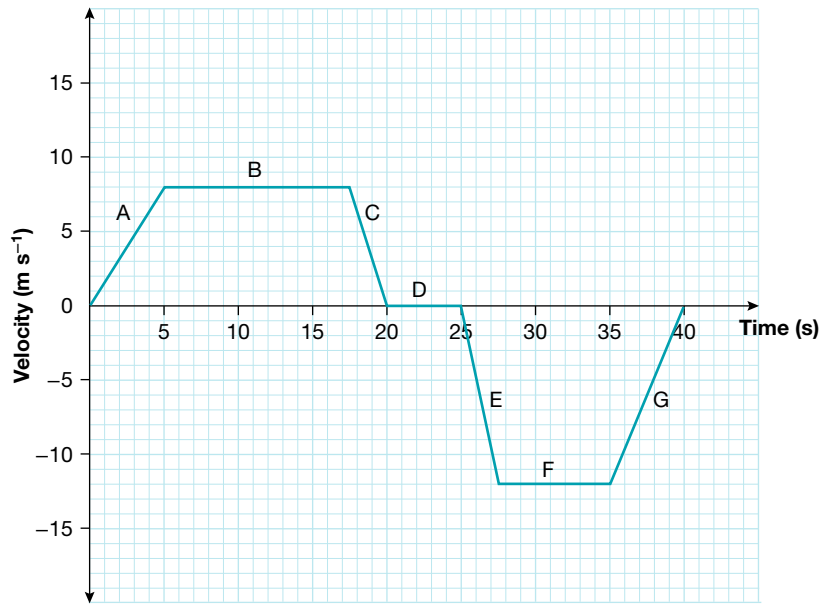
The acceleration at any instant during the motion can be determined by calculating the gradient of the graph. This is a consequence of the definition of acceleration. The gradient of a velocity-versus-time graph is a measure of the rate of change of velocity just as the gradient of a position-versus-time graph is a measure of the rate of change of position.

The gradient of a velocity-versus-time graph gives the acceleration of the object.

Throughout interval A (see figure 9.11), the acceleration, a , of the elevator is:

$$\begin{aligned} a &= \frac{\text{rise}}{\text{run}} \\ &= \frac{+8.0 \text{ m s}^{-1}}{5.0 \text{ s}} \\ &= +1.6 \text{ m s}^{-2} \text{ or } 1.6 \text{ m s}^{-2} \text{ up} \end{aligned}$$

FIGURE 9.11 The motion of an elevator



During intervals B, D and F, the velocity is constant and the gradient of the graph is zero. The acceleration during each of these intervals is, therefore, zero.

Throughout interval C, the acceleration is:

$$\begin{aligned} a &= \frac{-8.0 \text{ m s}^{-1}}{2.5 \text{ s}} \\ &= -3.2 \text{ m s}^{-2} \text{ or } 3.2 \text{ m s}^{-2} \text{ down} \end{aligned}$$

Throughout interval E, the acceleration is:

$$\begin{aligned} a &= \frac{-12 \text{ m s}^{-1}}{2.5 \text{ s}} \\ &= -4.8 \text{ m s}^{-2} \text{ or } 4.8 \text{ m s}^{-2} \text{ down} \end{aligned}$$

Throughout interval G, the acceleration is:

$$\begin{aligned} a &= \frac{+12 \text{ m s}^{-1}}{5.0 \text{ s}} \\ &= +2.4 \text{ m s}^{-2} \text{ or } 2.4 \text{ m s}^{-2} \text{ up} \end{aligned}$$

Notice that during interval G the acceleration is positive (up) while the velocity of the elevator is negative (down). The direction of the acceleration is the same as the direction of the *change* in velocity.

Finding the displacement

As explained previously, the area under the graph is equal to the displacement of the elevator. Dividing the area into triangles and rectangles and working from left to right yields an area of:

$$\begin{aligned}
 \text{Area} &= \left(\frac{1}{2} \times 5.0 \text{ s} \times 8.0 \text{ m s}^{-1} \right) + \left(12.5 \text{ s} \times 8.0 \text{ m s}^{-1} \right) + \left(\frac{1}{2} \times 2.5 \text{ s} \times 8.0 \text{ m s}^{-1} \right) + \\
 &\quad \left(\frac{1}{2} \times 2.5 \text{ s} \times -12 \text{ m s}^{-1} \right) + \left(7.5 \text{ s} \times -12 \text{ m s}^{-1} \right) + \left(\frac{1}{2} \times 5.0 \text{ s} \times -12 \text{ m s}^{-1} \right) \\
 &= 20 \text{ m} + 100 \text{ m} + 10 \text{ m} - 15 \text{ m} - 90 \text{ m} - 30 \text{ m} \\
 &= -5 \text{ m}
 \end{aligned}$$

This represents a downwards displacement of 5 metres, which is consistent with the elevator finally stopping two floors below the ground floor.



Resources



Digital documents. eModelling: Numerical model of motion 2. Finding position from speed–time data (doc-0049)

Investigation 9.2 Let's play around with some graphs (doc-31875)

eModelling: Numerical model for acceleration (doc-0050)



Video eLessons Motion with constant acceleration (eles-0030)

Ball toss (eles-0031)

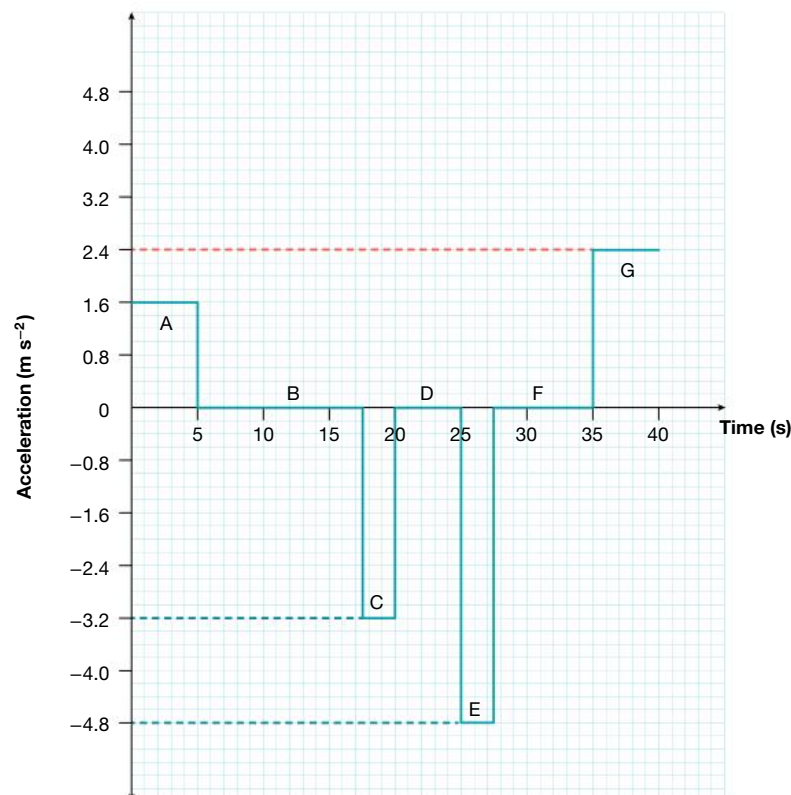


Teacher-led video Investigation 9.2 Let's play around with some graphs (tlvd-0820)

9.3.3 Acceleration-versus-time graphs

The graph in figure 9.12 represents the acceleration of the elevator described in the previous section.

FIGURE 9.12 An acceleration-versus-time graph for the elevator



The area under an *acceleration-versus-time* graph gives the *change in velocity* of the object during that time interval. To determine the velocity of the object you must know its starting velocity.

Just as the area under a velocity-versus-time graph is equal to the change in position of an object, the area under an acceleration-versus-time graph is equal to the change in velocity of an object. The area under the part of the graph representing the entire upwards part of the journey is given by:

$$\begin{aligned}\text{Area A} + \text{Area B} + \text{Area C} &= 5.0 \text{ s} \times 1.6 \text{ m s}^{-2} + 0 + 2.5 \text{ s} \times -3.2 \text{ m s}^{-2} \\ &= +8.0 \text{ m s}^{-1} + -8.0 \text{ m s}^{-1} \\ &= 0\end{aligned}$$

This indicates that change in velocity during the upward journey is zero. This is consistent with the fact that the elevator starts from rest and is at rest when it reaches the top floor. Similarly, the area under the whole graph is zero.

The change in velocity during intervals C, D and E is given by the sum of areas C, D and E. Thus:

$$\begin{aligned}\text{Area C} + \text{Area D} + \text{Area E} &= (2.5 \text{ s} \times -3.2 \text{ m s}^{-2}) + 0 + (2.5 \text{ s} \times -4.8 \text{ m s}^{-2}) \\ &= 8.0 \text{ m s}^{-1} + -12 \text{ m s}^{-1} \\ &= -20 \text{ m s}^{-1}\end{aligned}$$

The change in velocity is -20 m s^{-1} , or 20 m s^{-1} down.

At the beginning of time interval C, the velocity was 8 m s^{-1} upwards. A change of velocity of -20 m s^{-1} would result in a velocity at the end of interval E of 12 m s^{-1} downwards. This is consistent with the description of the motion in the velocity-versus-time graph in figure 9.11.

The change in velocity during interval G is $5 \text{ s} \times 2.4 \text{ m s}^{-1}$, or 12 m s^{-1} upwards, which is consistent with the elevator coming to rest at the end of its journey.

9.3.4 Working with motion graphs

Position-versus-time graphs

- The instantaneous velocity of an object can be obtained from a graph of the object's position versus time by determining the gradient of the curve at the point representing that instant. This is a direct consequence of the fact that velocity is a measure of the rate of change of position.
- Similarly, the instantaneous speed of an object can be obtained by determining the gradient of a graph of the object's distance travelled from a reference point versus time.

Velocity-versus-time graphs

- The displacement of an object during a time interval can be obtained by determining the area under the velocity-versus-time graph representing that time interval. The actual position of an object at any instant during the time interval can be found only if the starting position is known.
- Similarly, the distance travelled by an object during a time interval can be obtained by determining the corresponding area under the speed-versus-time graph for the object.
- The instantaneous acceleration of an object can be obtained from a graph of the object's velocity versus time by determining the gradient of the curve at the point representing that instant. This is a direct consequence of the fact that acceleration is defined as the rate of change of velocity.

Acceleration-versus-time graphs

- The change in velocity of an object during a time interval can be obtained by determining the area under the acceleration-versus-time graph representing that time interval. The actual velocity of the object can be found at any instant during the time interval only if the initial velocity is known.

TABLE 9.6 Summary of motion graphs

		Position-versus-time graphs	Velocity-versus-time graphs	Acceleration-versus-time graphs
Quantities that you can read directly from the graph	Horizontal axis	Time	Time	Time
	Vertical axis	Position	Velocity	Acceleration
Quantities that you can calculate from the graph	Gradient of tangent	Instantaneous velocity	Instantaneous acceleration	
	Area under the graph		Change in position (displacement)	Change in velocity



Resources



Digital document Investigation 9.3: On your bike or on your own two feet (doc-31876)

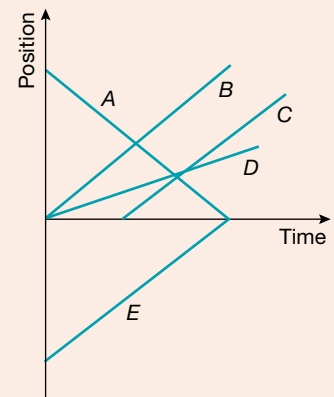


Weblink Constant acceleration app

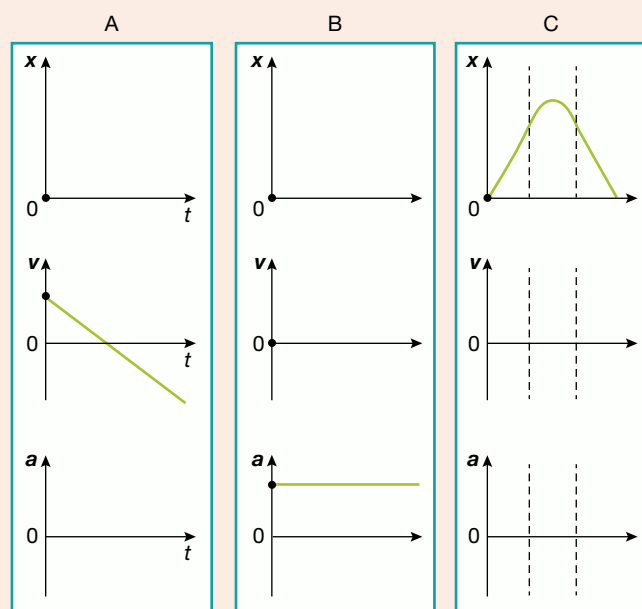
9.3 EXERCISE

To answer questions online and to receive **immediate feedback** and **sample responses** for every question go to your learnON title at www.jacplus.com.au.

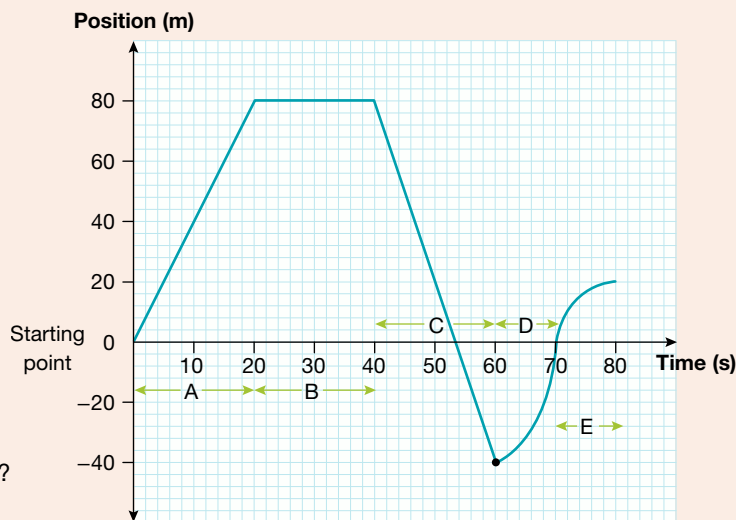
- The position-versus-time graph shown describes the motion of five different objects, labelled A to E.
 - Which two objects start from the same position, but at different times?
 - Which two objects start at the same position at the same time?
 - Which two objects are travelling at the same speed as each other, but with different velocities?
 - Which two objects are moving towards each other for the whole period shown on the graph?
 - Which of the five objects has the lowest speed?



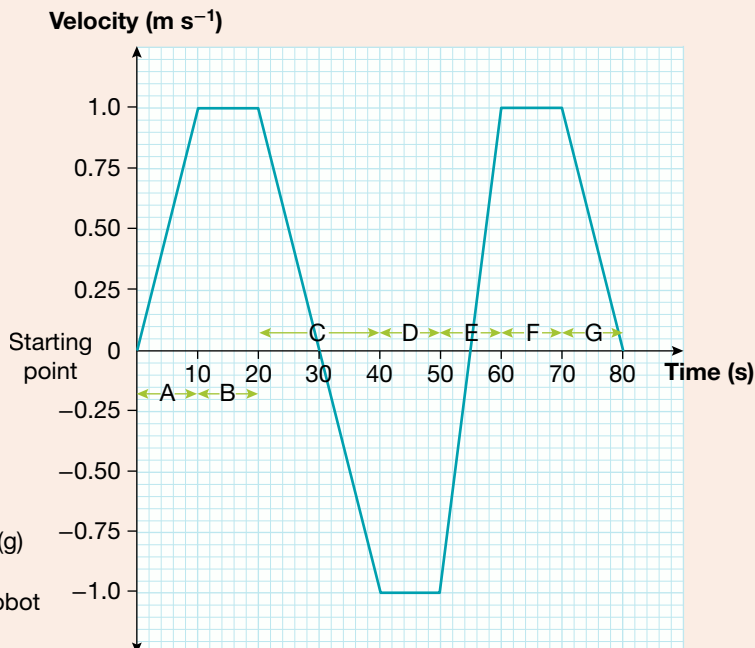
- Describe in words the motion shown for each of scenarios A, B and C shown on the right.
 - Copy the incomplete graphs for each scenario into your workbooks and then complete each graph.



3. Sketch a velocity-versus-time graph to illustrate the motion described in each of the following situations.
- A bicycle is pedalled steadily along a road. The cyclist stops pedalling and allows the bicycle to come to a stop.
 - A parachutist jumps out of a plane and opens his parachute midway through the fall to the ground.
 - A ball is thrown straight up into the air and is caught at the same height from which it was thrown.
4. Sketch a position-versus-time graph for each scenario in question 3.
5. The graph in the following figure is a record of the straight-line motion of a skateboard rider during an 80-second time interval. The time interval has been divided into sections labelled A to E. The skateboarder initially moves north from the starting point.



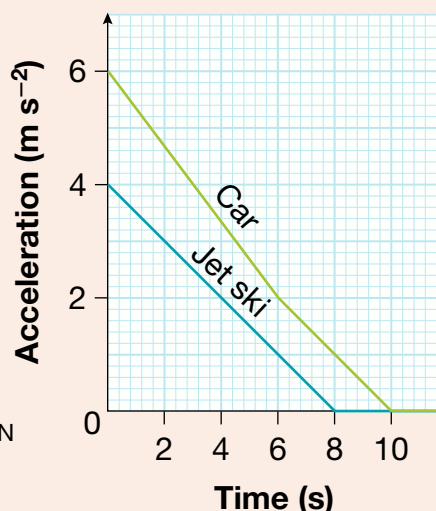
- During which section of the interval was the skateboard rider stationary?
 - During which sections of the interval was the skateboarder travelling north?
 - At what instant did the skateboard rider first move back towards the starting line?
 - What was the displacement of the skateboarder during the 80-second interval?
 - What distance did the skateboarder travel during the 80-second interval?
 - During which section of the interval was the skateboard rider speeding up?
 - During which section of the interval was the skateboard rider slowing down?
 - What was the skateboarder's average speed during the entire 80-second interval?
 - What was the velocity of the skateboarder throughout section C?
 - Estimate the velocity of the skateboarder 65 seconds into the interval.
6. The figure that follows is a record of the motion of a battery-operated toy robot during an 80-second time interval. The interval has been divided into sections labelled A to G.



- During which sections is the acceleration of the toy robot zero?
- What is the displacement of the toy robot during the 80-second interval?
- What is the average velocity of the toy robot during the entire interval?
- At what instant did the toy robot first reverse direction?
- At what instant did the toy robot first return to its starting point?
- During which intervals did the toy robot have a negative acceleration?
- During which intervals did the toy robot decrease its speed?
- Explain why your answers to (f) and (g) are different from each other.
- What is the acceleration of the toy robot throughout section E?
- What is the average acceleration during the first 20 seconds?
- Describe the motion of the toy robot in words.

7. The figure that follows compares the straight-line motion of a jet ski and a car as they each accelerate from an initial speed of 5 m s^{-1} .

- Which is first to reach a constant speed — the jet ski or the car — and when does this occur?
- What is the final speed of:
 - the jet ski
 - the car?
- Draw a speed-versus-time graph describing the motion of either the jet ski or the car.



studyon

To answer practice exam questions online and to receive immediate feedback and sample responses for every question go to your learnON title at www.jacplus.com.au.

studyON: Practice exam questions online only

Fully worked solutions and sample responses are available in your digital formats.

9.4 Equations for constant acceleration

KEY CONCEPT

- Analyse numerically and algebraically, straight-line motion under constant acceleration.

In the absence of a graphical representation, a number of formulae can be used to describe straight-line motion as long as the acceleration is constant. These formulae are expressed in terms of the quantities used to describe such motion. The terms are:

- initial velocity, u
- final velocity, v
- acceleration, a
- time interval, t
- displacement, s .

Because the formulae describe motion along a straight line, vector notation is not necessary. The displacement, velocity and acceleration can be expressed as positive or negative quantities.

9.4.1 Deriving the equations algebraically

The first formula is found by restating the definition of acceleration.

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

Where:

Δv = the change in velocity

Δt = the time interval.

Thus:

$$\begin{aligned} a &= \frac{v - u}{t} \\ \Rightarrow v - u &= at \\ \Rightarrow v &= u + at \end{aligned} \quad [1]$$

The second formula is found by restating the definition of average velocity.

$$v_{\text{av}} = \frac{\Delta s}{\Delta t}$$

Where:

Δs = the change in position.

But:

$$v_{\text{av}} = \frac{u + v}{2}$$

Thus:

$$\begin{aligned} \frac{u + v}{2} &= \frac{s}{t} \\ \Rightarrow s &= \frac{1}{2}(u + v)t \end{aligned} \quad [2]$$

Three more formulae are obtained by combining formulae [1] and [2].

$$\begin{aligned} s &= \frac{1}{2}(u + u + at)t && \text{(substituting } v = u + at \text{ from formula [1] into formula [2])} \\ &= \frac{1}{2}(2u + at)t \\ &= \left(u + \frac{1}{2}at\right)t \\ \Rightarrow s &= ut + \frac{1}{2}at^2 \end{aligned} \quad [3]$$

$$\begin{aligned} s &= \frac{1}{2}(v - at + v)t && \text{(substituting } u = v - at \text{ from formula [1] into formula [2])} \\ &= \frac{1}{2}(2v - at)t \\ &= \left(v - \frac{1}{2}at\right)t \\ \Rightarrow s &= vt - \frac{1}{2}at^2 \end{aligned} \quad [4]$$

A final formula can be found by eliminating t from formula [2].

$$s = \frac{1}{2}(u + v)t \quad \text{(formula [2])}$$

But:

$$t = \frac{v - u}{a}. \quad \text{(rearranging formula [1])}$$

$$\begin{aligned}
 \Rightarrow s &= \frac{1}{2}(u + v) \left(\frac{v - u}{a} \right) \\
 &= \frac{1}{2} \frac{v^2 - u^2}{a} \quad (\text{expanding the difference of two squares}) \\
 \Rightarrow 2as &= v^2 - u^2 \\
 \Rightarrow v^2 &= u^2 + 2as \quad [5]
 \end{aligned}$$

In summary, the formulae for straight-line motion under constant acceleration are:

$$v = u + at \quad [1]$$

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

$$s = ut + \frac{1}{2}at^2 \quad [3]$$

$$s = vt - \frac{1}{2}at^2 \quad [4]$$

$$v^2 = u^2 + 2as \quad [5]$$

9.4.2 Deriving the equations graphically

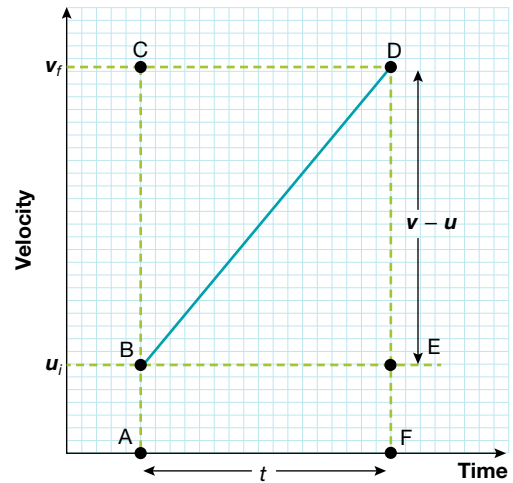
Each of the five formulae derived here allow you to determine an unknown characteristic of straight-line motion with a constant acceleration as long as you know three other characteristics. Although the formulae have not been derived from graphs, they are entirely consistent with a graphical approach.

acceleration = gradient of velocity-versus-time graph

$$\begin{aligned}
 &= \frac{\text{rise}}{\text{run}} \\
 &= \frac{v - u}{t} \\
 \Rightarrow a &= \frac{v - u}{t} \\
 \Rightarrow v &= u + at \quad [1]
 \end{aligned}$$

$$\begin{aligned}
 \text{displacement} &= \text{area under graph} \\
 &= \text{area of trapezium ABDF} \\
 &= \frac{1}{2}(u + v)t \quad [2]
 \end{aligned}$$

FIGURE 9.13 A velocity-versus-time graph for an object travelling in a straight line with constant acceleration



[2]

$$\begin{aligned}
\text{displacement} &= \text{area under graph} \\
&= \text{area of rectangle ABEF} + \text{area of triangle BDE} \\
&= ut + \frac{1}{2}t \times at \quad (v - u = at \text{ from [1]}) \\
&= ut + \frac{1}{2}at^2 \quad [3]
\end{aligned}$$

$$\begin{aligned}
\text{displacement} &= \text{area under graph} \\
&= \text{area of rectangle ACDF} - \text{area of triangle BCD} \\
&= vt - \frac{1}{2} \times t \times at \quad (v - u = at \text{ from [1]}) \\
&= vt - \frac{1}{2}at^2 \quad [4]
\end{aligned}$$

Formula [5] can be derived by combining formula [1] with any of formulae [2], [3] or [4].

9.4.3 Problem-solving steps

The following steps may help you when solving problems using the constant acceleration equations.

1. Sketch the situation.
2. Identify known quantities (converting to consistent units if necessary).
3. Identify the quantity to be determined.
4. Select an appropriate formula.
5. Substitute values and solve.

It is possible to rearrange each of the equations to make different variables the subject. Table 9.7 summarises all possible versions of the equations and may be useful when solving problems.

TABLE 9.7 Equations for solving problems

		Variables that are involved in the problem				
		<i>u v a t</i>	<i>u v a s</i>	<i>u v t s</i>	<i>u a t s</i>	<i>v a t s</i>
Variable that is to be calculated	<i>u</i>	$u = v - at$	$u^2 = v^2 - 2as$	$u = \frac{2s}{t} - v$	$u = \frac{s}{t} - \frac{at}{2}$	–
	<i>v</i>	$v = u + at$	$v^2 = u^2 + 2as$	$v = \frac{2s}{t} - u$	–	$v = \frac{s}{t} + \frac{at}{2}$
	<i>a</i>	$a = \frac{v - u}{t}$	$a = \frac{v^2 - u^2}{2s}$	–	$a = \frac{2(s - ut)}{t^2}$	$a = \frac{2(vt - s)}{t^2}$
	<i>t</i>	$t = \frac{v - u}{a}$	–	$t = \frac{2s}{(u + v)}$	Find <i>v</i> then solve	Find <i>u</i> then solve
	<i>s</i>	–	$s = \frac{v^2 - u^2}{2a}$	$s = \frac{1}{2}(u + v)t$	$s = ut + \frac{1}{2}at^2$	$s = vt - \frac{1}{2}at^2$

SAMPLE PROBLEM 6

Ying drops a coin into a wishing well and takes 3.0 seconds to make a wish. The coin splashes into the water just as she finishes making her wish. The coin accelerates towards the water at a constant 9.8 m s^{-2} .

- What is the coin's velocity as it strikes the water?
- How far does the coin fall before hitting the water?

 Teacher-led video: SP6 (tlvd-0074)

THINK

- Recall the appropriate constant acceleration formula.
 - Identify the values.
 - Substitute into the formula to find the final velocity.
 - State the solution.
- Recall the appropriate constant acceleration formula.
 - Identify the values.
 - Substitute into the formula to find the distance.
 - State the solution.

WRITE

a. $v = u + at$

$$u = 0, \quad a = 9.8 \text{ m s}^{-2}, \quad t = 3.0 \text{ s}$$

$$v = 0 + 9.8 \times 3.0 = 29 \text{ m s}^{-1}$$

The coin had a velocity of 29 m s^{-1} when it hit the water.

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

$$u = 0, \quad a = 9.8 \text{ m s}^{-2}, \quad t = 3.0 \text{ s}$$

$$s = 0 \times 3.0 + \frac{1}{2} \times 9.8 \times 3.0^2 = 44 \text{ m}$$

The coin fell 44 metres before hitting the water.



Resources



Digital document eModelling: Solving problems with a graphics calculator (doc-0051)

PRACTICE PROBLEM 6

A parked car with the handbrake off rolls down a hill in a straight line with a constant acceleration of 2 m s^{-2} . It stops after colliding with a brick wall at a speed of 12 m s^{-1} .

- For how long was the car rolling?
- How far did the car roll before colliding with the wall?

SAMPLE PROBLEM 7

The driver of a car was forced to brake in order to prevent serious injury to a neighbour's cat. The car skidded in a straight line, stopping just 2 centimetres short of the startled but lucky cat. The driver (who happened to be a physics teacher) measured the length of the skid mark to be 12 metres. His passenger (also a physics teacher with an exceptional skill for estimating small time intervals) estimated that the car skidded for 2 seconds.

- At what speed was the car travelling as it began to skid?
- What was the acceleration of the car during the skid?

 Teacher-led video: SP7 (tlvd-0075) ▶

THINK

- a. 1. Recall the appropriate constant acceleration formula.
 2. Identify the values.
 3. Substitute into the relationship to find the initial velocity.
 4. State the solution.
- b. 1. Recall the appropriate constant acceleration formula.
 2. Identify the values.
 3. Substitute into the relationship to find the acceleration.
 4. State the solution.

WRITE

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

$$v = 0, \quad t = 2 \text{ s}, \quad s = 12 \text{ m}$$

$$12 = \frac{1}{2}(u + 0) \times 2$$

$$u = 12 \text{ m s}^{-1}$$

The initial speed of the car was 12 m s^{-1} .

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

$$v = 0, \quad t = 2 \text{ s}, \quad s = 12 \text{ m}$$

$$12 = 0 \times 2 - \frac{1}{2}a \times 2^2$$

$$12 = -2a$$

$$a = -6 \text{ m s}^{-2}$$

The acceleration during the skid was -6 m s^{-2} ; that is, the car was decelerating at 6 m s^{-2} during the skid.

PRACTICE PROBLEM 7

A car travelling at 24 m s^{-1} brakes to come to a stop in 1.5 seconds. If its acceleration (deceleration in this case) was constant, what was the car's:

- a. stopping distance
 b. acceleration?

It is worth noting that sample problems 6 and 7 could both have been solved without the use of the constant acceleration formulae. Both examples could have been completed with a graphical approach and a clear understanding of the definitions of velocity and acceleration. Go ahead and try to answer both problems without the formulae.

9.4 EXERCISE

To answer questions online and to receive **immediate feedback** and **sample responses** for every question go to your learnON title at www.jacplus.com.au.

- How long does it take for:
 - a car to accelerate on a straight road at a constant 6 m s^{-2} from an initial speed of 60 km h^{-1} (17 m s^{-1}) to a final speed of 100 km h^{-1} (28 m s^{-1})
 - a downhill skier to accelerate from rest at a constant 2 m s^{-2} to a speed of 10 m s^{-1} ?
- In Acapulco, on the coast of Mexico, professional high divers plunge from a height of 36 metres above the water. (The highest diving boards used in Olympic diving events are 10 metres above the water.) Assuming that throughout their dive, the divers are falling vertically from rest with an acceleration of 9.8 m s^{-2} , estimate:
 - the length of the time interval during which the divers fall through the air
 - the speed with which the divers enter the water.
- A skateboard rider travelling down a hill notices the busy road ahead and comes to a stop in 2.0 seconds over a distance of 12 metres. Assume a constant negative acceleration.
 - What was the initial speed of the skateboarder?
 - What was the acceleration of the skateboarder as they came to a stop?

4. A car is travelling at a speed of 100 km h^{-1} when the driver sees a large fallen tree branch in front of her. At the instant that she sees the branch, it is 50 metres from the front of her car. The car travels a distance of 48 metres *after* the brakes are applied before coming to a stop.
 - (a) What is the average acceleration of the car while the car is braking?
 - (b) How long does the car take to stop once the brakes are applied?
 - (c) What other information do you need in order to determine whether the car stops before it hits the branch? Make an estimate of the missing item of information to predict whether or not the car is able to stop in time.
5. A dancer in a school musical is asked to leap 80 centimetres into the air, taking off vertically on one beat of the music and landing with the next beat. If the music beats every 0.5 seconds, is the leap possible? The acceleration of the dancer during the leap can be assumed to be 9.8 m s^{-2} downwards.
6. A brand-new Rolls Royce rolls off the back of a truck as it is being delivered to its owner. The truck is travelling along a straight road at a constant speed of 60 km h^{-1} . The Rolls Royce slows down at a constant rate, coming to a stop over a distance of 240 metres. It is a full minute before the truck driver realises that the precious load is missing. The driver brakes immediately, leaving a 25-metre skid mark on the road. The driver's reaction time (time interval between noticing the problem and depressing the brake) is 0.5 seconds. How far behind is the Rolls Royce when the truck stops?
7. A girl at the bottom of a 100-metre high cliff throws a tennis ball vertically upwards. At the same instant a boy at the very top of the cliff drops a golf ball so that it hits the tennis ball while both balls are still in the air. The acceleration of both balls can be assumed to be 9.8 m s^{-2} downwards.
 - (a) With what speed is the tennis ball thrown so that the golf ball strikes it at the top of its path?
 - (b) What is the position of the tennis ball when the golf ball strikes it?

studyon

To answer practice exam questions online and to receive immediate feedback and sample responses for every question go to your learnON title at www.jacplus.com.au.

studyON: Practice exam questions 

Fully worked solutions and sample responses are available in your digital formats.

9.5 Review

9.5.1 Summary

- Scalar quantities have a magnitude (size) only. Vector quantities have both a magnitude and a direction.
- Displacement is a measure of the change in position of an object. Displacement is a vector quantity.
- Speed is the rate at which distance changes over time and is a scalar quantity. Velocity is the rate at which displacement changes over time and is a vector quantity.

$$\text{average speed} = \frac{\text{distance travelled}}{\text{time interval}}$$

$$\text{average velocity} = \frac{\text{displacement}}{\text{time interval}}$$

The average velocity of an object, v_{av} , during a time interval, t , can be expressed as:

$$v_{\text{av}} = \frac{\Delta s}{\Delta t}$$

- Instantaneous speed is the speed at a particular instant of time. Instantaneous velocity is the velocity at a particular instant of time.

- The change in velocity during the time interval Δt can be expressed as:

$$\Delta v = \text{final velocity} - \text{initial velocity} = v - u$$

- The instantaneous velocity of an object can be found from a graph of its displacement versus time by calculating the gradient of the graph. Similarly, the instantaneous speed can be found from a graph of distance versus time by calculating the gradient of the graph.
- The displacement of an object during a time interval can be found by determining the area under its velocity-versus-time graph. Similarly, the distance travelled by an object can be found by determining the area under its speed-versus-time graph.
- Acceleration is the rate at which an object changes its velocity. Acceleration is a vector quantity. The average acceleration of an object, a_{av} , can be expressed as $a_{av} = \frac{\Delta v}{\Delta t}$ where Δv = the change in velocity during the time interval Δt .
- The instantaneous acceleration of an object can be found from a graph of its velocity versus time by calculating the gradient of the graph.
- When acceleration of an object is constant, the following formulae can be used to describe its motion.

$$v = u + at$$

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

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

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

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

studyon

To access key concept summaries and practice exam questions download and print the **studyON: Revision and practice exam question booklet** (sonr-0034).

9.5.2 Key terms

Acceleration is the rate at which an object changes its velocity. Acceleration is a vector quantity.

Displacement is a measure of the change in position of an object. It is a vector quantity.

Distance is a measure of the length of the path taken by an object. It is a scalar quantity.

Instantaneous speed is the speed at a particular instant of time.

Instantaneous velocity is the velocity at a particular instant of time.

Scalar quantities specify magnitude (size) but not direction.

Speed is the rate at which distance changes over time. Speed is a scalar quantity.

A **vector** quantity specifies direction as well as magnitude (size).

Velocity is the rate at which displacement changes over time, or the rate of change in position. Velocity is a vector quantity.



Resources

Digital document Key terms glossary (doc-32266)

9.5.3 Practical work and investigations

Investigation 9.1

Going home

Aim: To analyse your journey from home to school

Digital document: doc-31874

Investigation 9.2

Let's play around with some graphs

Aim: To demonstrate the motion represented by position-versus-time graphs and velocity-versus-time graphs

Digital document: doc-31875

Teacher-led video: tlvd-0820



Investigation 9.3

On your bike or on your own two feet

Aim: To record and analyse the motion of a bicycle or runner over a distance of 100 metres on a straight track

Digital document: doc-31876

Other practical work ideas:

- Place a small ruler with one end sitting over the edge of a desk. Hit the end so that it flies through the air. How far does it travel horizontally? What factors might affect this, and how? Investigate.
- How does the initial acceleration of a sprinter depend on the spacing between their feet on the blocks?
- Fill a bottle with some liquid. Lay it on its side and give it a push. The bottle may first move forward and then oscillate before it comes to rest. Investigate the bottle's motion.
- Make a small parachute from a piece of cloth, lengths of cotton and Blu-Tack. Hold it in the air and drop it with the canopy open. The parachute accelerates, then maintains a steady speed. Investigate the motion and what factors affect the initial acceleration and the final speed.



Resources



Digital document Practical investigation logbook (doc-32267)

9.5 Exercises

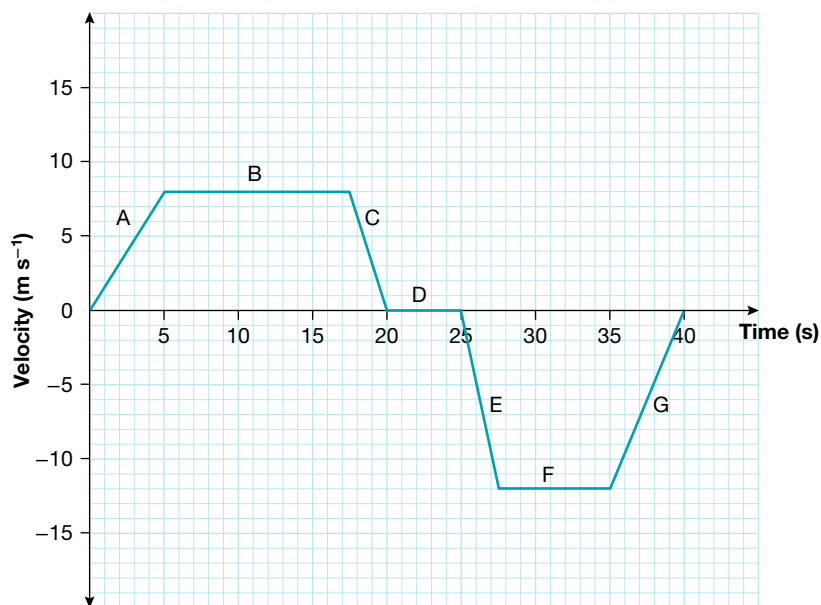
To answer questions online and to receive **immediate feedback** and **sample responses** for every question go to your learnON title at www.jacplus.com.au.

9.5 Exercise 1: Multiple choice questions

1. Which of the following does a vector quantity have?
 - A. Size (magnitude) only
 - B. Direction only
 - C. Both size (magnitude) and direction
 - D. None of the above
2. A track cyclist warming up for a race completes three laps of a 250-metre velodrome track. What is their displacement?
 - A. 0 m
 - B. 250 m
 - C. 500 m
 - D. 750 m

3. The Airbus A380 aircraft has a cruising speed 1060 km h^{-1} . How many metres does it travel in 1 second when cruising at this speed?
 - A. 3816 m
 - B. 1060 m
 - C. 294 m
 - D. 106 m
4. A hairy-nosed wombat that is feeling threatened runs as fast as its legs can take it. At its top speed it travels 21.0 metres in 1.90 seconds. What is its average velocity during this interval?
 - A. 0.09 m s^{-1}
 - B. 39.9 m s^{-1}
 - C. 1.11 m s^{-1}
 - D. 11.1 m s^{-1}
5. A car is travelling at 12 m s^{-1} . How fast is this in km h^{-1} ?
 - A. 3.3 km h^{-1}
 - B. 43.2 km h^{-1}
 - C. 33.3 km h^{-1}
 - D. 4.3 km h^{-1}
6. A Tesla Model S accelerates from a standstill to a speed of 97 km h^{-1} in 2.28 seconds. What is its average acceleration during this time interval?
 - A. 12 m s^{-2}
 - B. 43 m s^{-2}
 - C. 153 m s^{-2}
 - D. 27 m s^{-2}

Use the following graph, describing the motion of an elevator, to answer questions 7 and 8.

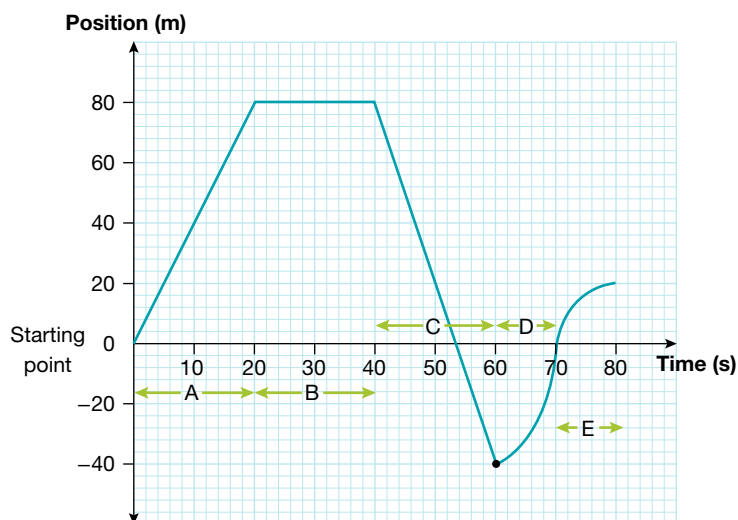


7. The acceleration of the elevator is zero at which intervals?
 - A. Intervals E, F and G
 - B. Interval D
 - C. Intervals B, D and F
 - D. Intervals B and F

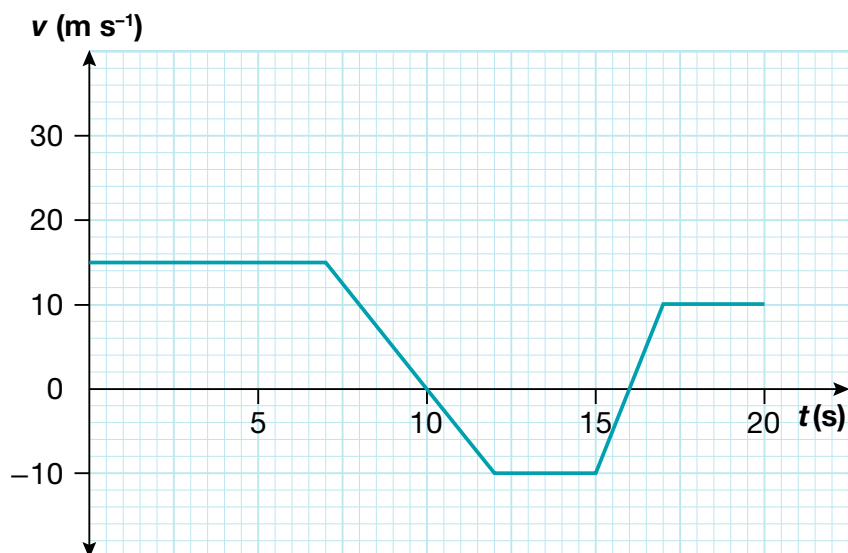
8. The accelerator reaches the maximum speed for the time period shown during which interval?
 - A. Interval B
 - B. Interval C
 - C. Interval E
 - D. Interval F
9. A student drops a stone into a wishing well (starting at rest). It falls at a rate of 9.80 m s^{-2} . The student hears the stone hit the water 2.00 seconds after they dropped it. How far down the well did the stone travel from the student's hand until it hit the water?
 - A. 9.80 m
 - B. 19.6 m
 - C. 39.2 m
 - D. 78.4 m
10. A shopping trolley rolls down a hill in a straight line with a constant acceleration of 3.00 m s^{-2} . It starts at rest beside a car and travels 100 metres before it collides with a picket fence. How fast is it travelling the instant before it collides with the fence?
 - A. 17.3 m s^{-1}
 - B. 600 m s^{-1}
 - C. 24.5 m s^{-1}
 - D. 300 m s^{-1}

9.5 Exercise 2: Short answer questions

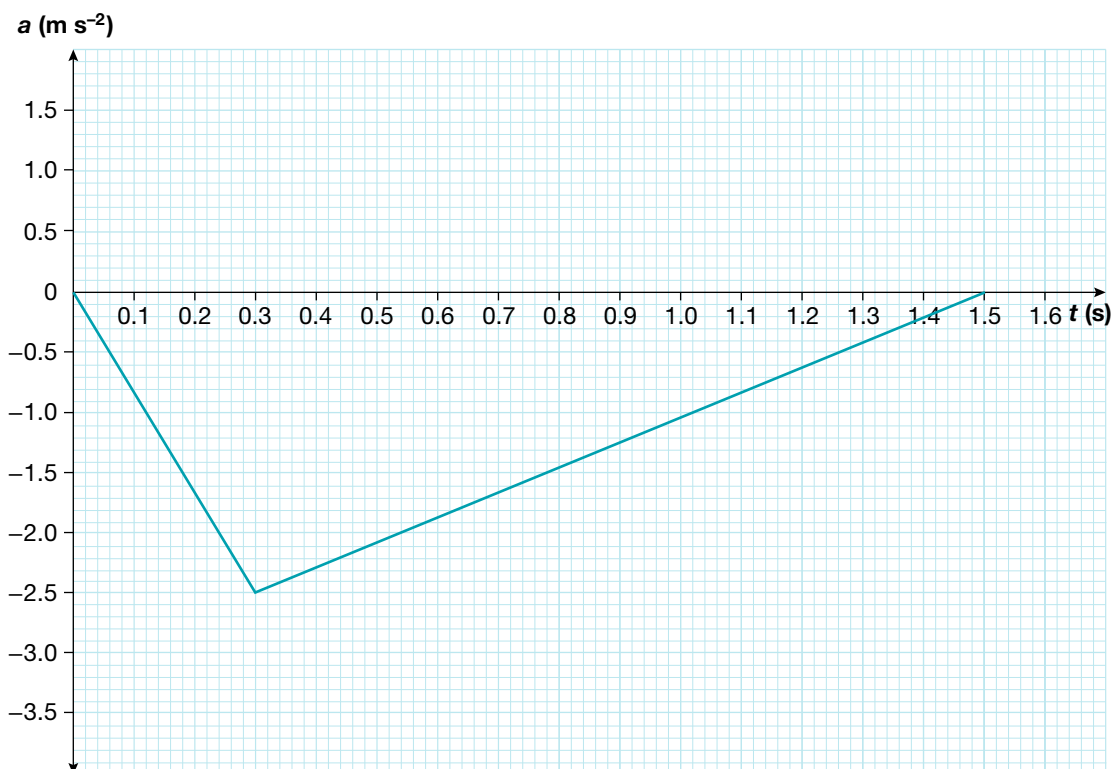
1. A student is doing a 'shuttle run' activity where they run backwards and forwards along a straight line that runs north–south. They run 10 metres north, then 5 metres south, then 7 metres north, then 9 metres south. What distance have they travelled? What is their displacement?
2. An engineer takes a direct flight from Munich to Detroit on an Airbus A350. The flight takes 10 hours and 30 minutes and covers a distance of 6980 kilometres. What is the average speed of the aircraft during this flight?
3. A shuttlecock in a game of badminton is travelling at 330 km h^{-1} when it strikes the racket of an opposing player and rebounds at 264 km h^{-1} . Assuming that the collision takes 0.25 seconds. Determine the average acceleration that it experiences during the collision with the racket.
4. The following graph records the straight-line motion of a skateboarder. Calculate the velocity of the skateboarder during section A.



5. The following velocity-versus-time graph was sketched by a physics student from data collected during a practical investigation. Determine the change in position of the object during the 20-second motion.



6. The student is analysing their data presented in question 5. Use the graph to estimate the largest magnitude acceleration that the object experiences during this motion.
7. A physics student records the acceleration versus time for a dynamics trolley colliding with a bumper. Use the following graph to estimate the change in velocity of the trolley during the collision.



8. A physics student has their very first experience of cross-country skiing on a school camp. They tentatively ski in a straight line down a gentle slope, with constant acceleration, starting from rest. They travel 50 metres in 40 seconds. What was their final speed?
9. A model rocket is launched directly upwards from a school oval. The engine switches off when it is 45 metres above the ground and travelling at 90 m s^{-1} directly upwards. Assuming that it continues to travel directly upwards with a constant downwards acceleration due to gravity of 9.8 m s^{-2} . What is the total height above the oval that the rocket reaches?
10. A car travelling in a 40 km h^{-1} speed limit zone brakes hard to avoid hitting a kangaroo that hops onto the road. It comes to a complete stop 4.5 seconds after the brakes were applied and left a skid mark that was 27 metres long. Was the driver travelling faster than the speed limit when they braked? Use a calculation to support your answer.

9.5 Exercise 3: Exam practice questions

Question 1 (1 mark)

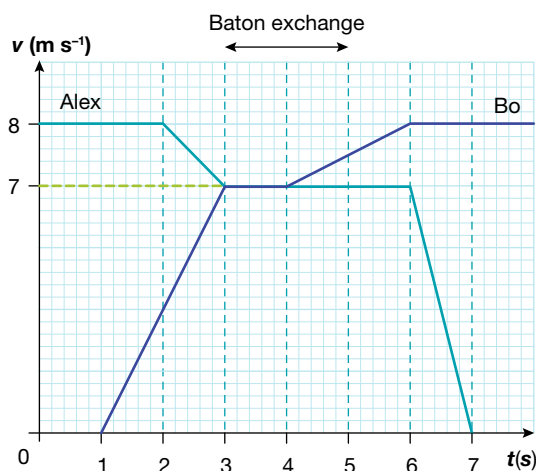
Jo is jogging around a track at a leisurely constant speed. He is joined by a friend who matches his speed and challenges him to a race to the finish. Jo accelerates to run as fast as he can and then continues at this speed until the finish line. Sketch a position-versus-time graph of Jo's motion.

Question 2 (1 mark)

A cyclist makes a left turn around a corner, keeping their speed constant. Do they experience an acceleration during this motion? Justify your response.

Question 3 (5 marks)

Two runners, Alex and Bo, are exchanging a baton in a 4×100 -metre track relay. Their motion is shown in the following velocity-versus-time graph.



- a. Calculate how far ahead Bo is of Alex at the instant Bo starts to run. **3 marks**
- b. The rules of the race require that the baton exchange takes place over a maximum of 20 metres distance and that the second runner can start running a maximum of 10 metres before the exchange. Use the graph to determine if Alex and Bo are likely to have complied with these rules. **2 marks**

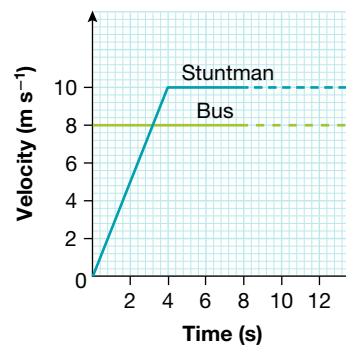
Question 4 (2 marks)

A diver is standing at the top of a 75-metre tall cliff. They leap off the cliff with an initial vertical velocity of 3 m s^{-1} . Assume that their acceleration throughout the dive is 9.8 m s^{-2} directly downwards. How long will it be from the beginning of their leap until the instant they hit the water below?

Question 5 (5 marks)

During the filming of a new movie, a stuntman has to chase a moving bus and jump into it. The stuntman is required to stand still until the bus passes him and then start chasing it. The velocity-versus-time graph in the figure that follows describes the motion of the stuntman and the bus from the instant that the bus door passes the stationary stuntman.

- a. At what instant did the stuntman reach the same speed as the bus? **1 mark**
- b. What is the magnitude of the acceleration of the stuntman during the first 4 seconds? **1 mark**
- c. At what instant did the stuntman catch up with the bus door? **2 marks**
- d. How far did the stuntman run before he reached the door of the bus? **1 mark**



9.5 Exercise 4: studyON topic test online only

Fully worked solutions and sample responses are available in your digital formats.

teachon

Test maker

Create unique tests and exams from our extensive range of questions, including practice exam questions.
Access the assignments section in learnON to begin creating and assigning assessments to students.

10 Forces in action

10.1 Overview

Numerous **videos** and **interactivities** are available just where you need them, at the point of learning, in your digital formats, learnON and eBookPLUS at www.jacplus.com.au.

10.1.1 Introduction

Have you ever seen somebody parachuting down from a skydive or BASE jump? They can land without injury as the force of the air resisting the motion of the parachute is large enough to slow them to a safe speed.

This explanation stems from the concept of forces, which are central to our understanding and analysis of motion. In his groundbreaking book *Philosophia Naturalis Principia*, published in 1687, Sir Isaac Newton proposed three laws of motion. These laws accurately explain the motion of objects on Earth and throughout the universe. In this topic we will use Newton's laws to explore the nature of forces and their relationship to motion.

FIGURE 10.1 BASE jumpers use a high point such as a cliff to launch themselves. The forces involved in the jump must be carefully calculated to allow the parachute to open in time.



10.1.2 What you will learn

KEY KNOWLEDGE

After completing this topic you will be able to:

- explain changes in momentum as being caused by a net force: $F_{net} = \frac{\Delta p}{\Delta t}$
- model the force due to gravity, F_g , as the force of gravity acting at the centre of mass of a body, $F_g = mg$, 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: $a = \frac{F_{net}}{m}$, $F_{\text{on A by B}} = -F_{\text{on B by A}}$
- 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 reaction forces
- calculate torque: $\tau = r_{\perp} F$
- investigate and analyse theoretically and practically translational forces and torques in simple structures that are in rotational equilibrium
- apply concepts of momentum to linear motion: $p = mv$.

Source: VCE Physics Study Design (2016–2021) extracts © VCAA; reproduced by permission.

PRACTICAL WORK AND INVESTIGATIONS

Practical work is a central component of learning and assessment. Experiments and investigations, supported by a **Practical investigation logbook** and **Teacher-led videos**, are included in this topic to provide opportunities to undertake investigations and communicate findings.

on Resources

-  **Digital documents** Key science skills — Units 1–4 (doc-31856)
Key terms glossary (doc-32268)
Practical investigation logbook (doc-32269)

studyon

To access key concept summaries and practice exam questions download and print the **studyON: Revision and practice exam question booklet** (sonr-0035).

10.2 Forces as vectors

KEY CONCEPTS

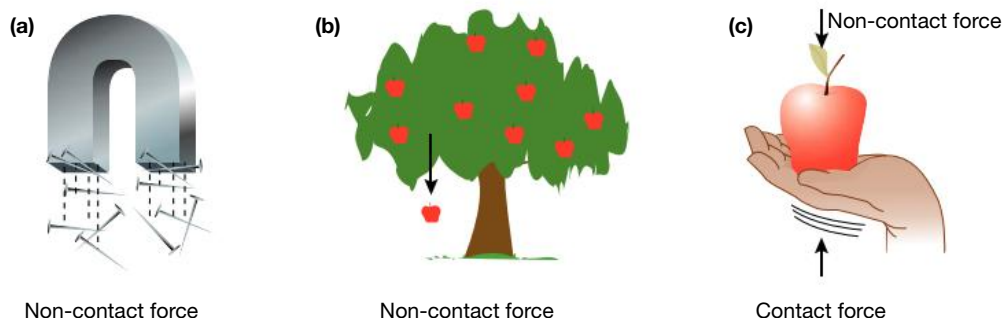
- Apply the vector model of forces, including vector addition and components of forces, to readily observable forces including the force due to gravity, friction and reaction forces.
- Model forces as vectors acting at the point of application (with magnitude and direction), labelling these forces using the convention 'force on A by B' or $F_{\text{on A by B}} = -F_{\text{on B by A}}$.
- Model the force due to gravity, F_g , as the force of gravity acting at the centre of mass of a body, $F_g = mg$, where g is the gravitational field strength (9.8 N kg^{-1} near the surface of Earth).

10.2.1 Describing a force

A **force** is a push or a pull applied by one object on another. Forces can start things moving, stop them, or change their speed or direction. Forces can spin objects or change their size or shape. Some types of force require contact. For example, the force applied by your hand on a netball or basketball when shooting a goal requires contact between your hand and the ball. The friction applied by the road on a bicycle or car

requires contact between the road surface and the tyres. Some forces do not require contact. For example, the force of gravity applied on your body by the Earth is present even when you are not in contact with the Earth. A magnet attracts certain materials without being in contact with them. Note that descriptions of forces indicate both the object that the force is applied on and the object that applies the force.

FIGURE 10.2 Contact and non-contact forces at work



In diagrams showing forces, such as figure 10.3, a labelled arrow should be drawn from the **centre of mass** of the object upon which the force acts (this was not included in figure 10.2 for the sake of simplicity). The length of the arrow should indicate the relative size of the force.

To fully describe a force, you need to specify its direction as well as its magnitude or size. A quantity that can be fully described only by specifying a direction as well as a magnitude is called a vector quantity. Force is a vector quantity. A vector quantity can be described in writing or by a labelled arrow. If a symbol is used to represent a vector quantity, it should have a half-arrow above it (some people use a 'squiggly' line below the symbol instead). In this text, vector quantities are represented by symbols in ***bold italic*** font. When bold can't be used to distinguish a vector (for example, writing by hand), a right-facing arrow may be used instead.

When labelling forces, it helps to describe the force as $F_{\text{on A by B}}$; for example, the arrow representing the force due to gravity of the apple is labelled $F_{\text{on apple by Earth}}$.

The SI unit of force is the newton (N). The force of gravity on a 100 gram apple is about 1 N downwards. A medium sized car starting from rest is subjected to a forward force of about 4000 N.

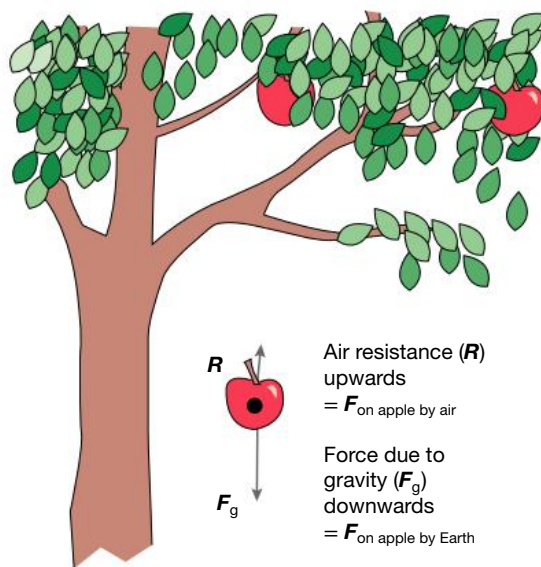
Quantities that can be described without specifying a direction are called scalar quantities. Mass, energy, time and temperature are all examples of scalar quantities.

The present understanding of our universe posits that there are four fundamental forces or interactions:

- strong nuclear force
- electromagnetic force
- weak nuclear force
- gravitational force.

While these categories are fundamental to our understanding of the physics of interactions in the universe, they are not wholly useful for describing and analysing everyday motion at a human scale. The following sections introduce some everyday categories of forces.

FIGURE 10.3 Force is a vector quantity. A vector quantity in this text is represented by symbols in ***bold italic*** font.



10.2.2 Force due to gravity (F_g)

The apple in figure 10.3 is attracted to the Earth by the **force due to gravity**. Even before it falls, the force due to gravity is pulling it down. However, before it falls, the tree branch is pulling it up with a force of equal magnitude.

The force due to gravity is a force of attraction that exists between any pair of objects that have mass. Gravity is such a small force that, unless at least one of the objects is as massive as a planet or a natural satellite like the Moon, it is too small to measure. The force due to gravity is a force that acts ‘at a distance’ in that the items that it acts on do not need to be in contact with each other.

The force on an object due to the pull of gravity is usually given the symbol $\vec{F}_g$. In simple scenarios where objects of relatively small mass (e.g. humans, buildings, whales) are in close proximity to a very massive object (e.g. the Earth) the force due to gravity can be represented by:

$$\vec{F}_g = m\vec{g}$$

Where:

m = the mass of the smaller object in kg

$\vec{g}$ = the **gravitational field strength** in N kg^{-1} due to the larger object.

The **gravitational field strength** is defined as the force of gravity on a unit of mass. The magnitude of g at the surface of the Moon is approximately one-sixth that at the surface of the Earth. Gravitational field strength is a vector quantity. The direction of the force due to gravity on an object is towards the centre of the source of attraction (e.g. the centre of the Earth).

The magnitude of gravitational field strength at the Earth’s surface is, on average, 9.8 N kg^{-1} . The magnitude of g decreases as altitude (height above sea level) increases. It also decreases as one moves from the poles towards the equator. Table 10.1 shows the magnitude of g at several different locations.

TABLE 10.1 Variation in gravitational field strength

Location	Altitude (m)	Latitude	Magnitude of g (N kg^{-1})
Equator	0	0°	9.780
Sydney	18	34°S	9.797
Melbourne	12	37°S	9.800
Denver	1609	40°N	9.796
New York	38	41°N	9.803
North Pole	0	90°N	9.832

The magnitude of g at the Earth’s surface will be taken as 9.8 N kg^{-1} throughout this text. At the surface of the Moon, the magnitude of g is 1.60 N kg^{-1} .

SAMPLE PROBLEM 1

What is the force due to gravity by the Earth acting on a 50-kilogram student:

- on the Earth
- on the Moon?

THINK

1. Recall the formula for force due to gravity.
2. Substitute the values to determine the force due to gravity.

WRITE

a. $F_g = mg$
 $F_g = 50 \times 9.8$
 $= 490 \text{ N downwards}$

3. State the solution.

The force due to gravity by the Earth acting on a 50-kilogram student on the Earth is 490 N downwards.

- b. 1. Recall the formula for force due to gravity.
2. Substitute the values to determine the force due to gravity.
3. State the solution.

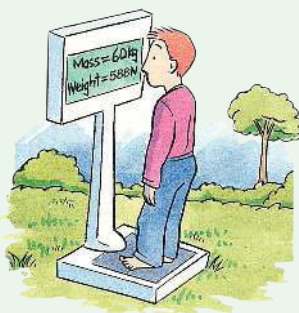
$$\begin{aligned} \text{b. } F_g &= mg \\ F_g &= 50 \times 1.60 \\ &= 80 \text{ N downwards} \end{aligned}$$

The force due to gravity by the Earth acting on a 50-kilogram student on the Moon is 80 N downwards.

PRACTICE PROBLEM 1

- a. What is the difference between the force due to gravity by the Earth acting on a 70-kilogram person at the North Pole and at the equator?
b. A hospital patient is very accurately measured to have a mass of 64.32 kilograms and the force due to gravity by the Earth acting on them is 630.08 N. In which of the locations in table 10.1 could the patient be?

WEIGHING IN



Bathroom scales are designed for use only on Earth. Fortunately (at this point in time), that's where most of us live.

If a 60-kilogram student stood on bathroom scales on the Moon, the reading would be only about 10 kilograms. Yet the mass of the student remains 60 kilograms. Bathroom scales measure force, not mass.

However, scales are designed so that you can read your mass in kilograms. Otherwise, you would have to divide the measured force by 9.8 to determine your mass. The manufacturer of the bathroom scales saves you the trouble of having to do this.

The 60-kilogram student experiences a force due to gravity from Earth of about 588 N. However, on the Moon the force due to gravity from the Moon is only about 100 N. The reading on the scales will be 100 N divided by 9.8 N kg⁻¹, giving the result of 10.2 kilograms.



The term weight is often used in high school physics texts in order to draw a distinction between the force due to gravity on an object and its mass. However, the accepted definition of the term weight in physics is more complex than this and there are different conventions for how it is defined. Confusion that this may cause is further compounded by inconsistent use of the term weight in everyday life. As such, the term weight is not used in this text or the VCE Physics Study Design.

on Resources

 **Digital document** Investigation 10.1 The relationship between mass and the force due to gravity (doc-31879)

10.2.3 Friction (F_{fr})

Friction is a force that surfaces exert on each other when they ‘rub’ together. The magnitude of the friction force depends greatly on the nature of each of the two surfaces. Smooth surfaces experience smaller friction forces than rough surfaces. However, even very smooth surfaces are rough on a microscopic scale.

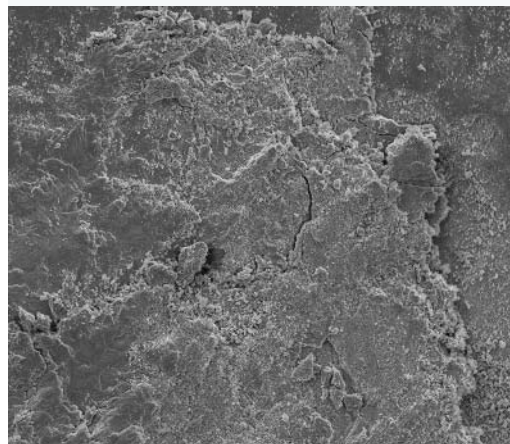
It is this roughness that is mostly responsible for the resistance to motion that we call friction. As two surfaces move across each other, they intermesh, resisting the motion.

Friction can seem to be a real nuisance at times. It makes doors squeak. It causes wear and tear in car engines and can make them overheat.

Friction is also a necessary force in many situations. If you have ever walked on a banana peel or ice, you know the importance of friction to walking. When you walk, you push backwards against the ground so that the ground pushes forward on your foot. Without a significant friction force, your foot slides backwards and you fall.

Friction is also needed for safe driving in a car. A large friction force is needed to start moving, change direction and stop. The rubber tyres of a car have a deep tread to ensure that the friction force is still present on a wet road when water forms a lubricating film between the road and the tyres. Smooth tyres would slide across a wet road, making it difficult to stop, turn or accelerate. The deep grooves in tyres pick up the water from the road and throw it backwards, providing a drier road surface and greater friction. The lubricating effect of water is also evident in ice skating. The moving blade melts the surface of the ice beneath it, creating a thin lubricating film of water on which it glides.

FIGURE 10.4 This scanning electron micrograph shows a magnified metal surface.



on Resources

-  **Digital document** Investigation 10.2 Friction (doc-31877)
-  **Teacher-led video** Investigation 10.2 Friction (tlvd-0822)
-  **Video eLesson** Friction as a driving force (eles-0032)
-  **Interactivity** Friction as a driving force (int-0054)

10.2.4 Forces from fluid motion

The motion of an object through fluids such as air or water results in forces acting on the object. One component of this is a force acting in the opposite direction of the motion. This resistance to the motion of objects through air and water is given a variety of names including fluid friction, fluid resistance, drag or **air resistance**.

Olympic swimmers, cyclists and track athletes are becoming increasingly aware of the effects of fluid resistance as the accuracy of timing improves.

The desire to win gold medals has resulted in swimmers shaving their heads, cyclists shaving their legs, new bicycle designs and tighter fitting costumes. Because fluid friction increases with the speed of the object, streamlining is particularly important in cars,

FIGURE 10.5 Racing cyclists reduce the effects of fluid friction (air resistance) by wearing streamlined costumes and using aerodynamically designed bicycles.



planes, watercraft and bicycles. Streamlining involves creating a shape that reduces the slowing effect of collisions with particles of the fluid.

While air resistance can be seen as a problem, it is an absolute necessity for parachutists and paragliders, who rely on it to slow their descent and land safely.

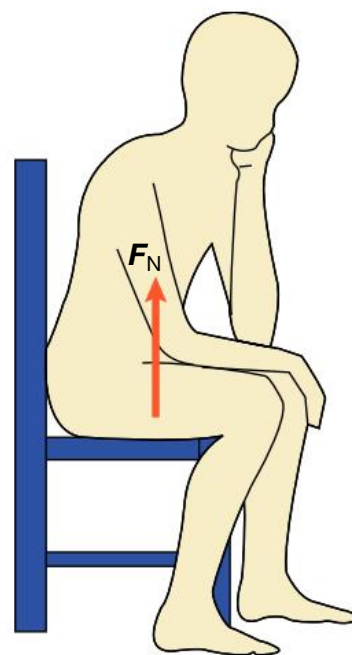
The forces arising from motion through fluids is very complex and has been very simply introduced here. To learn more about this, you may choose to study the option in topic 16 ‘How do heavy things fly?’ where more detail on these forces is provided.

10.2.5 The normal force (F_N)

At this moment you are probably sitting on a chair with your feet on the floor. The material in the chair, whether it is plastic, timber, foam or steel springs, has been compressed and is pushing back up. This force that is pushing up is called a reaction force because if you were not sitting on the chair, there would be no force. This force is more properly called a **normal force**, F_N , as it acts at right angles to the surface.

The normal force and the friction force comprise the two perpendicular components of forces that arise from the interactions between two objects or surfaces. In both instances the fundamental force involved is the electromagnetic interaction between the atoms in the materials.

FIGURE 10.6 The normal force acts perpendicular to the surface of the chair.

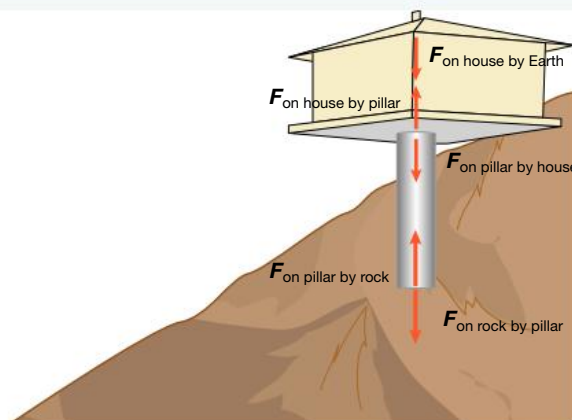
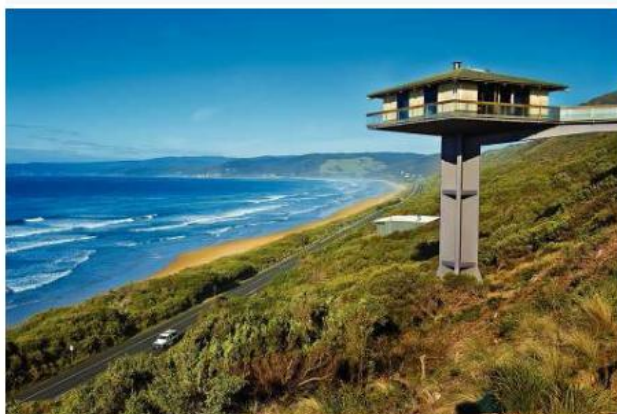


10.2.6 Compression and tension materials

Forces acting on materials, such as a concrete pillar or a steel cable, can cause the material to experience compression or tension. These are types of loadings on a material.

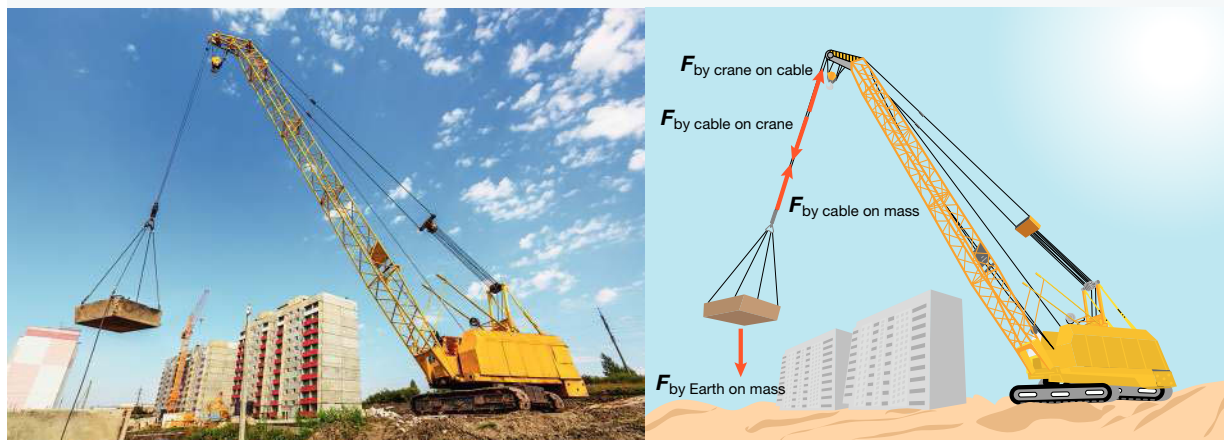
In a material that is experiencing compression, the atoms and molecules are pushed closer together. In the photo of the pole house in figure 10.7, the concrete pillar is in compression. The house is pushing down on the pillar and the rocky hillside below is pushing up on it, causing the pillar to be squashed in compression. An object that is in compression will be pushing against the objects that are compressing it. Some materials are best suited for withstanding compression, such as concrete, stone, brick and bone.

FIGURE 10.7 The Pole House located on the Great Ocean Road is supported by a concrete column that goes several metres into the ground.



Similarly, when atoms and molecules in a material are pulled further apart by a loading, it experiences **tension**. In the photo of the crane in figure 10.8, the steel cable is in tension. The crane is pulling up on the cable and the load that it is supporting is pulling down on the cable, causing it to be stretched in tension. An object that is in tension will be pulling against the objects that are stretching it. Metals are a common example of materials that are well suited to withstanding tension loading.

FIGURE 10.8 Cranes use metal cables in tension to lift large loads



10.2.7 Free body diagrams

A free body diagram or force diagram is used to depict all external forces acting upon an object (see figures 10.7 and 10.8).

The ability to accurately and effectively represent the forces on an object through a free body diagram is a critical skill in analysing forces and motion. The key to developing this skill is practice. To create a free body diagram consider the following steps.

- Represent the object with a suitable simplified shape or, if the problem is simple enough, a single point (e.g. a car could be represented very simply as a rectangular block).
- Identify each interaction that the object is experiencing and the force that represents that interaction (e.g. gravitational interaction with the Earth represented by the force due to gravity, F_g).
- Represent each force with an arrow drawn at the point where it acts on the object (e.g. a friction force on a car by the road will act where the car tyres contact the road; the force due to gravity will act at the centre of mass of an object).
- The direction of the arrow should be in the expected direction of the force. If the direction is not known, make an assumption (e.g. the force in a connection between a car and trailer could be either forwards or backwards).
- The length of the arrow should represent the expected magnitude (size) of the force. If unknown, make an assumption.

SAMPLE PROBLEM 2

Draw a forces diagram for each of the following.

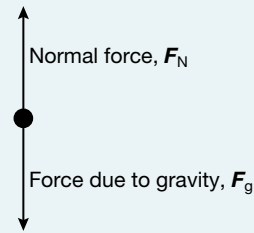
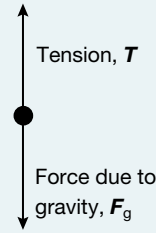
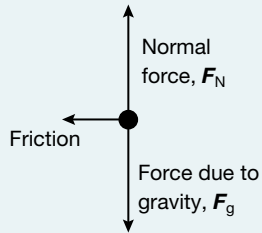
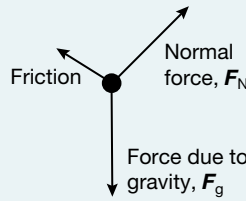
- An ice skater moving at a constant velocity
- Ball hanging straight down on a string
- Trolley slowing down
- Block stationary on slope

 **Teacher-led video:** SP2 (tlvd-0077)

THINK

- a. The only forces acting on the ice skater are the normal force and the force due to gravity.
- b. The forces acting on a ball hanging on a string are the force due to gravity and a tension force.
- c. The forces acting on a trolley that is slowing down are the force due to gravity, the normal force and a friction force.
- d. The forces acting on a stationary block on a slope are the force due to gravity, the normal force and a friction force in the direction up the slope.

WRITE

- a.
- 
- b.
- 
- c.
- 
- d.
- 

PRACTICE PROBLEM 2

Draw a forces diagram for each of the following.

- a. Falling stone
- b. Mass being pulled at a steady speed
- c. Piece of iron on a string, which is hanging near a strong magnet.

10.2.8 The net force (F_{net}) or sum of forces

What happens if more than one force acts on an object?

It is rare for just one force to be acting on an object. For example, a moving car has friction forces, the normal force and the force due to gravity acting on it. A suspended magnet will experience the force due to gravity, a tension force and a magnetic force.

The **net force** is the result of combining all the forces into one force. You may also see this referred to as the *sum of forces* or the *resultant force*.

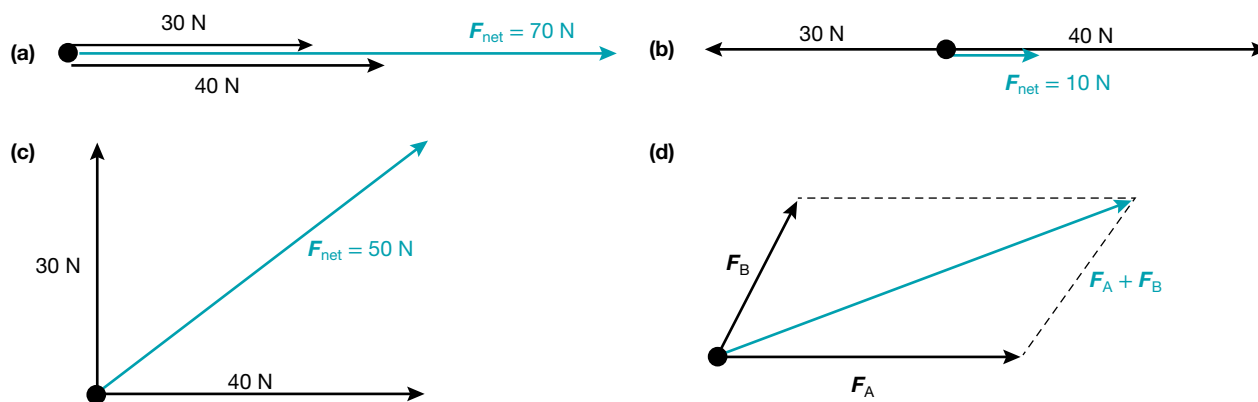
Sometimes all the forces can balance leaving a net or overall force of zero. At other times there is a non-zero force left, and because it is a vector, it has a particular direction, which may be different from any of the individual forces acting on the object. However, because force is a vector, combining forces is not just simple arithmetic, but is a vector sum as the direction of the force has to be taken into account.

When more than one force acts on an object, the net force is found by the vector addition of the forces. If an object has two forces acting on it, one of 30 N and another of 40 N, the sum of the two forces, or net force, is 70 N only if both forces are acting in the same direction. Figures 10.9b, c and d show these two forces acting in different directions; figure 10.9a shows them acting in the same direction. The net force is indicated in each of the three examples. The net force is usually denoted by the symbol F_{net} .

It is critical to distinguish that the net force is not a particular type or category of force that acts on an object. It is simply the combination of all forces.

To distinguish the net force vector from the vectors for the actual forces, the arrow for F_{net} is often drawn in another colour or as a dashed line. A geometric method of adding vectors uses a parallelogram, where the vector sum is the diagonal. This is shown in figure 10.9d.

FIGURE 10.9 Adding forces together

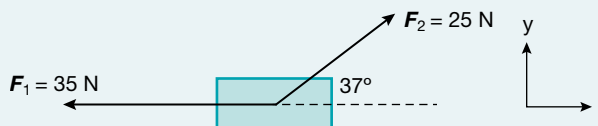


SAMPLE PROBLEM 3

The free body diagram on the right shows the forces acting on an object.

Calculate the:

- component of F_2 that acts in the x direction
- component of F_2 that acts in the y direction
- magnitude of the net force on the object.



Teacher-led video: SP3 (tlvd-0078)

THINK

- The force F_2 acts at an angle of 37° from the x -axis. Its x component can be found using trigonometry.

- State the solution.

1. Similarly the y component of F_2 can be found using $\sin$.

- State the solution.

WRITE

$$\text{a. } \cos \theta = \frac{\text{adjacent}}{\text{hypotenuse}}$$

$$\cos(37^\circ) = \frac{F_{2x}}{25}$$

$$F_{2x} = 25 \cos(37^\circ) \\ \approx 20 \text{ N}$$

The component of F_2 that acts in the x direction is 20 N.

$$\text{b. } \sin \theta = \frac{\text{opposite}}{\text{hypotenuse}}$$

$$\sin(37^\circ) = \frac{F_{2y}}{25}$$

$$F_{2y} = 25 \sin(37^\circ) \\ \approx 15 \text{ N}$$

The component of F_2 that acts in the y direction is 15 N.

c. 1. To find the net force, consider the force components in the x and y directions separately.

2. Combining these two forces, Pythagoras' theorem can be used to find the resultant net force.

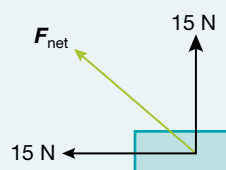
3. State the solution.

c. In the x direction:

$$\begin{aligned} F_{\text{net}, x} &= F_{2x} - F_1 \\ &= 20 - 35 \\ &= -15 \text{ N} \end{aligned}$$

In the y direction:

$$\begin{aligned} F_{\text{net}, y} &= F_{2y} \\ &= 15 \\ &= 15 \text{ N} \end{aligned}$$



$$c^2 = a^2 + b^2$$

$$F_{\text{net}}^2 = 15^2 + 15^2$$

$$F_{\text{net}}^2 = 450$$

$$F_{\text{net}} = \sqrt{450}$$

$$F_{\text{net}} \approx 21.2 \text{ N}$$

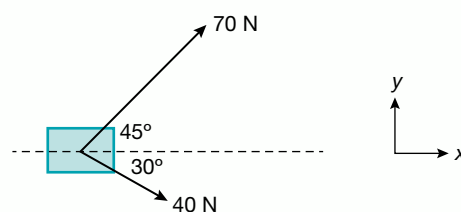
The magnitude of the net force on the object is 21.2 N.

Note: This problem only requires the magnitude of the net force. If the direction was required it would be necessary to calculate the angle that the force is acting at.

PRACTICE PROBLEM 3

The free body diagram on the right shows the forces acting on an object.

Calculate the magnitude of the net force acting on the object.



Resources



Digital document Investigation 10.3 Force as a vector (doc-32308)

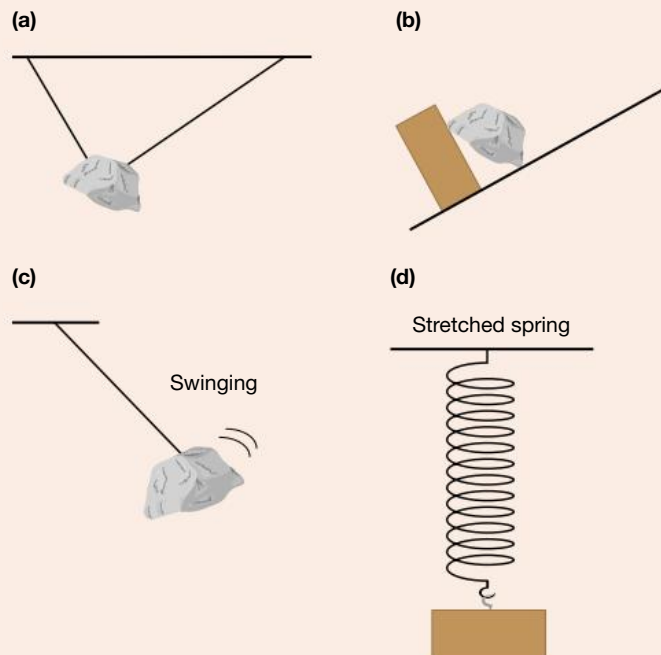
10.2 EXERCISE

To answer questions online and to receive **immediate feedback** and **sample responses** for every question go to your learnON title at www.jacplus.com.au.

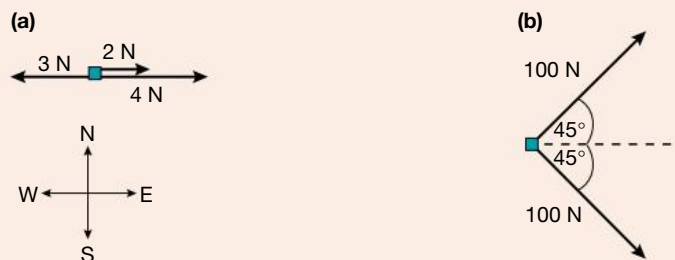
1. Describe the difference between a vector quantity and a scalar quantity.
2. Which of the following are vector quantities?
 - (a) Mass
 - (b) Force due to gravity
 - (c) Gravitational field strength
 - (d) Time
 - (e) Energy
 - (f) Temperature



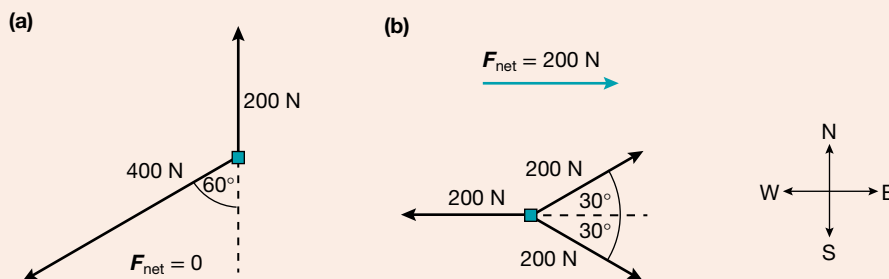
3. A car has a mass of 1400 kilograms with a full petrol tank.
 - (a) What is the magnitude of the force due to gravity acting on it at the surface of the Earth?
 - (b) What would be the magnitude of the force due to gravity acting on it on the surface of Mars where the magnitude of the gravitational field strength is 3.6 N kg^{-1} ?
 - (c) What is the mass of the car on the surface of Mars?
4. Estimate the magnitude of the force due to gravity acting at the surface of the Earth on:
 - (a) an apple
 - (b) a textbook
 - (c) your physics teacher.
5. Estimate your own mass in kilograms and determine:
 - (a) the magnitude of the force due to gravity acting on you at the surface of the Earth
 - (b) the magnitude of the force due to gravity acting on you at the surface of Mars where the magnitude of the gravitational field strength is 3.6 N kg^{-1}
 - (c) your mass on the planet Mars.
6. Draw force diagrams for:
 - (a) an open parachute falling slowly to the ground.
 - (b) a thrown basketball approaching its maximum height before coming down into the basket
 - (c) a car approaching a red light rolling slowly to a stop
 - (d) a rocket during liftoff.
7. Draw force diagrams for figures a–d. For figures a, b and c, show the forces acting on the rock. For figure d, show the force acting on the block.



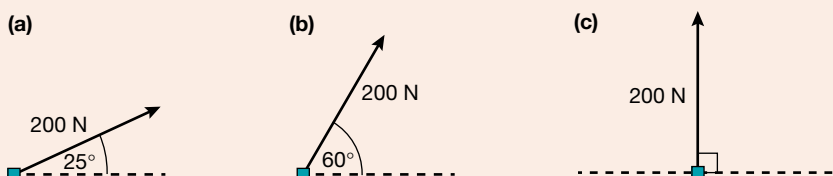
8. A person is standing on a horizontal floor. Draw and label in the form $F_{\text{on A by B}}$ all of the forces acting on the person, the floor and the Earth.
9. Determine the net force in the situations illustrated in diagrams a and b.



10. In the following diagrams, the net force is shown along with all but one of the contributing forces. Determine the magnitude and direction of the missing force.



11. A car is moving north on a horizontal road at a constant speed of 60 km h^{-1} . Draw a diagram showing all of the significant forces acting on the car. Show all of the forces as if they were acting through the centre of mass.
12. Determine the magnitude of the horizontal components of each of the forces shown in the following diagrams.



studyon

To answer practice exam questions online and to receive immediate feedback and sample responses for every question go to your learnON title at www.jacplus.com.au.

studyON: Practice exam questions **online only**

Fully worked solutions and sample responses are available in your digital formats.

10.3 Newton's First Law of Motion

KEY CONCEPT

- Apply Newton's three laws of motion to a body on which forces act: $\mathbf{a} = \frac{\mathbf{F}_{\text{net}}}{m}$, $\mathbf{F}_{\text{on A by B}} = -\mathbf{F}_{\text{on B by A}}$.

It is difficult to explain the motion of objects without an understanding of force. The ancient Greek philosopher Aristotle (384–322 BCE) concluded from his observations that a moving object would come to rest if no force was pushing it. Aristotle thought that steady motion required a constant force and that ‘being at rest’ was the natural state of matter. This view held sway for almost 2000 years, although contrary views were expressed by philosophers such as Epicurus and Lucretius.

It was not until Galileo (1564–1642) that this explanation of motion was seriously challenged. Galileo argued that if a ball rolled down an inclined plane gained speed and a ball rolled up an inclined plane lost speed, a ball rolled along a horizontal plane should neither gain nor lose speed. Galileo knew that this did not really happen. He claimed that if there was a lot of friction, the ball slowed down quickly; if there was little friction, the ball slowed down more gradually. However, he predicted that if there were no friction at all, the ball would continue to move with a constant speed forever unless something else caused it to slow down or stop.

Galileo introduced the concept of friction as a force and concluded that objects retain their velocity unless a force, often friction, acts upon them. Galileo stated in his *Discorsi* (1638):

A body moving on a level surface will continue in the same direction at constant speed unless disturbed.

Sir Isaac Newton (1643–1727) was able to refine Galileo’s ideas about motion. In 1687, he published his *Philosophia Naturalis Principia*, which included three laws of motion.

Newton’s First Law of Motion:

Every object continues in its state of rest or uniform motion unless made to change by a non-zero net force.

A coin flicked across a tabletop changes its motion because the net force on it is not zero. In fact, it slows down because the direction of the net force is opposite to the direction of motion. The vertical forces, gravity and the support force of the table balance each other. The only ‘unbalanced’ force is that of friction.

A coin pushed steadily across a tabletop moves in a straight line at constant speed as long as the net force is zero (that is, as long as the magnitude of the pushing force is equal to the magnitude of friction). The coin will speed up if you push horizontally with a force greater than the friction. It will slow down if the force of friction is greater than the horizontal pushing force.

The motion of a bungee jumper can be explained in terms of Newton’s First Law of Motion. Until the bungee cord tightens, the net force is downwards and the speed of the bungee jumper increases. As the jumper’s speed increases, so does the air resistance. However, the air resistance is quite small compared with the force due to gravity on the jumper. Until the cord begins to tighten, the tension pulling the jumper up is zero. As the rope tightens, the tension increases. Until the tension and air resistance forces together balance the force due to gravity, the bungee jumper continues to speed up. The tension continues to increase, eventually resulting in an upwards net force which allows the bungee jumper to slow down, stop (just in time) and rise again.

FIGURE 10.10 The changing net force on this bungee jumper determines their state of motion and whether or not they will stop in time.



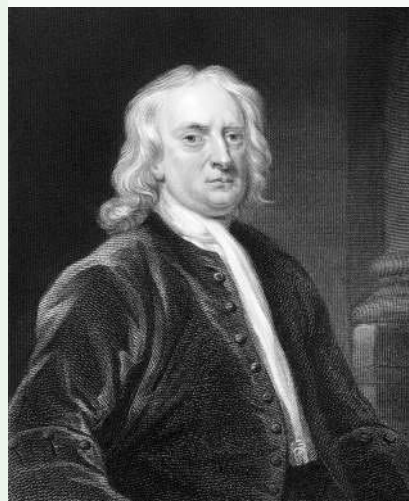
SIR ISAAC NEWTON

Sir Isaac Newton was one of many famous scientists who were not outstanding students at school or university. Newton left school at 14 years of age to help his widowed mother on the family’s farm. He turned out to be unsuited to farming and spent much of his time reading. At the age of 18, he went to Cambridge University, where he showed no outstanding ability.

When Cambridge University was closed down in 1665 due to an outbreak of the plague, Newton went home and spent the next two years studying and writing. During this time, he developed the laws of gravity that explain the motion of the planets, and his three famous laws of motion. Over the same period, he put forward the view that white light consisted of many colours and he invented calculus. Newton’s laws of gravity and motion were not published until about 20 years later.

Newton later became a member of Parliament, a warden of the Mint and President of the Royal Society. After his death in 1727, he was buried in Westminster Abbey, London, alongside many English kings, queens, political leaders and poets.

FIGURE 10.11 Sir Isaac Newton



10.3 EXERCISE

To answer questions online and to receive **immediate feedback** and **sample responses** for every question go to your learnON title at www.jacplus.com.au.

1. With reference to Newton's First Law of Motion explain why a coin flicked across a table does not move at a constant speed.
2. When you are standing on a bus, train or tram that stops suddenly, you lurch forwards. Explain why this happens in terms of Newton's first law.
3. If the bicycle that you are riding runs into an obstacle such as a large rock, you may be flung forwards over the handlebars. Explain in terms of Newton's first law why this happens.

studyon

To answer practice exam questions online and to receive immediate feedback and sample responses for every question go to your learnON title at www.jacplus.com.au.

studyON: Practice exam questions 

Fully worked solutions and sample responses are available in your digital formats.

10.4 Newton's Second Law of Motion

KEY CONCEPT

- Apply Newton's three laws of motion to a body on which forces act: $\mathbf{a} = \frac{\mathbf{F}_{\text{net}}}{m}$, $\mathbf{F}_{\text{on A by B}} = -\mathbf{F}_{\text{on B by A}}$.

Casual observations indicate that the acceleration of a given object increases as the net force on the object increases. It is also clear that lighter objects change their velocity at a greater rate than heavier objects when the same force is applied.

It can be shown experimentally that the acceleration, $\mathbf{a}$, of an object is:

- proportional to the net force, $\mathbf{F}_{\text{net}}$, applied to it
- inversely proportional to its mass, m .

$$\mathbf{a} \propto \mathbf{F}_{\text{net}} \qquad \mathbf{a} \propto \frac{1}{m}$$

Thus:

$$\begin{aligned} \mathbf{a} &\propto \frac{\mathbf{F}_{\text{net}}}{m} \\ \Rightarrow \mathbf{a} &= \frac{k\mathbf{F}_{\text{net}}}{m} \end{aligned}$$

Where:

k = a constant of proportionality.

The SI unit of force, the newton (N), is defined such that a net force of 1 N causes a mass of 1 kilogram to accelerate at 1 m s^{-2} . The value of the constant, k , is 1. It has no units. Thus:

$$\begin{aligned} \mathbf{a} &= \frac{\mathbf{F}_{\text{net}}}{m} \\ \mathbf{F}_{\text{net}} &= m\mathbf{a} \end{aligned}$$

This equation describes Newton's Second Law of Motion.

Newton's Second Law of Motion:

The acceleration of an object as produced by a net force is directly proportional to the magnitude of the net force, in the same direction as the net force, and inversely proportional to the mass of the object.

$$\vec{a} = \frac{\vec{F}_{\text{net}}}{m}$$

$$\vec{F}_{\text{net}} = m\vec{a}$$

This statement of Newton's second law allows you to:

- determine the net force acting on an object without knowing any of the individual forces acting on it. The net force can be deduced as long as you can measure or calculate (using formulae or graphs) the acceleration of a known mass
- determine the mass of an object. You can do this by measuring the acceleration of an object on which a known net force is exerted
- predict the effect of a net force on the motion of an object of known mass.

SAMPLE PROBLEM 4

A 65-kilogram physics teacher, starting from rest, glides gracefully down a slide in the local playground. The net force on her during the slide is a constant 350 N. How fast will she be travelling at the bottom of the 8-metre slide?

THINK

1. Recall Newton's Second Law of Motion.
2. Substitute the mass and force to find the acceleration.
3. As the acceleration is constant, a constant acceleration formula can be used.
4. State the solution.

WRITE

$$F_{\text{net}} = ma$$

$$F_{\text{net}} = ma$$

$$350 = 65a$$

$$a = \frac{350}{65}$$

$$\approx 5.38 \text{ m s}^{-2}$$

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

$$= 0 + 2 \times 5.38 \times 8$$

$$= 86.08$$

$$v = \sqrt{86.08}$$

$$\approx 9.3 \text{ m s}^{-1}$$

She will be travelling at approximately 9.3 m s^{-1} at the bottom of the slide.

PRACTICE PROBLEM 4

- a. What is the magnitude of the average force applied by a tennis racquet to a 58-gram tennis ball during service if the average acceleration of the ball during contact with the racquet is $1.2 \times 10^4 \text{ m s}^{-2}$?
- b. A toy car is pulled across a smooth, polished horizontal table with a spring balance. The reading on the spring balance is 2 N and the acceleration of the toy car is measured to be 2.5 m s^{-2} . What is the mass of the toy car? (*Note:* Because the table is described as smooth and polished, friction can be ignored.)



Resources



Video eLesson Newton's second law (eles-0033)

10.4.1 Applying Newton's second law in real life

Of course, the practice problems presented above do not reflect what really happens. When a tennis ball is served, the force applied by the tennis racquet is not the only force acting on the ball. However, the force due to gravity acting on the ball and the air resistance on the ball are **negligible**; that is, they are so small compared with the force of the racquet on the ball that they can be ignored while the racquet is in contact with the ball. The table surface in Practice problem 4b is smooth. This description was deliberately included so that you would know the force of friction on the toy car was negligible. If the table were not described as smooth, you could not have answered the question without taking friction into account. The event described in Sample problem 4 was also simplified. It is unlikely that the net force on the teacher gliding down the slide would be constant.

The assumptions made to answer each of the questions asked in the sample problem and practice problem are called **idealisations**. However, caution is needed when making idealisations. For example, it would be unreasonable to ignore the air resistance on a tennis ball while it was soaring through the air at 150 km h^{-1} (42 m s^{-1}) after the serve was completed.

Most applications of Newton's second law are not as simple as those given above. Some more typical examples are presented in the following sample problems.

SAMPLE PROBLEM 5

When the head of an 80-kilogram bungee jumper is 24 metres from the surface of the water below, her velocity is 16 m s^{-1} downwards and the tension in the bungee cord is 1200 N. Air resistance can be assumed to be negligible.

- a. What is her acceleration at that instant?
- b. If her acceleration remained constant during the rest of her fall, would she stop before hitting the water?



Teacher-led video: SP5 (tlvd-0080)

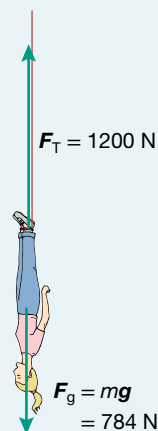
THINK

- a. 1. Calculate force due to gravity, then draw a diagram to show the forces acting on the bungee jumper.

WRITE

$$\begin{aligned} \text{a. } F_g &= mg \\ &= 80 \times 9.8 \\ &= 784 \text{ N} \end{aligned}$$





2. Calculate the net force.

$$F_{\text{net}} = 1200 - 784$$

$$= 416 \text{ N upwards}$$

3. Use Newton's second law to calculate the acceleration.

$$F_{\text{net}} = ma$$

$$416 = 80a$$

$$a = \frac{416}{80}$$

$$= 5.2 \text{ m s}^{-2} \text{ upwards}$$

Her acceleration at that instant is 5.2 m s^{-2} .

4. State the solution.

- b. 1. If the jumper's acceleration were constant, one of the constant acceleration formulae could be used to answer this question. Assign down as positive for this part of the question as the bungee jumper has a downwards initial velocity and displacement during the time period being considered.

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

$$u = 16 \text{ m s}^{-1}, v = 0, a = -5.2 \text{ m s}^{-2}, s = ?$$

2. Substitute the values into the formula and solve for s .

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

$$0 = 16^2 + 2 \times -5.2 \times s$$

$$0 = 256 - 10.4s$$

$$10.4s = 256$$

$$s = \frac{256}{10.4}$$

$$\approx 24 \text{ m}$$

3. State the solution.

The bungee jumper will not stop in time. However, don't be upset. In practice, the acceleration of the bungee jumper would not be constant. The tension in the cord would increase as she fell. Therefore, the net force on her would increase and her upwards acceleration would be greater in magnitude than the calculated value. She will therefore almost certainly come to a stop in a distance considerably less than that calculated.

PRACTICE PROBLEM 5

A 1200-kilogram sports car is testing its brakes by driving at a constant speed of 100 km h^{-1} and then braking hard. To pass the test it needs to come to a complete stop in a distance of 50 metres.

If the friction is a constant 1000 N, what force do the brakes need to apply for the sports car to pass the test?

SAMPLE PROBLEM 6

A waterskier of mass 80 kilograms, starting from rest, is pulled in a northerly direction by a horizontal rope with a constant tension of 240 N. After 6 seconds, he has reached a speed of 12 m s^{-1} .

- What is the net force on the skier?
- If the tension in the rope were the only horizontal force acting on the skier, what would his acceleration be?
- What is the sum of the resistance forces on the skier?

 Teacher-led video: SP6 (tlvd-0081)

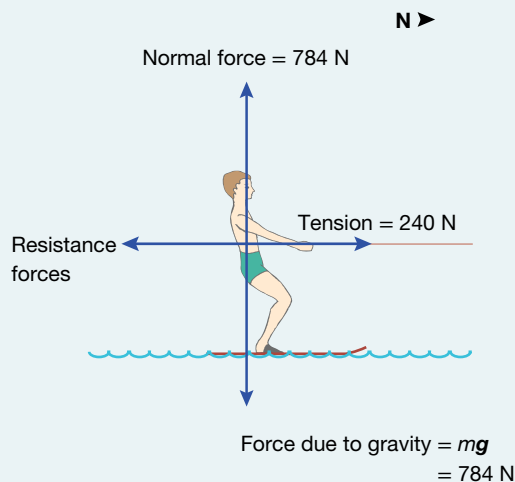
THINK

- a. 1. A good first step is to draw a labelled force diagram.

The force due to gravity can be calculated by the formula $F_g = mg$.

WRITE

$$\begin{aligned} \text{a. } F_g &= mg \\ &= 80 \times 9.8 \\ &= 784 \text{ N} \end{aligned}$$



2. The net force cannot be determined by adding the individual force vectors because the resistance forces are not given, nor is there any information in the question to suggest that they can be ignored.

To calculate the net force we will first need to find the acceleration.

3. Use Newton's second law to calculate the net force.

4. State the solution.

$$\begin{aligned} v &= u + at \\ 12 &= 0 + a \times 6 \\ a &= \frac{12}{6} \\ &= 2 \text{ m s}^{-2} \text{ north} \end{aligned}$$

$$\begin{aligned} F_{\text{net}} &= ma \\ &= 80 \times 2 \\ &= 160 \text{ N north} \end{aligned}$$

The net force on the skier is 160 N north.

- b. 1. As the vertical forces cancel out, the net force is determined by the horizontal forces. If the tension were the only horizontal force acting on the skier it would be the net force.

2. Use Newton's second law to calculate the acceleration.

3. State the solution.

- c. 1. The sum of the resistance forces (friction caused by the water surface and air resistance) on the skier is the difference between the net force and the tension.

2. State the solution.

b. $F_{\text{net}} = 240 \text{ N north}$

$$F_{\text{net}} = ma$$

$$240 = 80a$$

$$a = \frac{240}{80}$$

$$= 3 \text{ m s}^{-2} \text{ north}$$

If the tension in the rope were the only horizontal force acting on the skier, his acceleration would be 3 m s^{-2} north.

c. sum of resistance forces = $F_{\text{net}} - \text{tension}$
 $= 160 \text{ N north} - 240 \text{ N north}$
 $= 80 \text{ N south}$

The sum of the resistance forces on the skier is 80 N south .

PRACTICE PROBLEM 6

A loaded sled with a mass of 60 kilograms is being pulled across a level snow-covered field with a horizontal rope. It accelerates from rest over a distance of 9 metres, reaching a speed of 6 m s^{-1} . The tension in the rope is a constant. The frictional force on the sled is 200 N. Air resistance is negligible.

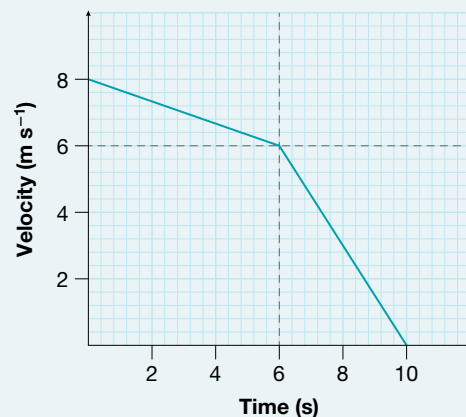
- a. What is the acceleration of the sled?
 b. What is the magnitude of the tension in the rope?

SAMPLE PROBLEM 7

The following velocity-versus-time graph describes the motion of a 45-kilogram girl on rollerblades as she rolls on a horizontal concrete path for 6 seconds before crossing onto a rough horizontal gravel path for the remaining 4 seconds.

- a. What was the magnitude of the net force on the girl on the concrete surface?
 b. If the only horizontal force acting on the blades is the friction force applied by the path, what is the value of the following ratio?

$$\frac{\text{friction force of gravel path on rollerblades}}{\text{friction force of concrete path on rollerblades}}$$



THINK

a. 1. The acceleration of the girl while she was on the concrete surface is given by the gradient of the corresponding section of the velocity-versus-time graph.

2. Use Newton's second law to calculate the magnitude of the net force on the girl while on the concrete surface.

3. State the solution.

b. 1. If the only horizontal force acting on the rollerblades is friction, the net force on the girl is the same as the friction force on the blades.

2. Apply Newton's second law and cancel out common terms.

3. Use the gradient of the graph to evaluate the ratio of accelerations.

4. State the solution.

WRITE

$$\begin{aligned} \text{a. } a &= \frac{\text{rise}}{\text{run}} \\ &= \frac{-2}{6} \\ &= \frac{-1}{3} \text{ m s}^{-2} \end{aligned}$$

$$\begin{aligned} F_{\text{net}} &= ma \\ &= 45 \times \frac{-1}{3} \\ &= -15 \text{ N} \end{aligned}$$

The magnitude of the net force on the girl on the concrete surface is -15 N .

b.
$$\frac{\text{friction force of gravel path on rollerblades}}{\text{friction force of concrete path on rollerblades}}$$

$$= \frac{F_{\text{net on girl while on gravel}}}{F_{\text{net on girl while on concrete}}}$$

$$\begin{aligned} \frac{F_{\text{net on girl while on gravel}}}{F_{\text{net on girl while on concrete}}} &= \frac{ma \text{ on gravel}}{ma \text{ on concrete}} \\ &= \frac{a \text{ (during last 4 s)}}{a \text{ (during first 6 s)}} \end{aligned}$$

$$\begin{aligned} \frac{a \text{ (during last 4 s)}}{a \text{ (during first 6 s)}} &= \frac{\text{gradient (for last 4 s)}}{\text{gradient (for first 6 s)}} \\ &= \frac{\left(\frac{-6}{4}\right)}{\left(\frac{-1}{3}\right)} \\ &= \frac{36}{8} \\ &= 4.5 \end{aligned}$$

The value of the ratio is 4.5.

PRACTICE PROBLEM 7

If the velocity-time graph in Sample problem 7 was applied to a car of mass 1200 kg on two road surfaces, what net force (in magnitude) acts on the car during:

a. the first 6 seconds

b. the final 4 seconds?

10.4.2 Falling down

Objects that are falling (or rising) through the air in the atmosphere near the surface of Earth are subjected to two forces — the force due to gravity and air resistance. The force due to gravity of the object is effectively constant. The magnitude of the air resistance, however, is not constant. It depends on many

factors, including the object's speed, surface area and density. It also depends on the density of the body of air through which the object is falling. The air resistance is always opposite to the direction of motion. The net force on a falling object of mass m and force due to gravity F_g can therefore be expressed as:

$$F_{\text{net}} = ma \text{ (where } a \text{ is the acceleration of the object)}$$

$$F_g - \text{air resistance} = ma$$

When dense objects fall through small distances near the surface of the Earth it is usually quite reasonable to assume that the air resistance is negligible. Thus:

$$\begin{aligned} F_g &= ma \\ \Rightarrow mg &= ma \text{ (where } g \text{ is the gravitational field strength)} \\ \Rightarrow g &= a \end{aligned}$$

The acceleration of a body in free fall in a vacuum or where air resistance is negligible is equal to the gravitational field strength. At the Earth's surface, where $g = 9.8 \text{ N kg}^{-1}$, this acceleration is 9.8 m s^{-2} . The units N kg^{-1} and ms^{-2} are equivalent.

$$\begin{aligned} 1 \text{ N} &= 1 \text{ kg m s}^{-2} \\ \Rightarrow 1 \text{ N kg}^{-1} &= 1 \text{ kg m s}^{-2} \text{ kg}^{-1} \text{ (multiplying both sides by } \text{kg}^{-1}) \\ \Rightarrow 1 \text{ N kg}^{-1} &= 1 \text{ m s}^{-2} \end{aligned}$$

TERMINAL VELOCITY

Terminal velocity is reached when the forces acting on a falling object are balanced and it stops accelerating. When considering objects falling vertically downwards in the atmosphere near the surface of the Earth, the two forces are air resistance or drag, F_D , acting to oppose the motion of the object and the force due to gravity, F_g , acting vertically downwards.

The force due to gravity and air resistance in balance when an object is at terminal velocity.

The force due to gravity, F_g , depends only on the mass of the object, m , and the gravitational field strength, g , which can both be assumed to be roughly constant during the fall of an object near the surface of Earth.

The air resistance or drag, F_D , acting on an object depends on a number of factors:

- C_D is the drag coefficient, which measures the ease with which air can move over an object. In simple terms this indicates how streamlined an object is. This is a constant value for a particular object shape and orientation and is often determined experimentally or via computer analysis.

FIGURE 10.12 Skydivers accelerate until the drag force equals the force due to gravity, at terminal velocity.



- ρ is the air density measured in kg m^{-3} , which can be assumed to be constant, however, in reality it will vary with altitude, temperature, humidity and pressure.
- v is the velocity that the object is moving through the air measured in m s^{-1} .
- A is the cross-sectional or reference area that is perpendicular to the direction of motion of the object measured in m^2 . For an object falling vertically this will be the horizontal cross-section.

When terminal velocity occurs these two forces must be in balance (net force is zero, acceleration is zero).

$$F_D = F_g$$

$$\frac{1}{2} C_D \rho v^2 A = mg$$

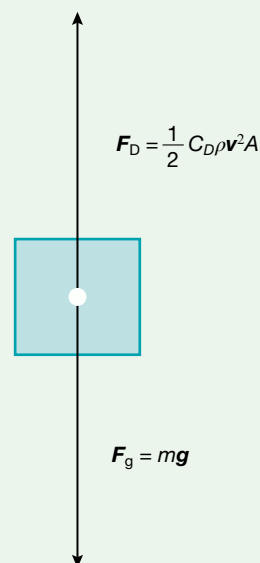
This can be rearranged to determine a relationship for the terminal velocity.

$$v = \sqrt{\frac{2mg}{C_D \rho A}}$$

Provided that reasonable estimates can be made of the quantities involved, this relationship can be used to calculate the theoretical terminal velocity of falling objects. This can provide an interesting focus for an extended practical investigation.

FIGURE 10.13

Forces acting on a falling object at terminal velocity



If a bowling ball, a golf ball and a table tennis ball were dropped at the same instant from a height of 2 metres in a vacuum, they would all reach the ground at the same time. Each ball would have an initial velocity of zero, an acceleration of 9.8 m s^{-2} and a downward displacement of 2 metres.

If, however, the balls are dropped either in a classroom or outside, the table tennis ball will reach the ground a moment later than the other two balls.

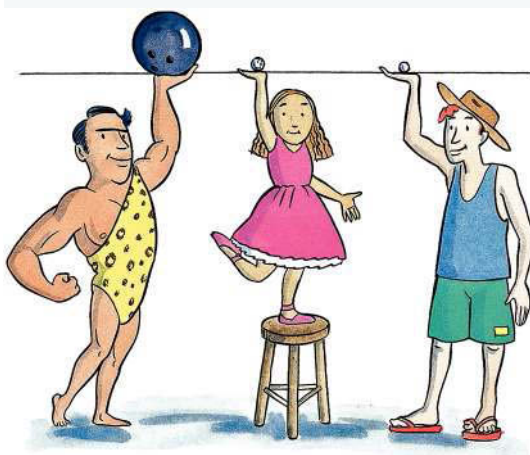
The acceleration of each of the balls is:

$$\begin{aligned} a &= \frac{F_{\text{net}}}{m} \\ &= \frac{mg - F_D}{m} \\ &= \frac{mg}{m} - \frac{F_D}{m} \quad (\text{where } F_D \text{ is air resistance}) \\ &= g - \frac{F_D}{m} \end{aligned}$$

$\frac{F_D}{m}$ is very small for the bowling ball and the golf ball.

Even though the air resistance on the table tennis ball is small, its mass is also small and $\frac{F_D}{m}$ is not as small as it is for the other two balls.

FIGURE 10.14 A bowling ball, a golf ball and a table tennis ball dropped from a height of 2 metres. Which one would you expect to reach the ground first?



WARNING: Do not drop a bowling ball from a height of 2 metres indoors. If you wish to try this experiment, replace the bowling ball with a medicine ball and keep your feet out of the way!

 **Digital document** Simulation of basketball throw (doc-0052)

 **Video eLesson** Air resistance (eles-0035)

10.4 EXERCISE

To answer questions online and to receive **immediate feedback** and **sample responses** for every question go to your learnON title at www.jacplus.com.au.

1. What is an idealisation? Provide an example of an idealism that could be used to simplify a physics problem.
2. When a space shuttle takes off, its initial acceleration is 3.0 m s^{-2} . It has an initial mass of about $2.2 \times 10^6 \text{ kg}$.
 - (a) Determine the magnitude of the net force on the space shuttle as it takes off.
 - (b) What is the magnitude of the upward thrust as it takes off?
3. A 6 kilogram bowling ball and a 60 kilogram gold bar are dropped at the same instant from the third floor of the Leaning Tower of Pisa. Use Newton's second law to explain why:
 - (a) they both reach the ground at the same time
 - (b) a 6 kilogram doormat dropped from the same location at the same time takes significantly longer to reach the ground.
4. A bungee jumper with a mass of 70 kilograms leaps from a bridge.
 - (a) What is the force due to gravity acting on the bungee jumper?
 - (b) During which part of the jump is:
 - i. the upwards force on the jumper due to the tension in the bungee cord greater than force due to gravity on the jumper
 - ii. the force due to gravity on the jumper greater than the upward pull of the bungee cord?
 - (c) What tension in the bungee cord is needed for the jumper to travel at a constant speed? Does this occur at any time during the jump? Explain.
5. A car of mass 1200 kilograms starts from rest on a horizontal road with a forward driving force of 10 000 N. The resistance to motion due to road friction and air resistance totals 2500 N.
 - (a) What is the magnitude of the net force on the car?
 - (b) What is the magnitude of the acceleration of the car?
 - (c) What is the speed of the car after 5 seconds?
 - (d) How far has the car travelled after 5 seconds?
6. A train of mass 8.0×10^6 kilograms travelling at a speed of 25 m s^{-1} is required to stop over a maximum distance of 360 metres. What frictional force must act on the train when the brakes are applied if the train is to do this?
7. A short-sighted skier of mass 70.0 kilograms suddenly realises while travelling at a speed of 12.0 m s^{-1} that there is a steep cliff 50.0 metres straight ahead. What frictional force is required on the skier if he is to stop just before he skis off the edge of the cliff?
8. A physics teacher decides, just for fun, to stand on some bathroom scales (calibrated in newtons) in a lift. The scales provide a measure of the force with which they push up on the teacher. When the lift is stationary, the reading on the bathroom scales is 700 N. What will be the reading on the scales when the lift is:
 - (a) moving upwards at a constant speed of 2.0 m s^{-1}
 - (b) accelerating downwards at 2.0 m s^{-2}
 - (c) accelerating upwards at 2.0 m s^{-2} ?
9. The cable holding a lift would break if the tension in it were to exceed 25 000 N. If the 480 kilograms lift has a load limit of 24 passengers whose average mass is 70 kilograms, what is the maximum possible upwards acceleration of the lift without breaking the cable?
10. A ball of mass 0.50 kilograms is thrown vertically upwards.
 - (a) What is the velocity of the ball at the top of its flight?
 - (b) What is the magnitude of the ball's acceleration at the top of its flight?
 - (c) What is the net force on the ball at the top of its flight?

10.5 Newton's Third Law of Motion

KEY CONCEPTS

- Apply Newton's three laws of motion to a body on which forces act: $\mathbf{a} = \frac{\mathbf{F}_{\text{net}}}{m}$, $\mathbf{F}_{\text{on A by B}} = -\mathbf{F}_{\text{on B by A}}$.
- 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 $\mathbf{F}_{\text{on A by B}} = -\mathbf{F}_{\text{on B by A}}$.

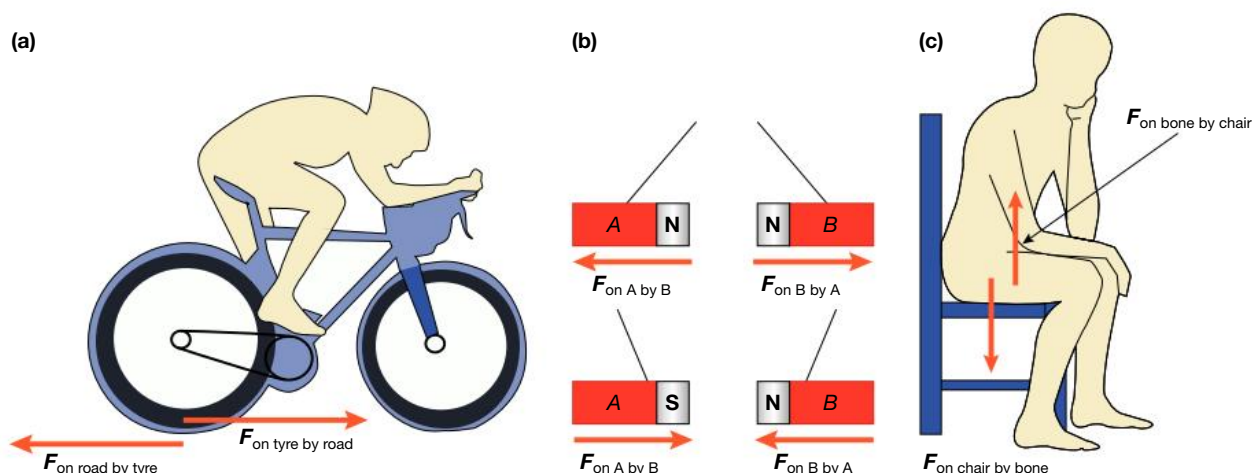
10.5.1 Forces in pairs

To explain the motion of everyday objects, Isaac Newton devised some basic principles. A key starting point is the nature of force. Newton said that forces always act in pairs. Forces explain the interaction between two objects. Each object acts on the other, so where there is one force by one object, there is always another force by the other object.

Examples of forces in pairs include:

- *bicycle back tyre*. The action of the pedals push the tyre backwards against the road surface. The frictional interaction between the tyre and the road results in a forward force by the road on the tyre.
- *two suspended magnets*. In the top diagram in figure 10.15b, each magnet is pushing the other away. In the bottom diagram, each is pulling the other towards it.
- *sitting in a chair*. The normal force from the chair pushes up on the bones in the pelvis and the compressed bone pushes down. This compression is what you feel when you are sitting.

FIGURE 10.15 Forces act in pairs



The pairing of these forces is apparent in the symmetry of their labels. If the label for one force is $F_{\text{on B by A}}$, then the label for the other is $F_{\text{on A by B}}$. It is important to note that in these pairs of forces, the forces act on different objects.

Newton not only identified forces acting in pairs, he also said that these two forces act in opposite directions and are equal in magnitude or size. This statement became Newton's Third Law of Motion. Figure 10.15

Newton's Third Law of Motion:

If object B applies a force to object A, then object A applies an equal and opposite force to object B.

$$\vec{F}_{\text{on A by B}} = -\vec{F}_{\text{on B by A}}$$

This symmetry between the pair of forces can be used to identify the other of the pair if only one is given.

on Resources

 **Digital document** eModelling: Skydiver spreadsheet (doc-0054)

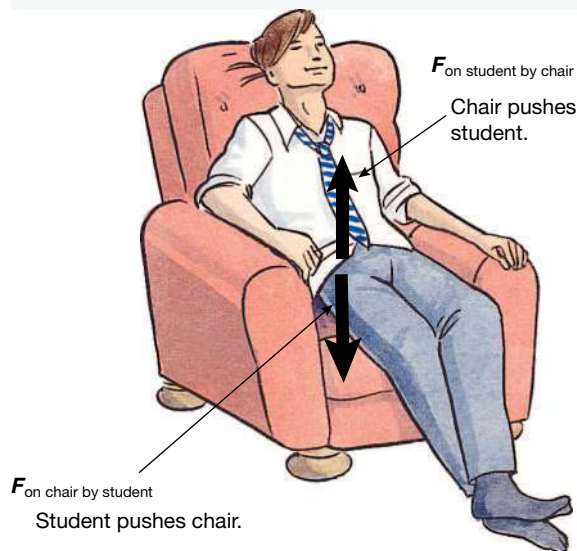
REACTION OR NORMAL FORCE?

Some texts summarise Newton's third law as 'For every action, there is an equal and opposite reaction'. This version is not preferred. The word 'reaction' here has a different meaning to its use in 'normal force'. The statement also implies one force in the pair is a response to the other, which is incorrect.

There are four forces acting as two force pairs when you sit on a comfortable chair. The Earth pulls down on you, compressing the springs and foam, and the compressed springs and foam push up on you, compressing the bones in your pelvis. So, one force pair is the upward push by the springs on you and the downward push by the bones in your pelvis on the chair. The second force pair is the Earth pulling down on you and you pulling the Earth upwards.

The net force on a person sitting in a chair is the vector sum of all the forces acting on the person. The net force is zero because the upward push by the chair, $F_{\text{on student by chair}}$, is balanced by the downward, and of equal size, pull of the force of gravity, $F_{\text{on chair by student}}$.

FIGURE 10.16 Forces while sitting



SAMPLE PROBLEM 8

Two ice skaters, Jack and Jill, push each other away. The figure on the right shows the force on Jill by Jack with a black arrow. Draw an arrow and label it to show the force on Jack by Jill.



THINK

1. Recall Newton's Third Law of Motion.
2. Draw the force on Jack by Jill as an arrow of equal length in the opposite direction.

WRITE

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



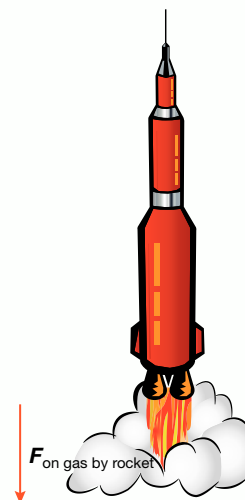
PRACTICE PROBLEM 8

Draw and label arrows for the other forces in the following force pairs.

a.



b.



c.



d.



10.5.2 Moving forward

The rowing boat in figure 10.17 is propelled forward by the push of water on the oars. As the face of each oar pushes back on the water, the water pushes back with an equal and opposite force on each oar. The push by the oars, which are held tightly by the rowers, propels the rowers and their boat forward. A greater push on the water results in a greater push on the oar.

In fact, none of your forward motion, whether you are on land, water or in the air, could occur without a third law force pair.

- When you swim, you push the water backwards with your hands, arms and legs. The water pushes in the opposite direction, propelling you forwards.
- In order to walk or run, you push your feet backwards and down on the ground. The ground pushes in the opposite direction, pushing forwards and up on your feet.
- The forward driving force on the wheels of a car is the result of a push back on the road by the wheels.
- A jet or a propeller-driven plane is thrust forwards by air. The jet engines or propellers are designed to push air backwards with a very large force. The air pushes forward on the plane with an equally large force.

FIGURE 10.17 This rowing team relies on a reaction force to propel itself forward.



on Resources

-  **Video eLesson** Newton's laws (eles-0036)
-  **Interactivity** Newton's laws (int-0055)

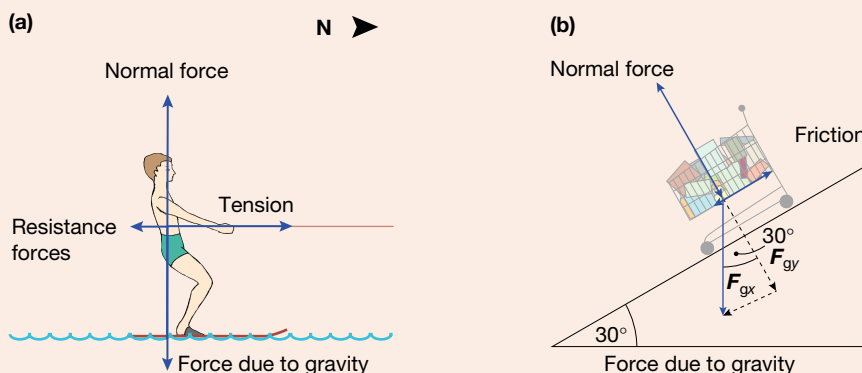
10.5 EXERCISE

To answer questions online and to receive **immediate feedback** and **sample responses** for every question go to your learnON title at www.jacplus.com.au.

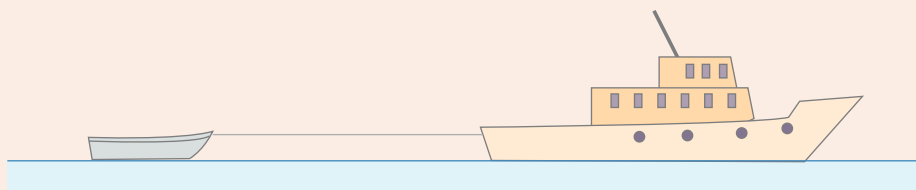
- Copy the following table into your workbook. Describe fully the missing half of the following force pairs.

Force 1	Pair of force 1
You push on a wall with the palm of your hand.	
Your foot pushes down on a bicycle pedal.	
The ground pushes up on your feet while you are standing.	
The Earth pulls down on your body.	
You push on a broken-down car to try to get it moving.	
A hammer pushes down on a nail.	

- Label all of the forces in the following figures in the form $F_{\text{on A by B}}$.



- Identify the force pairs in the following figure.



- Explain, in terms of Newton's first and third laws, why a freestyle swimmer moves faster through the water than a breaststroke swimmer.
- A student says that the friction forces on the front and back tyres of a car are an example of Newton's Third Law of Motion. Is the student correct? Explain.

studyon

To answer practice exam questions online and to receive immediate feedback and sample responses for every question go to your learnON title at www.jacplus.com.au.

studyON: Practice exam questions online only

Fully worked solutions and sample responses are available in your digital formats.

10.6 Forces in two dimensions

KEY CONCEPTS

- Apply Newton's three laws of motion to a body on which forces act: $\mathbf{a} = \frac{\mathbf{F}_{\text{net}}}{m}$, $\mathbf{F}_{\text{on A by B}} = -\mathbf{F}_{\text{on B by A}}$.
- 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 $\mathbf{F}_{\text{on A by B}} = -\mathbf{F}_{\text{on B by A}}$.

10.6.1 Vehicles on horizontal surfaces

The forces acting on a car being driven along a straight horizontal road are:

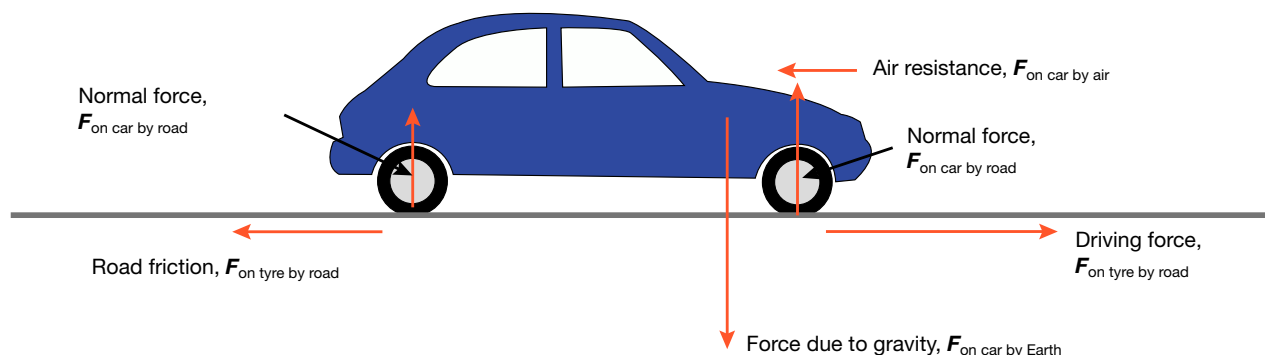
- *force due to gravity.* The force applied by the Earth on the car acts through the centre of mass, or balancing point, of the car. This is normally closer to the front of the car than the back due to the significant mass of the engine. A medium sized sedan containing a driver and passenger will experience a force due to gravity of about $1.5 \times 10^4 \text{ N}$.
- *the normal force.* The force applied on the car by the road is a reaction to the force applied on the road by the car. A normal force pushes up on all four wheels. Its magnitude is normally greater at the front wheels than the rear wheels. On a horizontal road, the sum of these normal forces has the same magnitude as the force due to gravity. What do you think would happen if this were not the case?
- *the driving force.* This is provided by the road and is applied to the driving wheels. The driving wheels are turned by the motor. In most cars, either the front wheels or the rear wheels are the driving wheels. The motor of a four-wheel-drive vehicle turns all four wheels. As a tyre on a driven wheel pushes back on the road, the road pushes forward on the tyre, propelling the car forward. The forward push of the road on the tyre is a type of friction commonly referred to as traction, or grip. If the tyres do not have enough tread, or the road is icy, there is not enough friction to push the car forward and the tyre slides on the road. The wheel spins and the car skids. The car cannot be propelled forward as effectively. Skidding also occurs if the motor turns the driving wheels too fast.
- *road friction.* This is the retarding force applied by the road on the tyres of the non-driving wheels. The non-driving wheels of front-wheel-drive cars roll as they are pulled along the road by the moving car. In older cars, the non-driving wheels are usually at the front. They are pushed along the road by the moving car. Rolling friction acts on the non-driving wheels in a direction opposite to the direction of the car's movement. When the driving wheels are not being turned by the motor, rolling friction opposes the forward movement of all four wheels. When the brakes are applied, the wheels to which the brakes are attached are made to turn too slowly for the speed at which the car is moving. They are no longer rolling freely. This increases the road friction greatly and the car eventually stops. If the brakes are applied hard enough, the wheels stop completely, or lock, and the car goes into a skid. The sliding friction that exists when the car is skidding is less than the friction that exists when the wheels are rolling just a little.
- *air resistance.* The drag, or air resistance acting on the car, increases as the car moves faster. As a fluid friction force, air resistance can be reduced by streamlining the vehicle.

The net force acting on the car in figure 10.18 is zero. It is therefore moving along the road at constant speed. We know that it is moving to the right because both the air resistance and road friction act in a direction opposite to that of motion. If the car were stationary, neither of these forces would be acting at all.

- If the driving force were to increase, the car would speed up until the sum of the air resistance and road friction grew large enough to balance the driving force. Then, once again, the car would be moving at a constant, although higher, speed.
- If the driver stopped pushing down on the accelerator, the motor would stop turning the driving wheels and the driving force would become zero. The net force would be to the left. As the car slowed down,

the air resistance and road friction would gradually decrease until the car came to a stop. The net force on the car would then be zero until such time as the driving force was restored.

FIGURE 10.18 Forces acting on a car. The state of motion of a front-wheel-drive car on a horizontal road depends on the net force acting on it.



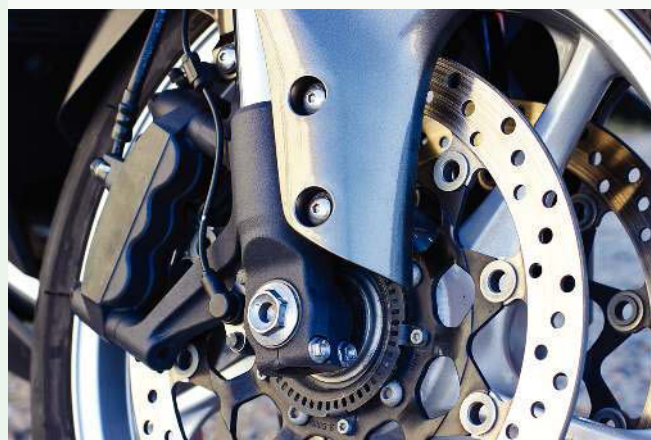
COMPUTER CONTROLLED BRAKE SYSTEMS

An anti-lock brake system (ABS) allows the wheels to keep rolling no matter how hard the brakes are applied. A small computer attached to the braking system monitors the rotation of the wheels. If the wheels lock and rolling stops, the pressure on the brake pads (or shoes) that stops the rotation is reduced briefly. This action is repeated up to 15 times each second. Anti-lock brake systems are most effective on wet roads. However, even on a dry surface, braking distances can be reduced by up to 20%.

When brakes in an older car without ABS are applied too hard, as they often are when a driver panics, the wheels lock. The resulting sliding friction is less than the friction acting when the wheels are still rolling. The car skids, steering control is lost and the car takes longer to stop than if the wheels were still rolling. Before ABS became commonplace, drivers were often advised to 'pump' the brakes in wet conditions to prevent locking. This involves pushing and releasing the brake pedal in quick succession until the car stops. This, however, is very difficult to do in an emergency situation.

Since the advent of ABS, a myriad additional computer controlled systems have been developed to improve safety when braking. One such system, often referred to as Brake Assist monitors the application of force to the brake pedal to detect an emergency and apply additional brake pressure. More advanced systems use a range of technology to monitor conditions on the road ahead and can warn the driver to apply the brakes and in some systems even apply the brakes automatically if there is no driver response. The development of systems such as these over recent decades has been a vital precursor to the rapid development of autonomous cars that is underway at present.

FIGURE 10.19 ABS on a motorcycle



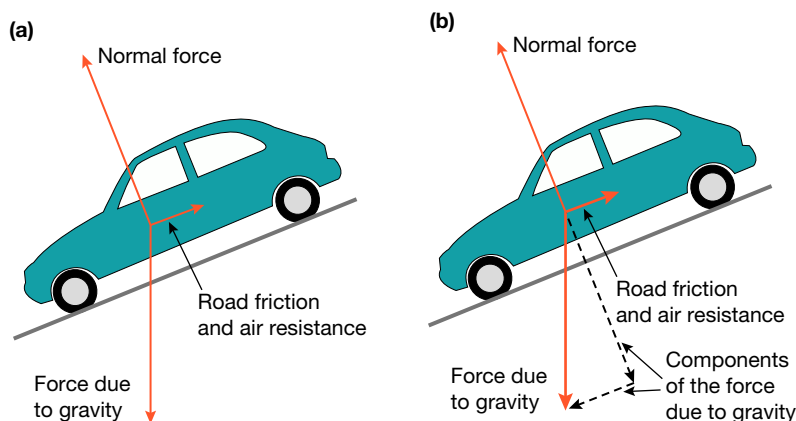
on Resources

 **Digital document** Investigation 10.4 Static, sliding and rolling friction (doc-32309)

10.6.2 Vehicles on inclined planes

A car left parked on a hill will begin to roll down the hill with increasing speed if it is left out of gear and the handbrake is off. Figure 10.20a shows the forces acting on such a car. In order to simplify the diagram, all of the forces are drawn as if they were acting through the centre of mass of the car. The forces on the car can then be modelled as acting on a single point. The direction of net force acting on the car is down the hill. It is clear that the force of gravity is a major contributor to the downhill motion of the car.

FIGURE 10.20 (a) A simplified diagram of the forces acting on a car rolling down a slope (b) Vectors can be resolved into components. In this case, the force due to gravity has been resolved into two components. The net force is parallel to the slope.

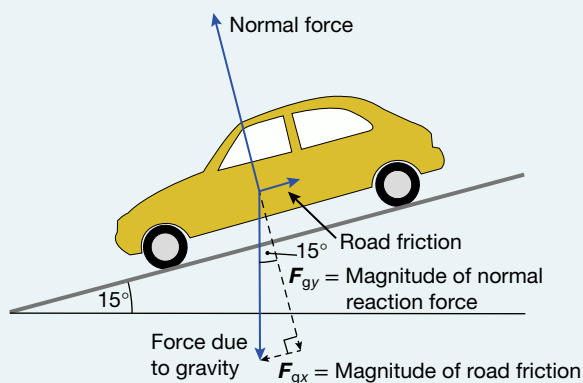


It is often useful to divide vectors into parts called **components**. Figure 10.20b shows how the force due to gravity can be broken up, or resolved, into two components — one parallel to the slope and one perpendicular to the slope. Notice that the vector sum of the components is the force due to gravity. By resolving it into these two components, two useful observations can be made:

1. The normal force is balanced by the component of force due to gravity that is perpendicular to the surface. The net force has no component perpendicular to the road surface. This must be the case because there is no change in motion perpendicular to the slope.
2. The magnitude of the net force is simply the difference between the magnitude of the component of the force due to gravity that is parallel to the surface and the sum of the road friction and air resistance.

SAMPLE PROBLEM 9

A car of mass 1600 kilograms left parked on a steep but rough road begins to roll down the hill. After a short while it reaches a constant speed. The road is inclined at 15° to the horizontal. The car's speed is sufficiently slow that the air resistance is insignificant and can be ignored. Determine the magnitude of the road friction on the car while it is rolling at constant speed.



Teacher-led video: SP9 (tlvd-0084)

THINK

1. Because the car is rolling at constant speed, the net force acting on it is zero.
2. As the net force is zero, the magnitude of the friction must be equal to the magnitude of the force due to gravity that is in the direction of the slope.
3. The force due to gravity in the direction of the slope can be calculated using the trigonometric ratio sine.
4. The force due to gravity can be found using the formula $F_g = mg$.
5. Substitute the force due to gravity into the formula for F_{gx} .

WRITE

$$F_{\text{net}} = 0$$

$$\text{Friction} = F_{gx}$$

$$\sin 15^\circ = \frac{F_{gx}}{F_g}$$

$$F_{gx} = F_g \sin(15^\circ)$$

$$\begin{aligned} F_g &= mg \\ &= 1600 \times 9.8 \\ &= 15\,680 \text{ N} \end{aligned}$$

$$\begin{aligned} F_{gx} &= F_g \sin(15^\circ) \\ &= 15\,680 \sin(15^\circ) \\ &\approx 4058 \text{ N} \end{aligned}$$

The road friction on the car is 4058 N.

Note: It is useful to consider the effect on the net force of the angle of the incline to the horizontal. If the angle is greater than 15° , the component of the force due to gravity parallel to the slope increases and the net force will no longer be zero. The speed of the car will therefore increase. The component of the force due to gravity perpendicular to the slope decreases and the normal force decreases by the same amount.

PRACTICE PROBLEM 9

- a. A 5000-kilogram truck is parked on a road surface inclined at an angle of 20° to the horizontal. Calculate the component of the force due to gravity on the truck that is:
 - i. down the slope of the road
 - ii. perpendicular to the slope of the road.
- b. In the case of the car in Sample problem 9, what is:
 - i. the component down the road surface of the normal force acting on it
 - ii. the normal force?

SAMPLE PROBLEM 10

A loaded supermarket shopping trolley with a total mass of 60 kilograms is left standing on a footpath that is inclined at an angle of 30° to the horizontal. As the tired shopper searches for his car keys, he fails to notice that the trolley is beginning to roll away. It rolls in a straight line down the footpath for 9 seconds before it is stopped by an alert (and very strong) supermarket employee. Find the:

- speed of the shopping trolley at the end of its roll
- distance covered by the trolley during its roll.

Assume that the footpath exerts a constant friction force of 270 N on the runaway trolley.

 **Teacher-led video:** SP10 (tlvd-0085)

THINK

1. Draw a diagram to show the three forces acting on the shopping trolley. Air resistance is not included as it is negligible. The forces should be shown as acting through the centre of mass of the loaded trolley as in the figure on the right. The components of the force due to gravity, which are parallel and perpendicular to the footpath surface, should also be shown on the diagram.

2. Calculate the net force.

3. Use Newton's second law to calculate the acceleration.

4. Use a constant acceleration formula to calculate the final speed.

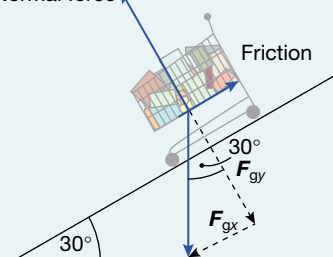
5. State the solution.

1. Use a constant acceleration formula to calculate the distance covered by the trolley.

2. State the solution.

WRITE

- a. Normal force



$$\begin{aligned}\text{Force due to gravity} &= mg \\ &= 588 \text{ N}\end{aligned}$$

$$\begin{aligned}F_{\text{net}} &= F_{\text{gx}} - \text{friction} \\ &= mg \sin(30^\circ) - 270 \text{ N} \\ &= 588 \text{ N} \sin(30^\circ) - 270 \text{ N} \\ &= 294 \text{ N} - 270 \text{ N} \\ &= 24 \text{ N}\end{aligned}$$

$$\begin{aligned}F_{\text{net}} &= ma \\ 24 &= 60a \\ a &= \frac{24}{60} \\ &= 0.4 \text{ m s}^{-2} \text{ down the slope}\end{aligned}$$

$$\begin{aligned}v &= u + at \\ &= 0 + 0.4 \times 9 \\ &= 3.6 \text{ m s}^{-1}\end{aligned}$$

The speed of the trolley at the end of its roll is 3.6 m s^{-1} .

$$\begin{aligned}\text{b. } s &= ut + \frac{1}{2}at^2 \\ &= 0 + \frac{1}{2} \times 0.4 \times 9^2 \\ &= 16.2 \text{ m}\end{aligned}$$

The trolley travels 16.2 metres before it is stopped.

PRACTICE PROBLEM 10

A cyclist rolls freely from rest down a slope inclined at 20° to the horizontal. The total mass of the bicycle and cyclist is 100 kilograms. The bicycle rolls for 12 seconds before reaching a horizontal surface. The surface exerts a constant friction force of 300 N on the bicycle.

- What is the net force on the bicycle (including the cyclist)?
- What is the acceleration of the bicycle?
- What is the speed of the bicycle when it reaches the horizontal surface?



Resources



Video eLesson Motion down an inclined plane (eles-0034)



Weblink Inclined plane

10.6.3 Connected objects

In many situations, Newton's laws need to be applied to more than one body.

Figure 10.21 shows a small dinghy being pulled by a larger boat. The forces acting on the larger boat are labelled in red, while the forces acting on the small dinghy are labelled in green. Newton's second law can be applied to each of the two boats separately.

FIGURE 10.21 The forces acting on each of the two boats

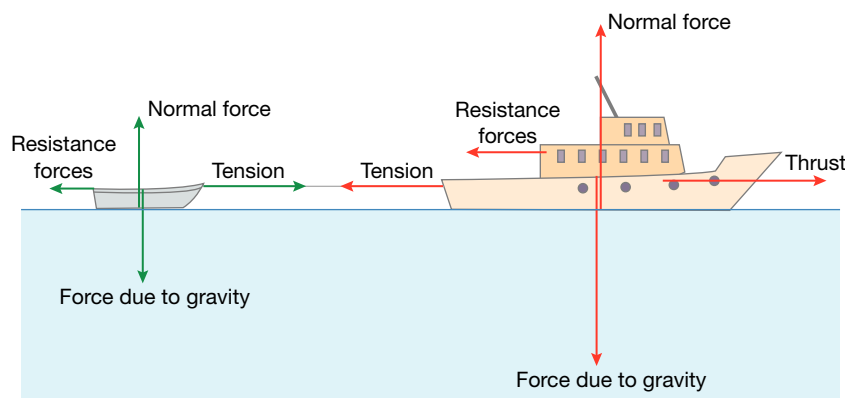
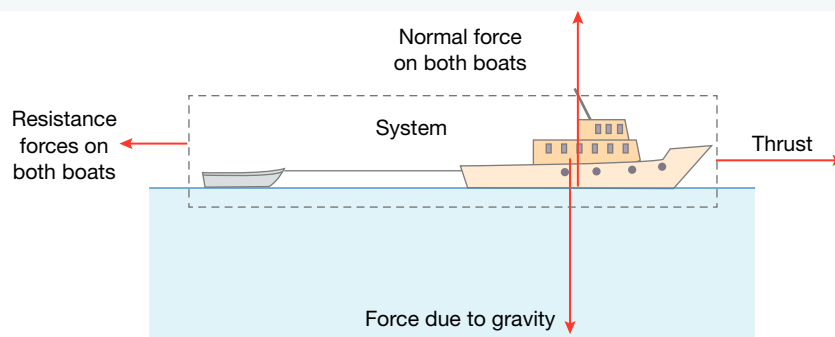


Figure 10.22 shows only the forces acting on the whole system of the two boats and the rope joining them. When Newton's second law is applied to the whole system, the system is considered to be a single object.

FIGURE 10.22 The forces acting only on the whole system. The system consists of the two boats and the rope joining them.



The thrust that acts on the larger boat and the system is provided by the water. The propeller of the larger boat pushes back on the water and the water pushes forwards on the propeller blades. The only force that can cause the small dinghy to accelerate forward is the tension in the rope.

If the tension in the rope is greater than the resistance forces on the dinghy, the dinghy will accelerate. If the tension in the rope is equal to the resistance forces on the dinghy, it will move with a constant velocity. If the tension in the rope is less than the resistance forces on the dinghy, it will slow down. That is, its acceleration will be negative.

The rope pulls back on the larger boat with the same tension that it applies in a forward direction on the small dinghy. This is consistent with Newton's third law. Through the rope, the larger boat pulls forward on the small dinghy with a force that is equal and opposite to the force with which the small dinghy pulls on the large boat.

SAMPLE PROBLEM 11

A car of mass 1400 kilograms towing a trailer of mass 700 kilograms accelerates at a constant rate on a horizontal road. A thrust of 5400 N is provided by the forward push of the road on the driving wheels of the car. The road friction on the car is 800 N, while that on the trailer is 400 N. The air resistance on both the car and the trailer is negligible. Determine the:

- acceleration of both the car and trailer
- force with which the trailer is pulled by the car (labelled P in the figure in the solution).

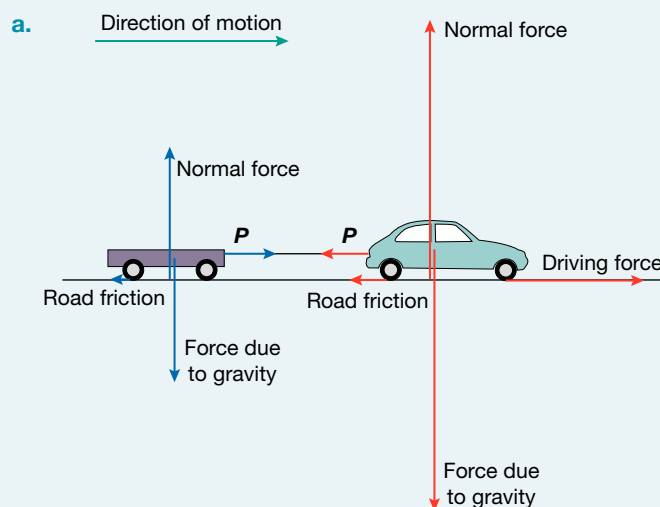
 Teacher-led video: SP11 (tlvd-0086)

THINK

1. Draw a diagram to show the forces acting on the car and trailer.

2. Consider the car and trailer as a system. The acceleration of the car and trailer can be calculated using Newton's second law if the net force on the system is known.
3. Use Newton's second law to calculate the acceleration.
4. State the solution.

WRITE



$$\begin{aligned}
 F_{\text{net}} &= \text{driving force} - \text{road friction (car)} \\
 &\quad - \text{road friction (trailer)} \\
 &= 5400 \text{ N} - 800 \text{ N} - 400 \text{ N} \\
 &= 4200 \text{ N}
 \end{aligned}$$

$$\begin{aligned}
 F_{\text{net}} &= ma \\
 4200 &= 2100a \\
 a &= \frac{4200}{2100} \\
 &= 2 \text{ m s}^{-2} \text{ to the right}
 \end{aligned}$$

The acceleration of both the car and trailer is 2 m s^{-2} to the right.

- b. 1. Calculate the force with which the trailer is pulled by the car, P , by considering the net force on the trailer.

2. State the solution.

$$\begin{aligned} \text{b. } F_{\text{net}} &= ma \\ P - 400 &= 700 \times 2 \\ P &= 700 \times 2 + 400 \\ P &= 1800 \text{ N} \end{aligned}$$

The force with which the trailer is pulled by the car is 1800 N.

PRACTICE PROBLEM 11

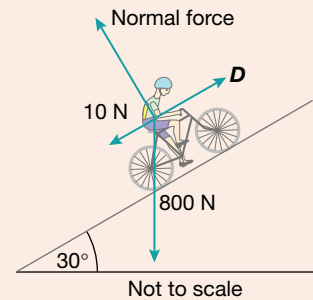
A boat of mass 2000 kilograms tows a small dinghy of mass 100 kilograms with a thick rope. The boat's propellers provide a forward thrust of 4700 N. The total resistance forces of air and water on the boat and dinghy system amount to 400 N and 100 N respectively.

- What is the acceleration of the boat and dinghy?
- What is the net force on the dinghy?
- What is the magnitude of the tension in the rope?

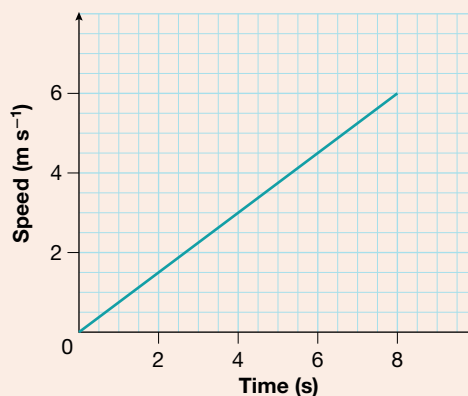
10.6 EXERCISE

To answer questions online and to receive **immediate feedback** and **sample responses** for every question go to your learnON title at www.jacplus.com.au.

- A ball rolls down a hill with an increasing speed.
 - Draw a diagram to show all of the forces acting on the ball.
 - What is the direction of the net force on the ball?
 - What is the largest single force acting on the ball?
 - When the ball reaches a horizontal surface, it slows, eventually coming to a stop. Explain, with the aid of a diagram, why this happens.
- When you try to push a broken-down car with its handbrake still on, it does not move. What other forces are acting on the car to produce a net force of zero?
- Redraw figure 10.18 for a car with rear-wheel drive.
- A cyclist of mass 60 kilograms is riding up a hill inclined at 30° to the horizontal at a constant speed. The mass of the bicycle is 20 kilograms. The figure on the right shows the forces acting on the bicycle–cyclist system.
 - What is the net force on the bicycle–cyclist system?
 - What is the magnitude of the component of the weight of the system that is parallel to the road surface?
 - The sum of the magnitudes of the road friction and air resistance on the system is 10 N. What is the magnitude of the driving force D ?
 - What is the magnitude of the normal force on the bicycle–cyclist system?
- An experienced downhill skier with a mass of 60 kilograms (including skis) is moving down a slope inclined at 30° with increasing speed. She is moving in a straight line down the slope.
 - What is the direction of the net force on the skier?
 - Draw a diagram showing the forces acting on the skier. Show all of the forces as if they were acting through her centre of mass.
 - What is the magnitude of the component of the skier's force due to gravity that is parallel to the slope?
 - If the sum of the forces resisting the movement of the skier down the slope is 8 N, what is the magnitude of the net force on her?
- A skateboarder of mass 60 kilograms accelerates down a slope inclined at an angle of 30° to the horizontal. Her acceleration is a constant 2.0 m s^{-2} . What is the magnitude of the friction force resisting her motion?
- A roller-coaster carriage (and occupants) with a total mass of 400 kilograms rolls freely down a straight track inclined at 40° to the horizontal with a constant acceleration. The frictional force on the carriage is a constant 180 N. What is the magnitude of the acceleration of the carriage?



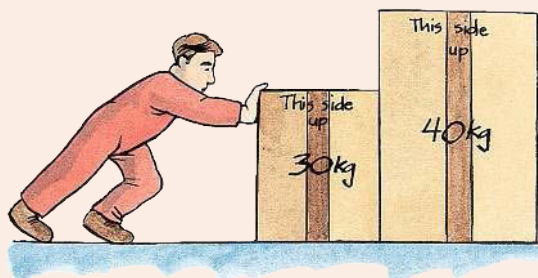
8. A skateboarder of mass 56 kilograms is rolling freely down a straight incline. The motion of the skateboarder is described in the graph on the right.
- What is the magnitude of the net force on the skateboarder?
 - If the friction force resisting the motion of the skateboarder is a constant 140 N, at what angle is the slope inclined to the horizontal?
9. What force provides the forward force that gets you moving when you are:
- ice skating
 - downhill skiing
 - waterskiing
 - skateboarding
 - swimming
 - rowing?



10. Front-wheel-drive cars have a number of advantages over rear-wheel-drive cars. Compare and comment on the forces acting on the tyres in the two different types of car while being driven at a constant speed on a horizontal road.
11. The magnitude of the force due to air resistance, R , on a car of mass 1200 kilograms can be approximated by the formula $R = 0.6v^2$, where R is measured in newtons and v is the speed of the car in m s^{-1} .
- Design a spreadsheet to calculate the magnitude of the force of air resistance and the net force on a car for a range of speeds as it accelerates from 20 km h^{-1} to 50 km h^{-1} on a horizontal road. Assume that, while accelerating, the driving force is a constant 1800 N and the road friction on the non-driving wheels is a constant 300 N.
 - Use your spreadsheet to plot a graph of the net force versus speed for the car.
 - Modify your spreadsheet to show how the net force on the car changes when the same acceleration from 20 km h^{-1} to 60 km h^{-1} is undertaken while driving down a road at an angle of 10° to the horizontal.
12. A well-coordinated rollerblader is playing with a yoyo while accelerating on a horizontal surface. When the yoyo is at its lowest point for several seconds, it makes an angle of 5° with the vertical. Determine the acceleration of the rollerblader.
13. A student argues that since there are friction forces on the front and back wheels of a bike that act in opposite directions, the bike cannot move. Explain how the bike moves.
14. Two loaded trolleys of masses 3.0 kilograms and 4.0 kilograms, which are joined by a light string, are pulled by a spring balance along a smooth, horizontal laboratory bench as shown in the following figure. The reading on the spring balance is 14 N.



- What is the acceleration of the trolleys?
 - What is the magnitude of the tension in the light string joining the two trolleys?
 - What is the net force on the 4.0 kilogram-trolley?
 - What would be the acceleration of the 4.0 kilogram trolley if the string was cut?
15. A warehouse worker applies a force of 420 N to push two crates across the floor as shown in the figure on the right. The friction force opposing the motion of the crates is a constant 2.0 N for each kilogram.
- What is the acceleration of the crates?
 - What is the net force on the 40-kilogram crate?
 - What is the force exerted by the 40-kilogram crate on the 30-kilogram crate?



- (d) What is the force exerted by the 30-kilogram crate on the 40-kilogram crate?
 (e) Would the worker find it any easier to give the crates the same acceleration if the positions of the two blocks were reversed? Support your answer with calculations.

studyon

To answer practice exam questions online and to receive immediate feedback and sample responses for every question go to your learnON title at www.jacplus.com.au.

studyON: Practice exam questions online only

Fully worked solutions and sample responses are available in your digital formats.

10.7 Momentum and impulse

KEY CONCEPTS

- Apply concepts of momentum to linear motion: $p = mv$.
- Explain changes in momentum as being caused by a net force: $F_{\text{net}} = \frac{\Delta p}{\Delta t}$.

10.7.1 Momentum

How difficult is it to stop a moving object? How difficult is it to make a stationary object move? The answer to both of these questions depends on two physical characteristics of the object:

- the object's mass
- how fast the object is moving, or how fast you want it to move.

The product of these two physical characteristics is called **momentum**.

The momentum, $\vec{p}$, of an object of mass m with a velocity $\vec{v}$ is defined as:

$$\vec{p} = m\vec{v}$$

Momentum is a vector quantity and has SI units of kg m s^{-1} .

SAMPLE PROBLEM 12

What is the momentum of a train of mass 8×10^6 kilograms that is travelling at a speed of 15 m s^{-1} in a northerly direction?

THINK

1. Recall the formula for momentum.
2. Substitute the mass and velocity in to find the momentum.
3. State the solution.

WRITE

$$p = mv$$

$$p = mv$$

$$= 8 \times 10^6 \times 15$$

$$= 1.2 \times 10^8 \text{ kg m s}^{-1}$$

The momentum of the train is $1.2 \times 10^8 \text{ kg m s}^{-1}$ north.

PRACTICE PROBLEM 12

A car of mass 1200 kilograms travels east with a constant speed of 15 m s^{-1} . It then undergoes a constant acceleration of 3 m s^{-2} for 2 seconds. What is the momentum of the car:

- a. before it accelerates
 - b. at the end of the 2 seconds acceleration?
-

10.7.2 Impulse

Making an object stop, or causing it to start moving, requires a non-zero net force. The relationship between the net force applied to an object and its momentum can be explored by applying Newton's second law to the object.

$$\begin{aligned}F_{\text{net}} &= ma \\ \Rightarrow F_{\text{net}} &= m \left(\frac{\Delta v}{\Delta t} \right) \\ \Rightarrow F_{\text{net}} \Delta t &= m \Delta v\end{aligned}$$

The product $F_{\text{net}} \Delta t$ is called the **impulse** of the net force. The impulse of any force is defined as the product of the force and the time interval over which it acts. Impulse is a vector quantity with SI units of N s.

$$\begin{aligned}m \Delta v &= m(v - u) \\ &= mv - mu \\ &= p_f - p_i\end{aligned}$$

Where:

p_f = the final momentum of the object

p_i = the initial momentum of the object.

Thus, the effect of a net force on the motion of an object can be summarised by the statement: impulse = change in momentum.

In fact, when translated from the original Latin, Newton's second law reads:

The rate of change of momentum is directly proportional to the magnitude of the net force and is in the direction of the net force.

This is expressed algebraically as:

$$\begin{aligned}F_{\text{net}} &\propto \frac{\Delta p}{\Delta t} \\ \Rightarrow F_{\text{net}} &= k \frac{\Delta p}{\Delta t}\end{aligned}$$

The SI unit of force, the newton, has been defined so that the constant of proportionality, k , equals 1.

Thus:

$$\Rightarrow F_{\text{net}} = \frac{\Delta p}{\Delta t}.$$

The effect of a net force on the motion of an object can be summarised by the statement:

impulse = change in momentum

$$\vec{F}_{\text{net}} \Delta t = m \Delta \vec{v}$$

SAMPLE PROBLEM 13

A 30-gram squash ball hits a wall horizontally at a speed of 15 m s^{-1} and bounces back in the opposite direction at a speed of 12 m s^{-1} . It is in contact with the wall for an interval of 1.5×10^{-3} seconds.

- What is the change in momentum of the squash ball?
- What is the impulse on the squash ball?
- What is the magnitude of the force exerted by the wall on the squash ball?

 Teacher-led video: SP13 (tlvd-0088)

THINK

1. Change in momentum is calculated from the initial and final momentums.

Consider towards the wall as the positive direction. (*Note:* This decision is arbitrary, you could choose the positive direction to be away from the wall, your answer will have the same magnitude but opposite sign.)

2. State the solution.

1. Impulse of the net force on the squash ball = change in momentum of the squash ball.

2. State the solution.

1. Recall the formula for the net force.

2. Substitute the change in momentum and change in time into the equation to find the net force.

3. State the solution.

WRITE

$$\begin{aligned} \text{a. } p_i &= mu \\ &= 0.03 \times 15 \\ &= 0.45 \text{ kg m s}^{-1} \\ p_f &= mv \\ &= 0.03 \times -12 \\ &= -0.36 \text{ kg m s}^{-1} \\ \Delta p &= p_f - p_i \\ &= -0.36 - 0.45 \\ &= -0.81 \text{ kg m s}^{-1} \end{aligned}$$

The change in momentum of the squash ball is 0.81 kg m s^{-1} away from the wall.

$$\begin{aligned} \text{b. } I &= \Delta p \\ &= -0.81 \text{ N s}^{-1} \end{aligned}$$

The impulse on the squash ball is 0.81 N s^{-1} away from the wall.

$$\begin{aligned} \text{c. } F_{\text{net}} &= \frac{\Delta p}{\Delta t} \\ F_{\text{net}} &= \frac{\Delta p}{\Delta t} \\ &= \frac{-0.81}{1.5 \times 10^{-3}} \\ &= 540 \text{ N} \end{aligned}$$

The magnitude of the force exerted by the wall on the squash ball is 540 N .

PRACTICE PROBLEM 13

During a crash test a 1400-kilogram car travelling at 16 m s^{-1} collides with a steel barrier and rebounds with an initial speed of 4.0 m s^{-1} before coming to rest. The car is in contact with the barrier for 1.4 seconds. What is the magnitude of:

- the change in momentum of the car during contact with the barrier
- the impulse applied to the car by the barrier
- the force exerted by the barrier on the car?

10.7.3 Impulse from a graph

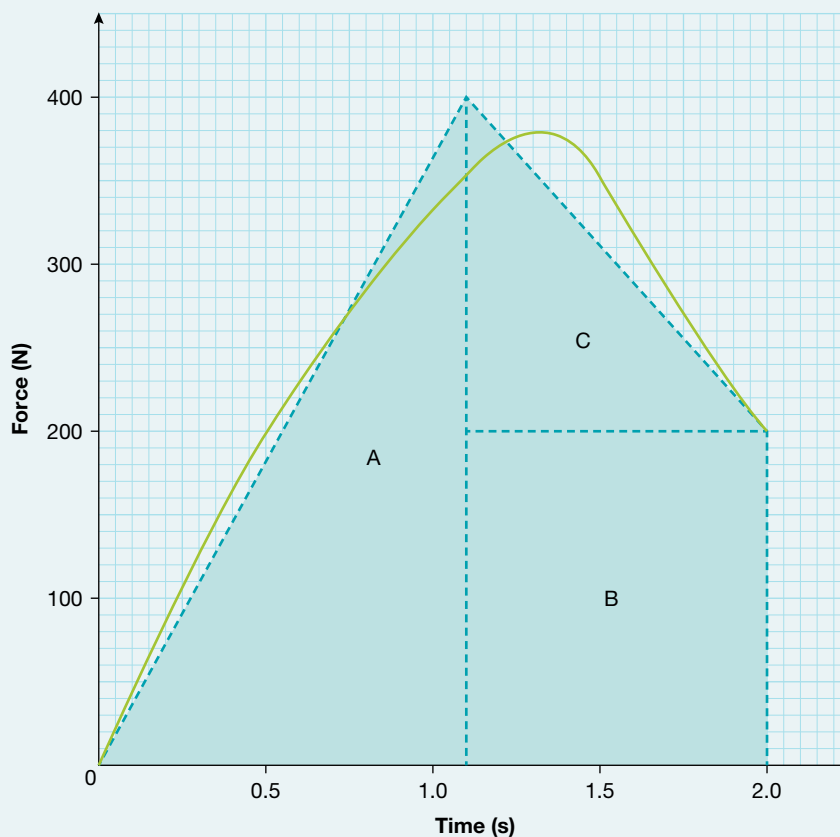
The force that was determined in Sample problem 13 was actually the average force on the squash ball. In fact, the force acting on the squash ball changes, reaching its maximum magnitude when the centre of the squash ball is at its smallest distance from the wall. The impulse (I) delivered by a changing force is given by:

$$I = F_{\text{av}} \Delta t$$

If a graph of force versus time is available, the impulse can be determined from the area under the graph. (You might recall that the displacement of an object can be determined by calculating the area under its velocity-versus-time graph — and displacement = $v_{\text{av}} \Delta t$. Similarly, the change in velocity of an object can be determined by calculating the area under its acceleration-versus-time graph — and change in velocity = $a_{\text{av}} \Delta t$.)

SAMPLE PROBLEM 14

The following graph describes the changing horizontal force on a 40-kilogram ice skater as she begins to move from rest. Estimate her velocity after 2 seconds.



THINK

1. The magnitude of the impulse on the skater can be determined by calculating the area under the graph.

2. Use the formula for impulse to calculate the change in velocity.

3. State the solution.

WRITE

$$\begin{aligned}
 \text{magnitude of impulse} &= \text{area A} + \text{area B} + \text{area C} \\
 &= \frac{1}{2} \times 1.1 \times 400 + 0.9 \times 200 + \frac{1}{2} \times 0.9 \times 200 \\
 &= 220 + 180 + 90 \\
 &= 490 \text{ N}
 \end{aligned}$$

$$\begin{aligned}
 I &= \Delta p \\
 I &= m\Delta v \\
 490 &= 40\Delta v \\
 \Delta v &= \frac{490}{40} \\
 &= 12.25 \text{ m s}^{-1}
 \end{aligned}$$

As the skater started at rest, her velocity after 2 seconds will be equal to the change in velocity.
The skater's velocity after 2 seconds is 12.25 m s^{-1} .

PRACTICE PROBLEM 14

Consider the motion described in Sample problem 14.

- a. Estimate the velocity of the skater after 1.1 seconds.
- b. What is the acceleration of the skater during the first 1.1 seconds?
- c. What constant force would produce the same change in velocity after 2.0 seconds?

10.7.4 Follow through

Players of ball games are often advised to 'follow through'. The force is then applied to the ball by the bat, racquet, club, stick or arm for a larger time interval. The impulse, $F\Delta t$, is larger and the change in momentum, Δp , is therefore larger. Consequently, the change in velocity of the ball as a result of the applied force is greater.

10.7.5 Protecting that frail human body

The human body does not cope very well with sudden blows. The skeleton provides a fairly rigid frame that protects the vital organs inside and, with the help of your muscles, enables you to move.

A sudden impact to your body, or part of your body, can:

- push or pull the bones hard enough to break them
- tear or strain the ligaments that hold the bones together
- tear or strain muscles or the tendons that join muscles to bones
- push bones into vital organs like the brain and lungs
- tear, puncture or crush vital organs like the kidneys, liver and spleen.

The damage that is done depends on the magnitude of the net force and the subsequent acceleration to which your body is subjected. In any collision, the net force acting on your body, or part of your body, can be expressed as:

$$F_{\text{net}} = \frac{\Delta p}{\Delta t}$$

FIGURE 10.23 Golfers are advised to 'follow through'. The force is applied to the ball for a longer time, giving it more momentum.



The symbol Δp represents the change in momentum of the part of your body directly affected by that net force. The magnitude of your change in momentum is usually beyond your control. For example, if you are sitting in a car travelling at 100 km h^{-1} when it hits a solid concrete wall, the magnitude of the change in momentum of your whole body during the collision will be your mass multiplied by your initial speed. When you land on a basketball court after a high jump, the magnitude of the change in momentum of each knee will be its mass multiplied by its speed just as your feet hit the floor. You have no control over your momentum.

You do, however, have control over the time interval during which the momentum changes. If Δt can be increased, the magnitude of the net force applied to you will be decreased. You can do this by:

- bending your knees when you land after jumping in sports such as netball and basketball. This increases the time interval over which your knees change their momentum, and decreases the likelihood of ligament damage
- moving your hand back when you catch a fast-moving ball in sports such as cricket. The ball changes its momentum over a longer time interval, reducing the force applied to it by your hand. In turn, the equal and opposite force on your hand is less
- wearing gloves and padding in sports such as baseball, softball and gridiron. Thick gloves are essential for wicketkeepers in cricket, who catch the solid cricket ball while it is travelling at speeds up to 150 km h^{-1}
- wearing footwear that increases the time interval during which your feet stop as they hit the ground. This is particularly important for people who run on footpaths and other hard surfaces. Indoor basketball and netball courts have floors that, although hard, bend a little, increasing the period of impact of running feet.

FIGURE 10.24 Gloves make it possible for wicketkeepers to catch a solid cricket ball travelling at high speed without severe pain and bruising.



DON'T BE AN EGGHEAD

After bicycle helmets became compulsory in Victoria in July 1990, the number of head injuries sustained by cyclists decreased dramatically. Bicycle helmets typically consist of an expanded polystyrene liner about 2 centimetres thick, covered in a thin, hard, polymer shell. They are designed to crush on impact.

In a serious bicycle accident, the head is likely to collide at high speed with the road or another vehicle. Even a simple fall from a bike can result in the head hitting the road at a speed of about 20 km h^{-1} . Without the protection of a helmet, concussion is likely as the skull decelerates and collides with the brain because of the large net force on it. If the net force and subsequent deceleration is large enough, the brain can be severely bruised or torn, resulting in permanent brain damage or death. The effect is not unlike that of dropping a soft-boiled egg onto a hard floor.

Although a helmet does not guarantee survival in a serious bicycle accident, it does reduce the net force applied to the skull, and therefore increases the chances of survival dramatically. The polystyrene liner of the helmet increases the time interval during which the skull changes its momentum.

Helmets used by motorcyclists, as well as in horse riding, motor racing, cricket and many other sports, all serve the same purpose — to increase the time interval over which a change in momentum takes place.

FIGURE 10.25 Helmets save lives and prevent serious injury in many activities.



BUCKLE UP

Seatbelts are a relatively new introduction to vehicles, with Victoria being one of the first places in the world to make wearing them compulsory in 1970. Their introduction and the increasing emphasis on vehicle safety over recent decades has drastically reduced the number of fatalities.

In a collision a car comes to a stop rapidly. An occupant not wearing a seatbelt continues at the original speed of the car (as described by Newton's first law) until acted on by a non-zero net force. An unrestrained occupant therefore moves at speed until:

- colliding with part of the interior of the car, stopping even more rapidly than the car itself, usually over a distance of only several centimetres
- crashing through the stationary, or almost stationary, windscreen into the object collided with, or onto the road
- crashing into another occupant closer to the front of the car.

An occupant properly restrained with a seatbelt stops with the car. In a typical suburban crash, the acceleration takes place over a distance of about 50 centimetres. The rate of change of the momentum of a restrained occupant is much less. Therefore, the net force on the occupant is less.

The addition of airbags to complement seatbelts has further improved occupant safety. Airbags provide an additional means of restraining the occupant and reducing the force experienced.

As well as increasing the time interval over which the occupant comes to a stop, the combination of seatbelts and airbags:

- spreads the force over a larger area of the body
- reduces the likelihood of a collision between the body and the interior of the vehicle
- keeps the occupant in an aligned position, reducing injuries to vulnerable areas such as the neck, as well as stopping them from crashing through the windscreen.

COMPUTER CRASH MODELLING

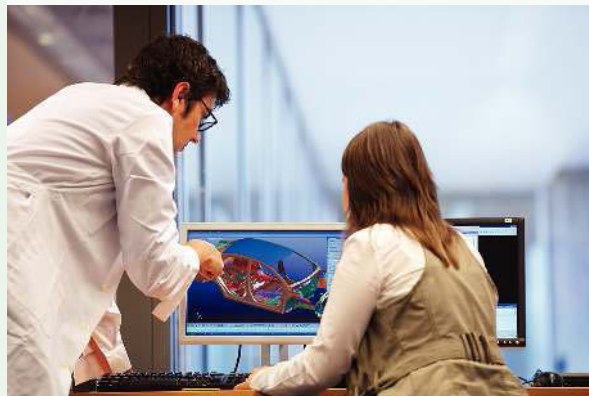
Automotive engineers use computer modelling during the design and development of new vehicles to investigate the effectiveness of safety features. This sort of crash modelling takes place long before the first prototype is built and the first physical crash tests take place.

Computer crash modelling has resulted in improvements to front and side structural design and to internal safety features such as seatbelt and airbag systems. Modelling crashes allows the investigation of a wide range of collision types, including full frontal, offset frontal, angled frontal and pole or barrier; collisions between trucks and cars; and rear impacts. The possibilities are endless. The computer models are then verified with the crash testing of real vehicles.

During side-impact modelling, the computer is used to test thousands of combinations of seatbelt, cushioning and airbag designs. For each test, the computer can be set up to calculate the forces acting on occupants, estimate the severity of injuries and compare results with other design solutions.

One aspect of design that can be tested is the sensor that triggers airbags to inflate. Complex calculations and comparisons are performed by a microprocessor within the sensing module before it 'decides' whether or not to trigger the airbags. The crash events that are modelled to develop the airbag sensors include high- and low-speed collisions, full-frontal and angled-frontal impacts and pole- or tree-type collisions.

FIGURE 10.26 Engineers use computers to model collisions to design and develop features that improve the safety characteristics of cars. Computer modelling takes place long before the real crash tests are performed.



CARS THAT CRUMPLE

Modern cars are designed to crumple at the front and rear. This provision increases the time interval during which the momentum of the car changes in a collision, further protecting its occupants from death or serious injury.

Even though the front and rear of the car crumple, the passenger compartment is protected by a rigid frame. The engine is also surrounded by rigid structures that prevent it from being pushed into the passenger compartment. The tendency of the roof to crush is currently being reduced by increasing the thickness of the windows, using stronger adhesives and strengthening the structure of the roof panel and pillars.

The inside of the passenger compartment is also designed to protect occupants. Padded dashboards, collapsible steering wheels and airbags are designed to reduce the rate of change of momentum of occupants in the event of a collision. Interior fittings like switches, door knobs and handbrakes are sunk so that the occupants do not collide with them.

FIGURE 10.27 A vehicle that has undergone a roof crush test



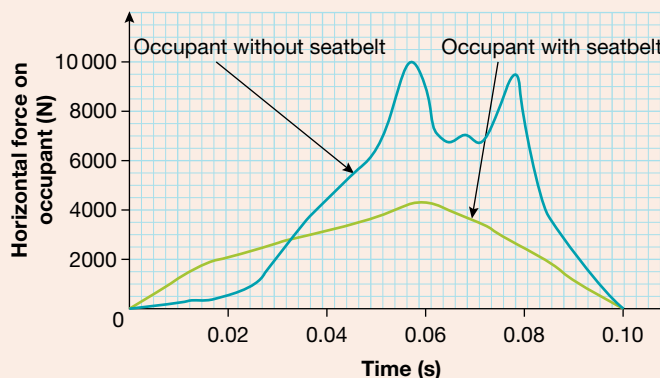
10.7 EXERCISE

To answer questions online and to receive **immediate feedback** and **sample responses** for every question go to your learnON title at www.jacplus.com.au.

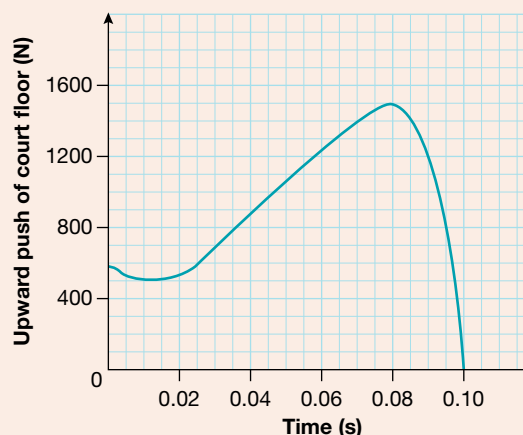
1. A 1400-kilogram car travels at 60 km h^{-1} east. Calculate the momentum of the car.
2. Make an estimate to one significant figure of the magnitude of each of the following.
 - (a) The average net force on a car while it is accelerating from 0 to 40 km h^{-1} in 3.2 seconds
 - (b) The magnitude of the air resistance on an 80 kg skydiver who has reached a terminal velocity of 200 km h^{-1}
 - (c) The momentum of an Olympic class athlete participating in the 100-metre sprint event
 - (d) The momentum of a family car travelling at the speed limit along a suburban street
 - (e) The impulse that causes a 70-kilogram football player who is running at top speed to stop abruptly as he collides with a goal post that he didn't see
 - (f) The impulse applied to a netball by a goal shooter as she pushes it up towards the goal at a speed of 5 m s^{-1}
 - (g) The change in momentum of a tennis ball as it is returned to the server in a Wimbledon final
3. A 60 gram tennis ball is bounced vertically onto the ground. After reaching the ground with a downwards velocity of 8.0 m s^{-1} , the ball rebounds with a velocity of 6.0 m s^{-1} vertically upwards.
 - (a) What is the change in momentum of the tennis ball?
 - (b) What is the impulse applied by the tennis ball to the ground? Explain how you obtained your answer without any information about the change in momentum of the ground.
 - (c) Does the ground actually move as a result of the impulse applied by the tennis ball? Explain your answer.
 - (d) If the tennis ball is in contact with the ground for $2.0 \times 10^{-3} \text{ s}$, what is the average net force on the tennis ball during this interval?
 - (e) What is the average normal force during this time interval?
4. A 75-kilogram basketballer lands vertically on the court with a speed of 3.2 m s^{-1} .
 - (a) What total impulse is applied to his feet by the ground?
 - (b) If the basketballer's speed changes from 3.2 m s^{-1} to zero in 0.10 seconds, what total force does the ground apply to his feet?
 - (c) Estimate the height from which the basketballer fell to the court.

5. A car with a total mass of 1400 kilograms (including occupants) travelling at 60 km h^{-1} hits a large tree and stops in 0.080 seconds.
- What impulse is applied to the car by the tree?
 - What force is exerted by the tree on the car?
 - What is the magnitude of the deceleration of the 70-kilogram driver of the car if he is wearing a properly fitted seatbelt?
6. Airbags are fitted to the centre of the steering wheel of many new cars. In the event of a sudden deceleration, the airbag inflates rapidly, providing extra protection for a driver restrained by a seatbelt. Explain how airbags reduce the likelihood of serious injury or death.
7. Joggers are advised to run on grass or other soft surfaces rather than concrete paths or bitumen roads to reduce the risk of knee and other leg injuries. Explain why this is so.

8. The graph on the right shows how the horizontal force on the upper body of each of two occupants of a car changes as a result of a head-on collision. One occupant is wearing a seatbelt while the other is not. Both occupants are stationary 0.10 seconds after the initial impact.



- What is the horizontal impulse on the occupant wearing the seatbelt?
 - If the mass of the occupant wearing the seatbelt is 60 kilograms, determine the speed of the car just before the initial impact.
 - Is the occupant who is not wearing the seatbelt heavier or lighter than the other (more sensible) occupant?
 - Write a paragraph explaining the difference in shape between the two curves on the graph.
9. The graph on the right shows how the upward push of the court floor changes as a 60-kilogram basketballer jumps vertically upwards to complete a slam dunk.
- What is the impulse applied to the basketballer by the floor?
 - With what speed did the basketballer leave the ground?
 - What was the average force exerted on the basketballer by the floor during the 0.10 second interval?
 - Explain why the initial upward push of the floor is not zero.
10. A well-known politician makes the suggestion that if cars were completely surrounded by rubber 'bumpers' like those on dodgem cars, they would simply bounce off each other in a collision and passengers would be safer. Discuss the merits of this suggestion in terms of Newton's laws of motion.



studyon

To answer practice exam questions online and to receive immediate feedback and sample responses for every question go to your learnON title at www.jacplus.com.au.

studyON: Practice exam questions online only

Fully worked solutions and sample responses are available in your digital formats.

10.8 Torque

KEY CONCEPT

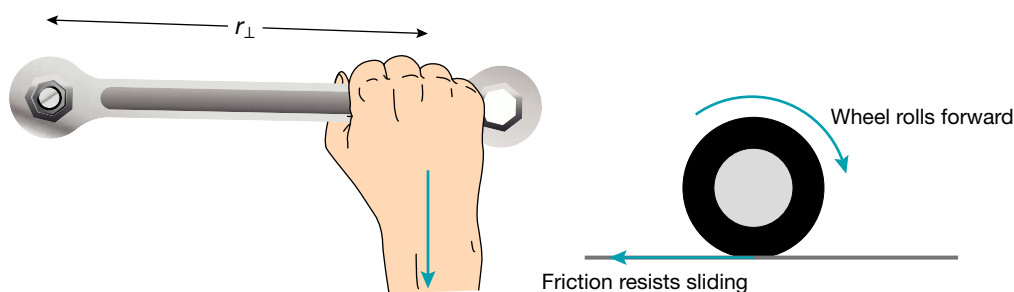
- Calculate torque: $\tau = r_{\perp} F$.

10.8.1 Torque or the turning effect of a force

So far the explanation of forces and motion has treated objects as if they are a single point, or as if the force acts through the middle of the object; that is, its centre of mass. However, nature is more complicated than this. Friction acts at the rim of the front tyre of a bike to make it roll, the thigh muscle straightens the leg, a billiard cue hits the bottom edge of a ball to make it spin backwards, the wind blows over a tree, a pull on a handle opens the door. All these actions involve rotation, and a force has made the object turn.

The turning effect of a force is called a torque. The symbol for torque is τ , the Greek letter *tau*. Torque is always measured about a particular point. In some situations, the point about which an object will rotate is obvious (such as in a see-saw), and it may be referred to as a pivot or fulcrum.

FIGURE 10.28 Examples of torque being applied



The size of a torque about a point or pivot is determined by the product of two factors:

- the size of the force, $\vec{F}$
- the perpendicular distance between the line of action of the force and the pivot, $r_{\perp}$.

$$\vec{\tau} = r_{\perp} \vec{F}$$

As a product of force and distance, torque has the units of newton metre (N m). It is also a vector, but because its effect is rotation, the direction of the vector is set by a rule.

The rule is:

If the rotation in the plane of the page is clockwise, the direction of the vector is into the page.

SAMPLE PROBLEM 15

A torque wrench is used to tighten nuts onto their bolts to a specific tightness or force.

A torque wrench has a handle (black in the photo on the right)

on one end and a socket that fits over a nut on the other end. In between is a scale that gives a reading in Newton metres.



The scale on a torque wrench has a reading of 30 Newton metres. If the hand applying the force is 30 centimetres from the end, what is the size of the force by the hand on the wrench?

 **Teacher-led video:** SP15 (tlvd-0090)

THINK

1. Recall the formula for calculating torque.
2. Substitute the torque and perpendicular distance into the equation to find the force applied.
3. State the solution.

WRITE

$$\tau = r_{\perp} F$$

$$30 = 0.3 \times F$$

$$F = \frac{30}{0.3}$$

$$F = 100 \text{ N}$$

The force by the hand on the wrench is 100 N.

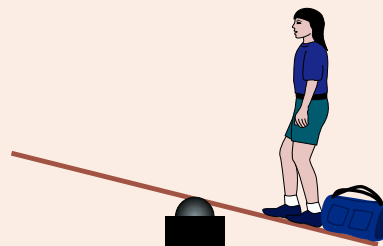
PRACTICE PROBLEM 15

The handle of a torque wrench is hollow so an extension rod can be inserted. If you can exert only 30 N of force, how far along the extension rod from the handle should you place your hand to achieve a torque of 30 N m?

10.8 EXERCISE

To answer questions online and to receive **immediate feedback** and **sample responses** for every question go to your learnON title at www.jacplus.com.au.

1. (a) A mechanic applies a force of 200 N to a wheel nut using a shifter. The perpendicular distance from where they apply the force to the nut is 25 centimetres. What torque are they applying to the nut?
(b) The mechanic is unable to loosen the nut using the torque applied. Suggest two ways that they could increase the torque in this situation.
2. A lever is used to apply a torque of 20 N m about a pivot point. The perpendicular distance is 0.25 metres between the application of the force and the pivot point. What is the applied force?
3. There are myriad examples of everyday situations where we use devices that have a lever of some form to increase the torque that we apply. Examples include door handles, car steering wheels, electric motors, push bike pedals, wrenches, wheelbarrows, bottle lids. For one of these examples, or another that you can identify, estimate the force applied and the perpendicular distance to calculate an estimate of the torque involved.
4. Sam is standing at the right-hand end of the seesaw shown in the following figure. He places a bag on the seesaw and then begins walking up the plank to the left. Describe what happens as he walks towards, and then beyond, the fulcrum.



10.9 Equilibrium

KEY CONCEPT

- Investigate and analyse theoretically and practically translational forces and torques in simple structures that are in rotational equilibrium.

10.9.1 Equilibrium or keeping still

Earlier in this topic, ‘keeping still’ meant not moving. If the net force was zero and the object was at rest, it would stay still. The forces were considered as acting on a single point. However, if the forces act at different points on the object, it is possible to have a net force of zero, but the object can still spin. In figure 10.29 the force upwards equals the force downwards, so the net force is zero, but the sphere rotates. In this case there is a net torque. The torques of the two forces about the centre add together.

In cases such as car engines and electric motors, the production of a torque is essential for rotation and movement. But torque, and the rotation and movement it causes, can be detrimental. In bridges and building, the torque effect of a force can’t be avoided, but needs to be controlled if the structure is to remain standing. Such structures need to be designed so that not only is the net force equal to zero, but the net torque is also zero, and importantly this is true about every point in the structure.

For a structure to be in equilibrium, two conditions need to apply.

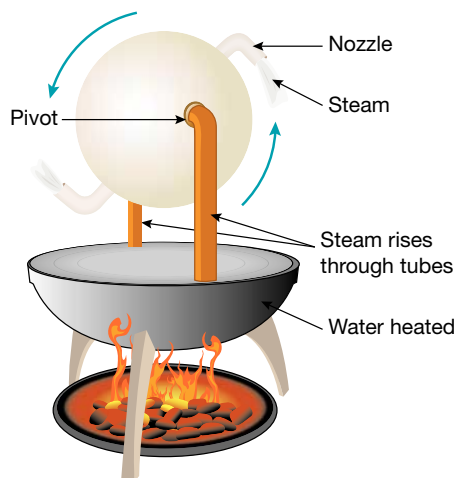
1. Translational equilibrium: net force = zero
2. Rotational equilibrium: net torque about any point = zero

10.9.2 Strategy for solving problems involving torque

Questions regarding torque will often involve determining the value of two forces, so the solution will require generating two equations, which can then be solved simultaneously.

First, draw a diagram with all the forces acting on the structure. Label each force. If its size is given in the question, write the value, for example, 10 N. If the size of the force is unknown, use a symbol such as ***F*** or ***R***.

FIGURE 10.29 A zero net force can cause rotation.



1. Using translational equilibrium: net force = zero

It is easier to break this into two simpler tasks such as:

- a. sum of forces up = sum of forces down
 - b. sum of forces left = sum of forces right
2. Using rotational equilibrium: net torque about any point = zero

Choose a point about which to calculate the torques.

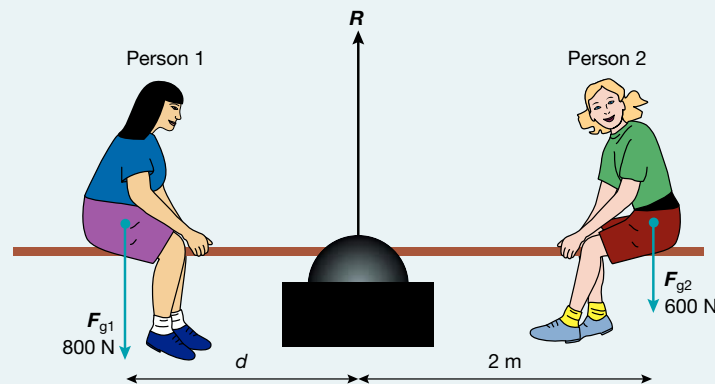
Any point is acceptable, however, it can make solving the problem easier if you choose a point through which an unknown force acts. The torque of this force about that point will be zero as its line of action passes through the point, so that unknown will be effectively eliminated from this equation.

$$\text{sum of clockwise torques} = \text{sum of anticlockwise torques}$$

Now you will have two equations with two unknowns: one equation from the net force and one from the net torque. You can then solve the equations simultaneously to determine the unknown quantities.

SAMPLE PROBLEM 16

Where should person 1 sit to balance the seesaw?



THINK

1. To satisfy equilibrium, both the sum of the forces acting on the seesaw and the sum of the torques must equal zero.

2. Consider the net force equilibrium. The sum of the upwards forces must equal the sum of the downwards forces.

3. Consider the net torque, taking the torques about the fulcrum at the centre.

4. State the solution.

WRITE

$$F_{\text{net}} = 0$$

$$\tau_{\text{net}} = 0$$

$$R = 800 + 600$$

$$R = 1400 \text{ N upwards}$$

$$\tau_{\text{net}} = 0$$

$$\Rightarrow \text{sum of clockwise torques} = \text{sum of anticlockwise torques}$$

$$600 \times 2 = 800 \times d$$

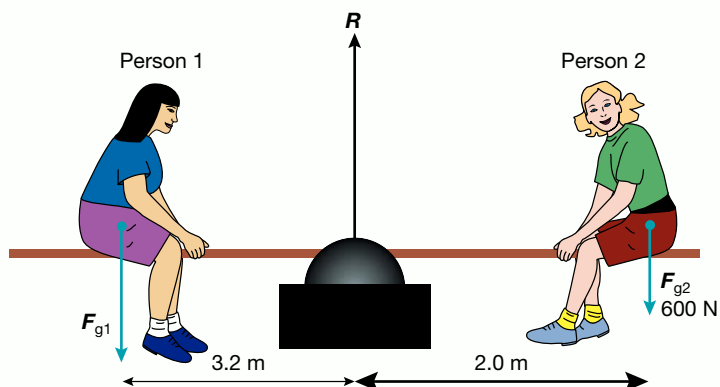
$$d = \frac{1200}{800}$$

$$= 1.5 \text{ m}$$

To balance the seesaw person 1 must sit 1.5 metres to the left of the fulcrum.

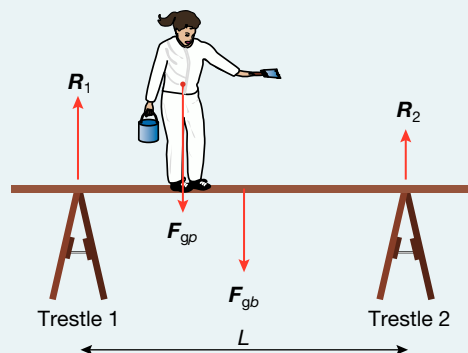
PRACTICE PROBLEM 16

The following seesaw is balanced. Calculate the mass of person 1.



SAMPLE PROBLEM 17

Consider the painter's plank supported between two trestles shown. The plank behaves as a simple bridge or beam and the weight of the painter must be transferred through the plank to the two trestles. The mass of the beam is 40 kilograms, the mass of the painter is 60 kilograms and she is a quarter of the distance from trestle 1. What is the magnitude of the reaction forces R_1 and R_2 ?



Teacher-led video: SP17 (tlvd-0092)

THINK

- For the structure to be stable, the sum of the forces and the sum of the torques must both equal zero.
- Consider the net force. The sum of the upwards forces must equal the sum of the downwards forces.
- Consider the net torque, taking the torques about trestle 1.

WRITE

$$F_{\text{net}} = 0$$

$$\tau_{\text{net}} = 0$$

$$R_1 + R_2 = 40 \times 9.8 + 60 \times 9.8 \\ = 980 \text{ N}$$

$$\tau_{\text{net}} = 0$$

$\Rightarrow$ sum of clockwise torques = sum of anticlockwise torques

$$40 \times 9.8 \times \frac{1}{2}L + 60 \times 9.8 \times \frac{1}{4}L = R_2 \times L$$

$$40 \times 9.8 \times \frac{1}{2} + 60 \times 9.8 \times \frac{1}{4} = R_2$$

$$196 + 147 = R_2$$

$$R_2 = 343 \text{ N}$$

4. Substitute the value of R_2 into the equation for the net force.

$$R_1 + R_2 = 980$$

$$R_1 + 343 = 980$$

$$R_1 = 980 - 343$$

$$R_1 = 637 \text{ N}$$

5. State the solution.

The magnitude of R_1 is 637 N and R_2 is 343 N.

PRACTICE PROBLEM 17

A eucalyptus tree, 15 metres high and with a 200 centimetre diameter, was pulled over until it failed. The applied load was 6.0 kN m about the base of the tree.

- If the root ball of the tree has an average depth of 0.80 metres, what is the size of the force by the soil on the root ball at the point of failure?
- If the rope pulling on the tree was attached halfway up the tree, calculate the size of the force at the point of failure:
 - in the rope (assuming the rope is horizontal)
 - by the ground at the base of the tree.

10.9.3 Types of structures: cantilevers

A cantilever is a beam with one end free to move. A diving board, flagpole and a tree are examples of cantilevers.

The diving board in figure 10.30 is supported by an upward force, R_1 , from the bracket. The force due to gravity acts down through the middle of the board at a point further out. If these were the only forces on the diving board, the board would rotate anticlockwise. To prevent this rotation, the other end of the bracket pulls down on the diving board. The board is bolted to each end of the bracket. At which end are the bolts not needed?

The tree in figure 10.31 is buffeted by winds from the left. The soil on the right at the base of the tree is compressed and pushes back to the left. The combination of these two forces pushes the roots of the tree to the left, and the soil to the left of the roots pushes back to the right.

FIGURE 10.30 A diving board is an example of a cantilever.

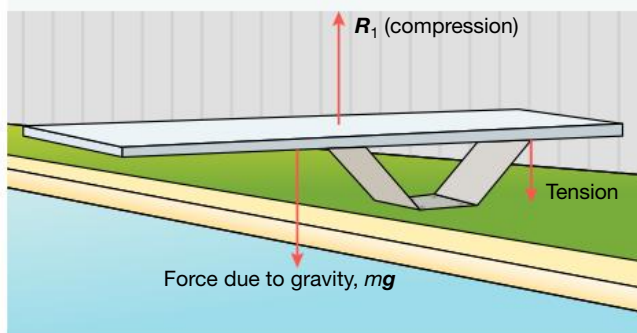
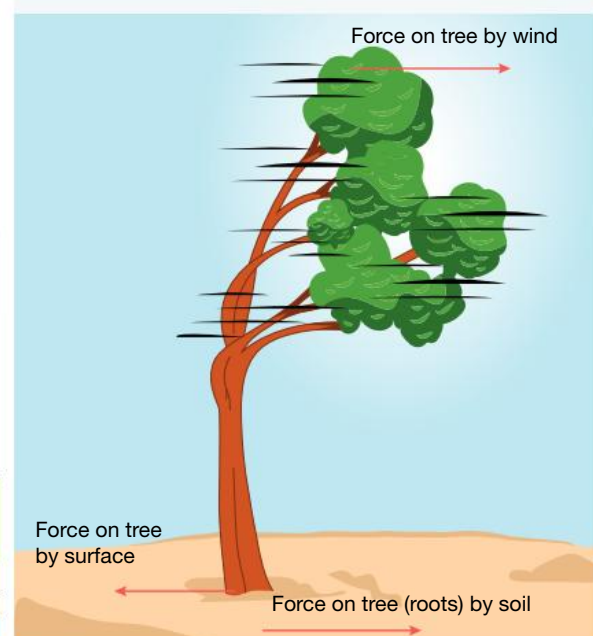


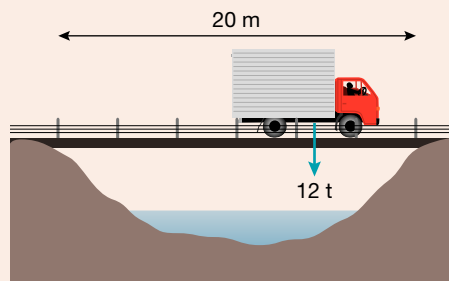
FIGURE 10.31 A tree buffeted by winds is a cantilever.



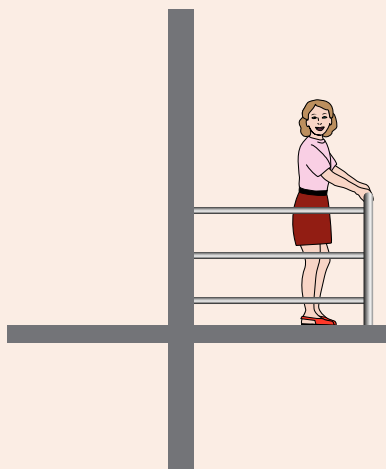
10.9 EXERCISE

To answer questions online and to receive **immediate feedback** and **sample responses** for every question go to your learnON title at www.jacplus.com.au.

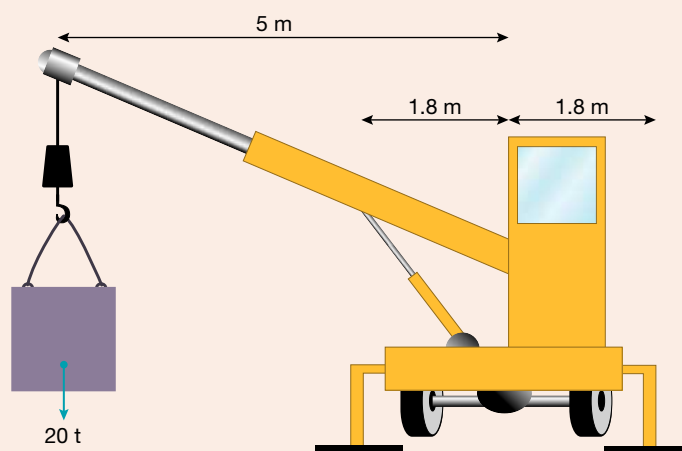
1. A truck crosses a concrete girder bridge (as shown in the figure on the right). The bridge spans 20 metres and is supported at each end on concrete abutments.
 - (a) Describe what happens to the reaction at each abutment as the truck moves across the bridge from left to right.
 - (b) The truck weighs 12 tonne. Calculate the reaction at each support when the centre of gravity of the truck is 4 metres from the right abutment.



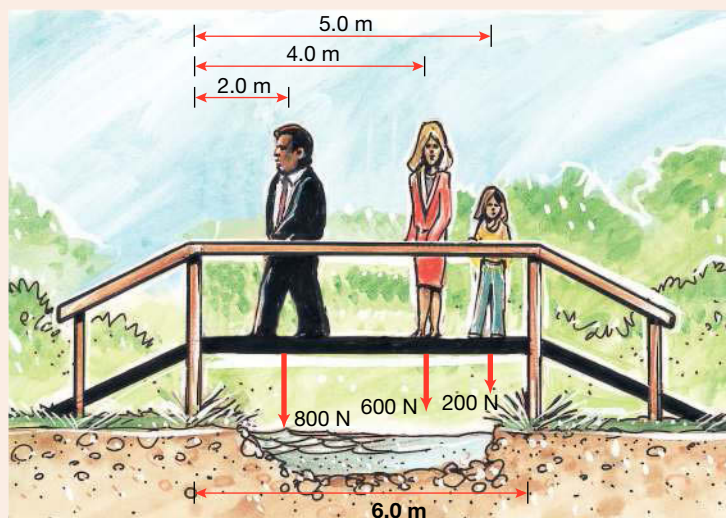
2. A person standing on the outside edge of the cantilevered balcony shown in the following figure walks inside.



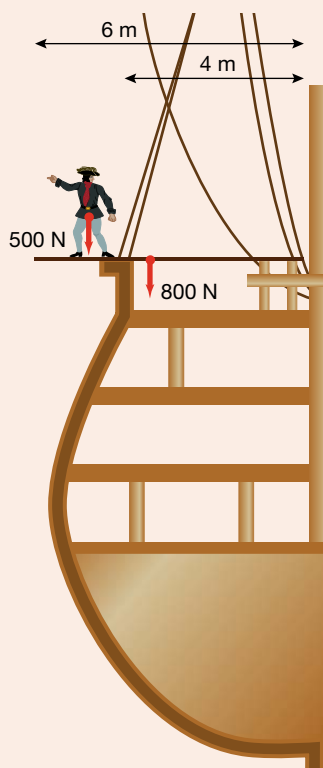
- (a) Explain what forces are necessary to support the balcony.
 - (b) As the person walks across the balcony, describe what happens to the reaction at the support.
3. The truck crane in the following figure is able to lift a 20-tonne load at a radius of 5 metres. If the weight of the truck is evenly distributed, how heavy must the truck be if it is not to tip over? Assume the weight of the truck is uniformly distributed.



4. The pedestrian bridge spanning the creek in the following figure weighs 2 kN. Calculate the reaction at each end when the three people are in the positions shown.



5. How far beyond the edge of the boat can Pirate Bill walk along the plank before it tips and he falls into the water? The 6-metre long plank weighs 800 N and Pirate Bill weighs 500 N.



studyon

To answer practice exam questions online and to receive immediate feedback and sample responses for every question go to your learnON title at www.jacplus.com.au.

studyON: Practice exam questions **online** only

Fully worked solutions and sample responses are available in your digital formats.

10.10 Review

10.10.1 Summary

- Forces are used to model interactions between objects.
- Force is a vector quantity.
- Force due to gravity is a measure of the force on an object due to the pull of gravity.
- The force due to gravity on an object is directly proportional to its mass.
- A free body diagram depicts all external forces acting upon an object.
- The vector sum of the forces acting on an object is called the net force.
- The velocity of an object can change only if a non-zero net force acts on it. This statement is an expression of Newton's First Law of Motion.
- When a non-zero net force acts on an object, the object accelerates in the direction of the net force.
- Newton's Second Law of Motion describes the relationship between the acceleration of an object, the net force acting on it and the object's mass. It can be expressed as $\mathbf{F}_{\text{net}} = m\mathbf{a}$.
- When an object applies a force to a second object, the second object applies an equal and opposite force to the first object: $\mathbf{F}_{\text{on A by B}} = -\mathbf{F}_{\text{on B by A}}$. This statement is an expression of Newton's Third Law of Motion.
- The forces acting on a moving vehicle are:
 - force due to gravity, acting down through the centre of mass
 - the normal force, applied perpendicular to the surface of the road
 - the driving force, applied in the direction of motion by the road
 - road friction, applied to the non-driving wheels opposite to the direction of motion
 - air resistance, applied opposite to the direction of motion.
- Newton's second law can be applied to a single object or a system of multiple bodies that are in contact or connected together.
- The momentum of an object is the product of its mass and its velocity, $\mathbf{p} = m\mathbf{v}$.
- The impulse delivered to an object by a force is the product of the force and the time interval during which the force acts on the object, $\mathbf{I} = \mathbf{F}\Delta t$.
- The impulse delivered by the net force on an object is equal to the change in momentum of the object. This can be expressed as $\mathbf{F}_{\text{net}}\Delta t = m\Delta\mathbf{v}$.
- The impulse delivered by a force can be found by determining the area under a graph of force versus time.
- The damage done to the human body during a collision depends on the magnitude of the net force and subsequent acceleration the body is subjected to.
- The net force on a human body during a collision can be decreased by increasing the time interval during which the body's momentum changes. Increasing the time interval to reduce the net force, and hence damage, to the human body is used to advantage in many sports and in road safety.
- Torque is a measure of the turning effect of a force and is calculated as $\tau = r_{\perp}\mathbf{F}$.
- Translational equilibrium occurs when all forces acting on an object are in balance.
- Rotational equilibrium occurs when all torques acting on an object are in balance.

Resources

studyon

To access key concept summaries and practice exam questions download and print the **studyON: Revision and practice exam question booklet** (sonr-0035).

10.10.2 Key terms

Air resistance is the force applied to an object, opposite to its direction of motion, by the air through which it is moving.

The **centre of mass** of an object is the point at which all of its mass can be considered to be.

Components are parts. Any vector can be resolved into a number of components. When all the components are added together, the result is the original vector.

A **force** is a push or a pull. Forces model interactions between objects. Force is a vector quantity.

The **force due to gravity** is the force applied to an object, due to gravitational attraction.

Friction is the force applied to the surface of an object when it is pushed or pulled against the surface of another object.

Gravitational field strength (g) is the force of gravity on a unit of mass.

An **idealisation** makes modelling a phenomenon or event easier by assuming ideal conditions that don't exactly match the real situation.

The **impulse** of a force is the product of the force and the time interval over which it acts. Impulse is a vector quantity.

Momentum is the product of the mass of an object and its velocity. It is a vector quantity.

A quantity that is **negligible** is so small that it can be ignored when modelling a phenomenon or an event.

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

The **normal force** is a force that acts perpendicularly to a surface as a result of an object applying a force to the surface.



Resources



Digital document Key terms glossary (doc-32268)

10.10.3 Practical work and investigations

Investigation 10.1

The relationship between mass and the force due to gravity

Aim: To examine the relationship between the force due to gravity and mass

Digital document: doc-31879

Investigation 10.2

Friction

Aim: To observe differences in friction when a wooden block is pulled across a surface

Digital document: doc-31877

Teacher-led video: tlvd-0822



Investigation 10.3

Force as a vector

Aim: To show that force is a vector and that the net force is the vector sum of all the forces acting on an object; To analyse the forces acting on an object by resolving the forces into components

Digital document: doc-32308

Investigation 10.4

Static, sliding and rolling friction

Aim: To compare the relative sizes of different forms of friction

Digital document: doc-32309

Investigation 10.5

Impulse, momentum and Newton's Second Law of Motion

Aim: To measure and record the velocity of the trolley (or glider) at two separate instants as the load is falling

Digital document: doc-31880

Other practical work ideas:

- Compare the accuracy of different methods of determining g .
- Investigate the friction of running shoes or of a towel falling off a rack.
- Investigate the compression and tension behaviour of plasticine.
- A wet rag is hard to drag when it is spread out and pulled across the floor. What does the resistive force depend on?
- Design and test a safety helmet for a papier mâché 'egg'.



Resources



Digital document Practical investigation logbook (doc-32265)

10.10 Exercises

To answer questions online and to receive **immediate feedback** and **sample responses** for every question go to your learnON title at www.jacplus.com.au.

In answering the following questions, assume the magnitude of the gravitational field strength near the Earth's surface is 9.8 N kg^{-1} .

10.10 Exercise 1: Multiple choice questions

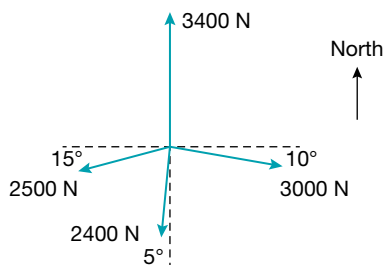
1. Which of the following is *not* a vector quantity?
 - A. Force
 - B. Mass
 - C. Acceleration
 - D. Momentum
2. Which of the following forces would be acting on a basketball falling through the air during a game of basketball?
 - A. Gravity
 - B. Normal force
 - C. Net force
 - D. Air resistance
3. Which of the following is *not* at rest or in a uniform state of motion?
 - A. A car travelling along a highway at a constant velocity using cruise control
 - B. A rocket sitting motionless on the launch pad
 - C. A ladder leaning against a wall
 - D. A train accelerating uniformly as it departs a station
4. An object of mass 43 kilograms has a net force of 86 N applied to it. Calculate its acceleration.
 - A. 9.8 m s^{-2}
 - B. 0.50 m s^{-2}
 - C. 2.0 m s^{-2}
 - D. 1.6 m s^{-2}

5. Which of the following is *not* a Newton's third law pair of forces?
 - A. The force of a book on a table and the force of the table on the book
 - B. The normal force on someone sitting in a chair and the force of gravity on them
 - C. The force of a car tyre on the road and the force of the road on the car tyre
 - D. The force due to gravity of the Earth on you and the force due to gravity of you on the Earth
6. A car of mass 2250 kilograms is travelling at 20 m s^{-1} . Calculate its momentum.
 - A. $45\,000 \text{ kg m s}^{-1}$
 - B. 4500 kg m s^{-1}
 - C. 1125 kg m s^{-1}
 - D. $112.5 \text{ kg m s}^{-1}$
7. A tennis ball of mass 58 grams experiences a change in velocity of 155 km h^{-1} when struck by a racquet during a serve. Calculate the change in momentum it experiences.
 - A. 90 kg m s^{-1}
 - B. 9 kg m s^{-1}
 - C. 25 kg m^{-1}
 - D. 2.5 kg m s^{-1}
8. A car of mass 1850 kilograms is travelling at 8 m s^{-1} around a carpark when it collides with a parked car. The collision lasts 0.2 seconds, after which the car has come to a complete stop. Determine the magnitude of the average force acting on the car.
 - A. 9250 N
 - B. 74 000 N
 - C. 2960 N
 - D. 14 800 N
9. Some engineering students are discussing ways to reduce the force acting on a car during a collision. Based on your understanding of impulse and momentum, which of the following will *not* be effective in reducing the force acting on the car?
 - A. Reduce the initial speed of the car (using more effective braking or lowered speed limits).
 - B. Decrease the mass of the car (through better structural design and material selection).
 - C. Reduce the duration (time taken) for the collision.
 - D. All of the above will be effective.
10. A student sits at the end of pipe attached to a shifter to apply a force of 735 N at a perpendicular distance of 125 centimetres from a wheel nut that they are struggling to undo. Calculate the torque applied to the nut.
 - A. 93.8 N m
 - B. 9380 N m
 - C. 919 N m
 - D. 91 900 N m

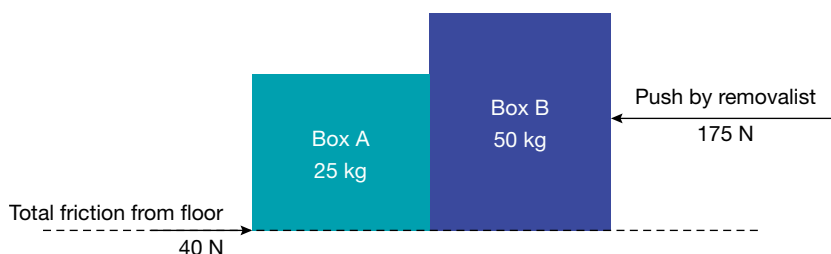
10.10 Exercise 2: Short answer questions

1. As part of a practical investigation a physics student rolls objects horizontally off the edge of a table and records the motion of their fall onto the floor below. Identify the forces that will be acting on these objects during their fall to the floor. For each force you identify, describe the interaction it represents and the likely direction of the force.
2. A rear-wheel-drive car is accelerating forwards along a horizontal road surface. Draw and label a complete diagram of all external forces acting on the car.
3. A child pulls along a toy on a piece of string at an angle of 30 degrees to the horizontal. They apply a force of 25 N along the string. Determine the horizontal and vertical components of this force.

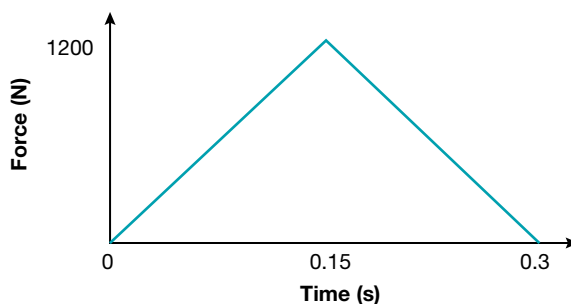
4. The following forces are acting on ropes used in a four-way tug of war (as viewed from above) as part of a school athletics carnival. Resolve all of the forces into north–south or east–west components and determine the size and direction of the net force.



5. A sports car of mass 1645 kilograms accelerates at 9.6 m s^{-2} . Determine the net force that would be required to produce this acceleration.
6. The Falcon Heavy rocket produces approximately $2.2 \times 10^6 \text{ N}$ of thrust during the first moments of liftoff. If the acceleration of the rocket at this instant is 1.57 m s^{-2} , calculate its mass.
7. A piano is falling through the air near the surface of Earth. It has a mass of 410 kilograms.
- At a particular instant during its fall, the force of air resistance acting to oppose its fall is 2400 N. Calculate its acceleration at this instant.
 - Determine the magnitude of air resistance force that would be required for the piano to reach a constant velocity during its fall.
8. A removalist is pushing two heavy boxes across the floor of their truck. The horizontal forces acting on the boxes are shown in the following diagram.
- Calculate the acceleration of the boxes.
 - Calculate the compression force acting between the two boxes.



9. A tennis ball is travelling at 65 m s^{-1} towards a player's racquet an instant before it collides with it. A moment later, the ball leaves the racquet travelling at 33 m s^{-1} in the opposite direction. Assume that the ball has a mass of 57 grams.
- Determine the change in momentum that the ball experiences during this collision.
 - Assuming that the collision duration is 0.0020 seconds, determine the average force applied by the racquet on the ball during the collision.
10. The following graph is a simplified representation of the force applied by a trampoline on an acrobat over the duration of a single rebound. Use this graph to determine the impulse applied to the acrobat.



10.10 Exercise 3: Exam practice questions

Question 1 (1 mark)

Consider the example of a textbook at rest on a table. Explain why the normal force acting on the book and the force due to gravity are not a Newton's third law pair of forces.

Question 2 (3 marks)

A cycle tourist is towing all of their camping equipment, clothes and food behind their pushbike in a bike trailer. Whilst pedalling at a reasonable pace they produce a driving force of 172 N acting forwards from the rear wheel of their bike. The road friction and air resistance opposing the motion of the bike and trailer is equal to 34 N acting backwards (20 N on the bike and 14 N on the trailer). The total mass of the cyclist and bike is 95 kilograms. The total mass of the trailer and all of its payload is 20 kilograms. Determine the tension force in the link between the trailer and the bike.

Question 3 (3 marks)

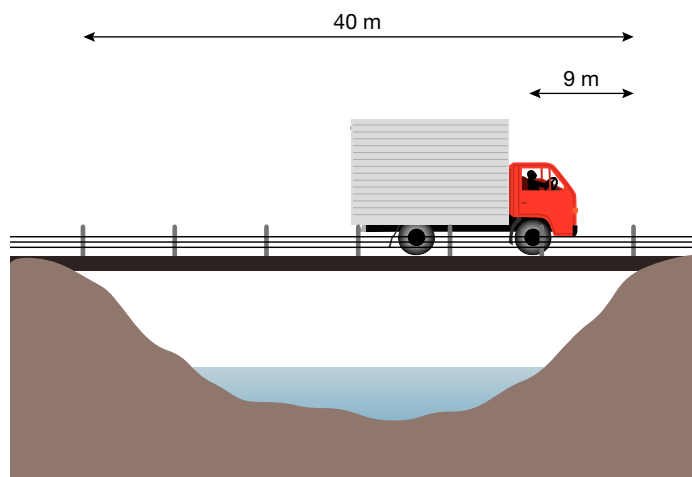
A small rocket of mass 2500 kg is launched up along an inclined ramp at an angle of 42° from the horizontal. During the launch, the rocket engine provides a constant thrust of 18 000 N. Determine the acceleration of the rocket during its launch. It is reasonable to consider air resistance and friction to be negligible in this situation.

Question 4 (2 marks)

During a standardised car crash test, a vehicle of mass 1980 kilograms is travelling at 64.0 km h^{-1} when it strikes a barrier. The car rebounds and is travelling at 12.0 km h^{-1} in the opposite direction immediately after the collision. The duration of the collision with the barrier is 160 milliseconds. Determine the average force exerted by the car on the barrier during the collision.

Question 5 (3 marks)

A truck of mass 14 500 kilograms is crossing a bridge over a small river. The bridge span is 40.0 metres between the two supports. The bridge has a total mass of 46 000 kilograms, with its centre of gravity exactly in the middle of its span. Determine the reaction at each of the supports when the centre of mass of the truck is 9.00 metres from the right-hand support.



10.10 Exercise 4: studyON topic test online only

Fully worked solutions and sample responses are available in your digital formats.

teachon

Test maker

Create unique tests and exams from our extensive range of questions, including practice exam questions. Access the assignments section in learnON to begin creating and assigning assessments to students.

11 Energy and motion

Numerous **videos** and **interactivities** are available just where you need them, at the point of learning, in your digital formats, eBookPLUS and learnON at www.jacplus.com.au.

11.1 Overview

11.1.1 Introduction

What happens when a ball is dropped from a height of 1 metre? Depending on the type of ball, and the surface it is bounced on, there will be a variety of different answers, but could a ball ever rebound to a greater height than it started at? The answer to this question is based on the conservation of energy, a law of nature which is inherent to the world we live in.

In this topic we will learn about the different forms of energy and how it can be transferred from one form to another. These transfers allow energy from the food we eat to be turned into mechanical energy, powering the body throughout the day.

FIGURE 11.1 In this collision the kinetic energy of a car is transferred into many other forms of energy. Energy from the car is used up as the car's front is deformed and a large amount of energy is transferred to the object it collides with, the road and the particles of air around the car. Some of the energy is transferred into sound and heat.



11.1.2 What you will learn

KEY KNOWLEDGE

After completing this topic you will be able to:

- apply the concept of work done by a constant force using:
 - work done = constant force $\times$ distance moved in direction of force: $W = Fs$
 - work done = area under force-distance graph
- investigate and analyse theoretically and practically Hooke's Law for an ideal spring: $F = -k\Delta x$
- analyse and model mechanical energy transfers and transformations using energy conservation:
 - changes in gravitational potential energy near Earth's surface: $E_g = mg\Delta h$
 - potential energy in ideal springs: $E_s = \frac{1}{2}k\Delta x^2$
 - 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: $\eta = \frac{\text{useful energy out}}{\text{total energy in}}$
- analyse impulse (momentum transfer) in an isolated system (for collisions between objects moving in a straight line): $I = \Delta p$
- investigate and analyse theoretically and practically momentum conservation in one dimension.

Source: VCE Physics Study Design (2016–2021) extracts © VCAA; reproduced by permission.

PRACTICAL WORK AND INVESTIGATIONS

Practical work is a central component of learning and assessment. Experiments and investigations, supported by a **Practical investigation logbook** and **Teacher-led videos**, are included in this topic to provide opportunities to undertake investigations and communicate findings.

on Resources

 **Digital documents** Key science skills — VCE Units 1–4 (doc-31856)

Key terms glossary (doc-32270)

Practical investigation logbook (doc-32271)

studyon

To access key concept summaries and practice exam questions download and print the **studyON: Revision and practice exam question booklet** (sonr-0036).

11.2 Impulse and momentum

KEY CONCEPTS

- Analyse impulse (momentum transfer) in an isolated system (for collisions between objects moving in a straight line): $I = \Delta p$.
- Investigate and analyse theoretically and practically momentum conservation in one dimension.

11.2.1 Impulse and momentum in collisions

When two objects, A and B, collide with each other, each object exerts a force on the other. These two forces are an example of Newton's Third Law of Motion. The two forces act on different objects, are equal in magnitude and act in opposite directions.

The collision starts at some point in time and finishes at another point in time. The symbol Δt represents the duration of the collision. From Newton's point of view, both objects measure the same duration. Multiplying $\vec{F}_{\text{on B by A}}$ by Δt gives $\vec{F}_{\text{on B by A}} \Delta t$, which is the impulse on B by A. This impulse produces a change in momentum, but whose momentum? A or B? Because it is the impulse by A on B, it is B's momentum that is changed.

$$\vec{F}_{\text{on B by A}} \Delta t = I_{\text{on B by A}} = \Delta \vec{p}_B$$

Similarly, the force on A by B produces a change in A's momentum.

$$\vec{F}_{\text{on A by B}} \Delta t = I_{\text{on A by B}} = \Delta \vec{p}_A$$

Forces are actions by one object on another, but momentum can be said to be a quantity an object has, even if it is a vector. So a force acting for a time changes how much momentum an object has.

In a collision, the two forces are equal in magnitude and opposite in direction. So the changes in momentum of A and B are also equal in magnitude and opposite in direction.

$$\Delta \vec{p}_B = -\Delta \vec{p}_A$$

Because momentum is a quantity, this statement can be interpreted as 'the momentum that B gains equals the momentum that A loses'. This is the basis of a conservation principle. Total momentum is conserved.

The 'change' in something is always the 'final' value minus the 'initial' value, or what is added to the 'initial' value to get the 'final'.

$$\Delta p = p_{\text{final}} - p_{\text{initial}} \text{ or } p_{\text{final}} = p_{\text{initial}} + \Delta p$$

For object B: $\Delta p_B = p_{B \text{ final}} - p_{B \text{ initial}}$

For object A: $\Delta p_A = p_{A \text{ final}} - p_{A \text{ initial}}$

So, from the above relationship:

$$\begin{aligned} \Delta p_B &= -\Delta p_A \\ p_{B \text{ final}} - p_{B \text{ initial}} &= -(p_{A \text{ final}} - p_{A \text{ initial}}) \end{aligned}$$

Putting the initial momenta together gives:

$$p_{A \text{ final}} + p_{B \text{ final}} = p_{A \text{ initial}} + p_{B \text{ initial}}$$

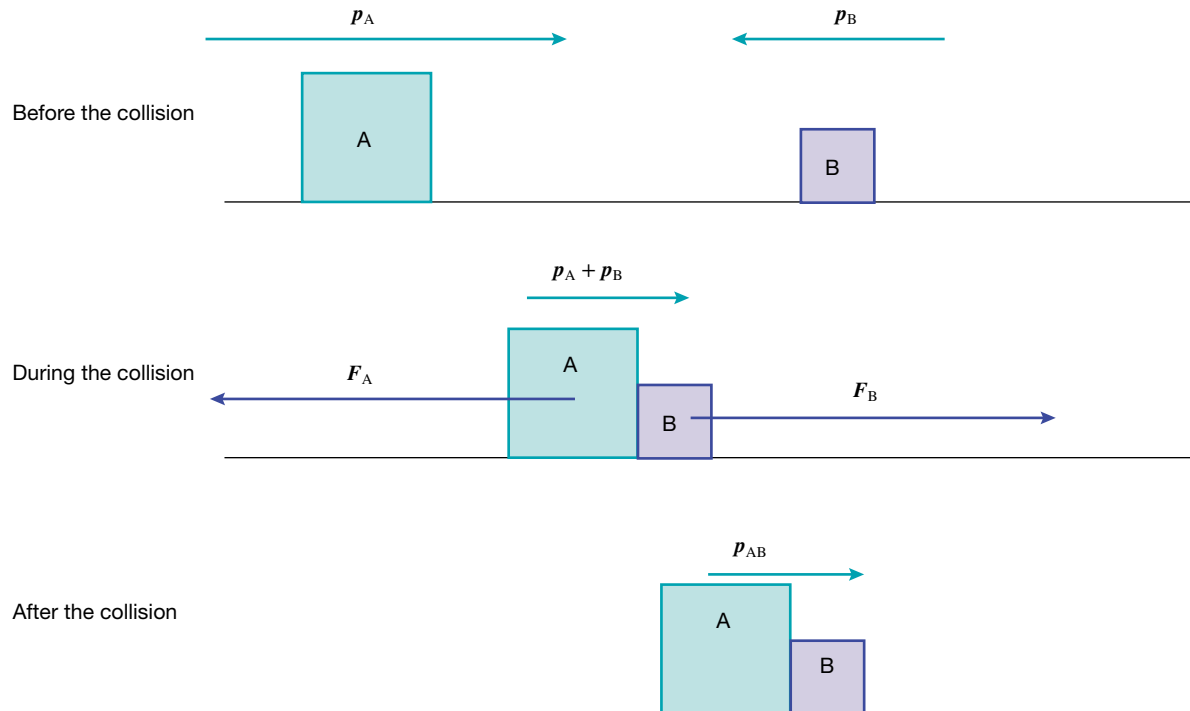
sum of momentum after = sum of the momentum before
Total momentum is conserved.

From this analysis it can be seen that the conservation of momentum is a logical consequence of Newton's third law.

The interaction between objects A and B can be summarised as follows.

- The total momentum of the system remains constant.
- The change in momentum of the system is zero.
- The change in momentum of object A is equal and opposite to the change in momentum of object B.

FIGURE 11.2 The net force on this system of two blocks is zero; therefore, momentum is conserved.



The total momentum of the system p_{AB} after the collision is the same as the total momentum of the system before and during the collision.

SAMPLE PROBLEM 1

Consider the collision illustrated in figure 11.2. Block A has a mass of 5 kilograms, block B has a mass of 3 kilograms and each block has a speed of 4 m s^{-1} before the collision. After the collision, the blocks move off together. Friction may be ignored.

- Determine the velocity of the blocks after the collision.
- What is the change in momentum of each of the blocks?
- What is the impulse on block A during the collision?
- Determine the final velocity of block B if, instead of moving off together, block A rebounds to the left with a speed of 0.5 m s^{-1} .

Teacher-led video: SP1 (tlvd-0093)

THINK

- Recall the formula for conservation of momentum.
- Calculate the momentum of each block to find $p_A + p_B$. Take right as the positive direction.
- Use the formula for conservation of momentum to find the velocity of the blocks after the collision.

WRITE

a. $p_A + p_B = p_{A+B}$

$$\begin{aligned} p_A + p_B &= m_A v_A + m_B v_B \\ &= 5 \times 4 + 3 \times -4 \\ &= 20 - 12 \\ &= 8 \text{ kg m s}^{-1} \text{ to the right} \end{aligned}$$

$$\begin{aligned} p_{A+B} &= p_A + p_B \\ m_{A+B} v_{A+B} &= 8 \\ (5 + 3)v &= 8 \\ v &= 1 \text{ m s}^{-1} \end{aligned}$$

4. State the solution.

The velocity of the blocks after the collision is 1 m s^{-1} to the right.

b. 1. Consider block A only.

$$\begin{aligned}\text{b. } \Delta p_A &= m_A \Delta v_A \\ &= 5(1 - 4) \\ &= 5 \times -3 \\ &= -15 \text{ kg m s}^{-1} \\ &= 15 \text{ kg m s}^{-1} \text{ to the left}\end{aligned}$$

2. Δp_B should be 15 kg m s^{-1} to the right since the change in momentum of the whole system is zero. To confirm this, consider block B alone.

$$\begin{aligned}\Delta p_B &= m_B \Delta v_B \\ &= 3(1 - (-4)) \\ &= 3 \times 5 \\ &= 15 \text{ kg m s}^{-1} \text{ to the right}\end{aligned}$$

3. State the solution.

The change in momentum of each of the blocks is 15 kg m s^{-1} .

c. 1. Impulse is equal to the change in momentum.

c. The impulse on block A is equal to the change in momentum of block A: 15 kg m s^{-1} to the left.

d. 1. By conservation of momentum
 $p_A + p_B = 8 \text{ kg m s}^{-1}$.

$$\begin{aligned}\text{d. } p_{Af} + p_{Bf} &= 8 \\ 5 \times -0.5 + 3v_{Bf} &= 8 \\ -2.5 + 3v_{Bf} &= 8 \\ 3v_{Bf} &= 10.5 \\ v_{Bf} &= \frac{10.5}{3} \\ v_{Bf} &= 3.5 \text{ m s}^{-1} \text{ to the right}\end{aligned}$$

2. State the solution.

The final velocity of block B if, instead of moving off together, block A rebounds to the left with a speed of 0.5 m s^{-1} is 3.5 m s^{-1} to the right.

PRACTICE PROBLEM 1

Consider a collision in which a model car of mass 5 kilograms travelling at 2 m s^{-1} in an easterly direction catches up to and collides with an identical model car travelling at 1 m s^{-1} in the same direction. The cars lock together after the collision. Friction can be assumed to be negligible.

- What was the total momentum of the two-car system before the collision?
- Calculate the velocity of the model cars as they move off together after the collision.
- What is the change in momentum of the car that was travelling faster before the collision?
- What is the change in momentum of the car that was travelling slower before the collision?
- What was the magnitude of impulse on both cars during the collision?
- How are the impulses on the two cars different from each other?

11.2.2 Modelling real collisions

The Law of Conservation of Momentum makes it possible to predict the consequences of collisions between two cars or between two people on a sporting field. For example, if a 2000-kilogram delivery van travelling at 30 m s^{-1} (108 km h^{-1}) collided with a small, stationary car of mass 1000 kilograms, the speed of the tangled wreck (the two vehicles locked together) could be predicted. However, you would need to assume that the frictional forces and driving force acting on both cars were zero after the collision. A reasonably good estimate can be made of the speed of the tangled wreck immediately after the collision in this way.

The initial momentum $\vec{p}_i$ of the system is given by:

$$\begin{aligned}\vec{p}_{\text{van}} + \vec{p}_{\text{car}} &= 2000 \text{ kg} \times 30 \text{ m s}^{-1} + 0 \text{ kg m s}^{-1} \\ &= 60\,000 \text{ kg m s}^{-1}\end{aligned}$$

Where the initial direction of the van is taken to be positive.

The momentum of the system after the collision p_f is the momentum of just one object — the tangled wreck:

$$p_f = 3000 \text{ kg} \times v$$

where v is the velocity of the tangled wreck after the collision.

But since $p_f = p_i$:

$$\begin{aligned}3000 \text{ kg} \times v &= 60\,000 \text{ kg m s}^{-1} \\ \Rightarrow v &= \frac{60\,000 \text{ kg m s}^{-1}}{3000 \text{ kg}} \\ &= 20 \text{ m s}^{-1}\end{aligned}$$

The speed of the small car changes a lot more than the speed of the large van. However, the change in the momentum of the car is equal and opposite to that of the van.

$$\begin{aligned}\Delta p_{\text{car}} &= 1000 \text{ kg} \times 20 \text{ m s}^{-1} - 0 \text{ kg m s}^{-1} \\ &= 20\,000 \text{ kg m s}^{-1} \\ \Delta p_{\text{van}} &= 2000 \text{ kg} \times 20 \text{ m s}^{-1} - 2000 \text{ kg} \times 30 \text{ m s}^{-1} \\ &= 40\,000 \text{ kg m s}^{-1} - 60\,000 \text{ kg m s}^{-1} \\ &= -20\,000 \text{ kg m s}^{-1}\end{aligned}$$

If the small car hit the stationary van at a speed of 30 m s^{-1} , and the two vehicles locked together, the speed of the tangled wreck would be less than 20 m s^{-1} . Apply the Law of Conservation of Momentum to predict the speed of the tangled wreck immediately after this collision.



Resources



Digital document Investigation 11.1 Simulating a collision (doc-31878)



Teacher-led video Investigation 11.1 Simulating a collision (tlvd-0823)

11.2 EXERCISE

To answer questions online and to receive **immediate feedback** and **sample responses** for every question go to your learnON title at www.jacplus.com.au.

1. Explain in terms of the Law of Conservation of Momentum how astronauts walking in space can change their speed or direction.
2. A physics student is experimenting with a low-friction trolley on a smooth horizontal surface. Predict the final velocity of the 2-kilogram trolley in each of the following two experiments.
 - (a) The trolley is travelling at a constant speed of 0.6 m s^{-1} . A suspended 2 kilograms mass is dropped onto it as it passes.
 - (b) The trolley is loaded with 2 kilograms of sand. As the trolley moves with an initial speed of 0.6 m s^{-1} , the sand is allowed to pour out through a hole behind the rear wheels.

3. Two stationary ice skaters, Catherine and Lauren, are facing each other and use the palms of their hands to push each other in opposite directions. Catherine, with a mass of 50 kilograms, moves off in a straight line with a speed of 1.2 m s^{-1} . Lauren moves off in the opposite direction with a speed of 1.5 m s^{-1} .
 - (a) What is Lauren's mass?
 - (b) What is the magnitude of the impulse that results in Catherine's gain in speed?
 - (c) What is the magnitude of the impulse on Lauren while the girls are pushing each other away?
 - (d) What is the total momentum of the system of Catherine and Lauren just after they push each other away?
 - (e) Would it make any difference to their final velocities if they pushed each other harder? Explain.



4. Nick and his brother Luke are keen rollerbladers. Nick approaches his stationary brother at a speed of 2.0 m s^{-1} and bumps into him. As a result of the collision Nick, who has a mass of 60 kilograms, stops moving and Luke, who has a mass of 70 kilograms, moves off in a straight line. The surface on which they are 'blading' is smooth enough that friction can be ignored.
 - (a) With what speed does Luke move off?
 - (b) What is the magnitude of the impulse on Nick as a result of the bump?
 - (c) What is the magnitude of Nick's change in momentum?
 - (d) What is the magnitude of Luke's change in momentum?
 - (e) How would the motion of each of the brothers after their interaction be different if they pushed each other instead of just bumping?
 - (f) If Nick held onto Luke so that they moved off together, what would be their final velocity?



5. An unfortunate driver of mass 50 kilograms travelling on an icy road in her 1200-kilogram car collides with a stationary police car of total mass 1500 kilograms (including occupants). The tangled wreck moves off after the collision with a speed of 7.0 m s^{-1} . The frictional force on both cars can be assumed to be negligible.
 - (a) At what speed was the unfortunate driver travelling before her car hit the police car?
 - (b) What was the impulse on the police car due to the collision?
 - (c) What was the impulse on the driver of the offending car (who was wearing a properly fitted seatbelt) due to the impact with the police car?
 - (d) If the duration of the collision was 0.10 seconds, what average net force was applied to the police car?
6. The Law of Conservation of Momentum can be written as $\Delta \mathbf{p}_B = -\Delta \mathbf{p}_A$, which equates the change in momentum of two different objects, A and B. Newton's third law is often expressed as $\mathbf{F}_{\text{on B by A}} = -\mathbf{F}_{\text{on A by B}}$. Although this equation looks very similar to a law of conservation, no such law exists for forces. Explain why this is the case.

11.3 Work and energy

KEY CONCEPTS

- Apply the concept of work done by a constant force using:
 - work done = constant force $\times$ distance moved in direction of force: $W = Fs$
 - work done = area under force-distance graph.

11.3.1 The concept of energy

A lot has already been said about energy in previous topics of this text. The word *energy* is used often in everyday language. Try writing down your own definition of energy. Look up a dictionary — any dictionary — to find out what it means. Most dictionaries and some physics textbooks define energy as the capacity to do work. The term *work* is defined as the quantity of energy transferred when an object moves in the direction of a force applied to it. These definitions do not, however, provide a clear understanding of what energy actually is.

Energy is a concept — an idea — that is used to describe and explain change. The following list of some of the characteristics of energy provides some clues as to what it really is.

- All matter possesses energy.
- Energy takes many different forms. It can therefore be classified. Light, internal energy, kinetic energy, gravitational potential energy, chemical energy and nuclear energy are some of the different forms of energy. The names given to different forms of energy sometimes overlap. For example, light is an example of radiant energy. Gamma radiation could be described as nuclear energy or radiant energy. Sound energy and electrical energy involve kinetic energy of particles.
- Energy cannot be created or destroyed. This statement is known as the Law of Conservation of Energy. The quantity of energy in the universe is a constant. However, nobody knows how much energy there is in the universe.
- Energy can be stored, transferred to other matter or transformed from one form into another.
- Some energy transfers and transformations can be seen, heard, felt, smelt or tasted.
- It is possible to measure the quantity of energy transferred or transformed. However, many energy transfers and transformations are not observable and therefore cannot be measured.

The concept of energy allows us to keep track of the changes that take place in a system. The system could be the universe, Earth, your home, the room you are in, your body or a car.

11.3.2 Getting down to work

Energy can be transferred to or from matter in several different ways. It can be transferred by:

- emission or absorption of electromagnetic radiation or nuclear radiation
- heating or cooling as the result of a temperature difference
- the action of a force on an object resulting in movement.

An interaction that involves the transfer of energy by the action of a force is called a **mechanical interaction**.

When mechanical energy is transferred to or from an object, the amount of mechanical energy transferred is called **work**.

The work (W) done when a force ($\vec{F}$) causes a displacement ($\vec{s}$) in the direction of the force is defined as:

work = magnitude of the force $\times$ magnitude of displacement in the direction of the force

$$W = \vec{F} \cdot \vec{s}$$

Work is a scalar quantity. The SI unit of work is the joule. One joule of work is done when a force of magnitude of 1 newton (N) causes a displacement of 1 metre in the same direction of the force. That is:

$$\begin{aligned} 1 \text{ J} &= 1 \text{ N} \times 1 \text{ m} \\ &= 1 \text{ N m} \end{aligned}$$

It is important to remember that work is always done *by* a force acting *on* something.

SAMPLE PROBLEM 2

A shopper pushes horizontally on a loaded supermarket trolley of mass 30 kilograms with a force of 150 N to move it a distance of 5 metres along a horizontal, straight path. The friction force opposing the motion of the trolley is a constant 120 N. How much work is done on the trolley by:

- the force applied by the shopper
- the net force
- the shopper to oppose the friction force?

 **Teacher-led video:** SP2 (tlvd-0094)

THINK

- Recall the formula for work done.
 - State the solution.
- Calculate the net force on the trolley, then use the formula for work done.
 - State the solution.

WRITE

- $$\begin{aligned} W &= Fs \\ &= 150 \times 5 \\ &= 750 \text{ J} \end{aligned}$$

750 J of work is done on the trolley by the force applied by the shopper.
- $$\begin{aligned} F_{\text{net}} &= 150 - 120 \\ &= 30 \text{ N} \end{aligned}$$
$$\begin{aligned} W &= F_{\text{net}}s \\ &= 30 \times 5 \\ &= 150 \text{ J} \end{aligned}$$

150 J of work is done on the trolley by the new force.

- c. 1. The force applied to oppose the friction is equal to the friction force.

Use this force to calculate the work done.

2. State the solution.

$$\begin{aligned} \text{c. } W &= Fs \\ &= 120 \times 5 \\ &= 600 \text{ J} \end{aligned}$$

600 J of work is done on the trolley by the shopper to oppose the friction force.

PRACTICE PROBLEM 2

A warehouse worker pushes a heavy crate a distance of 2 metres across a horizontal concrete floor against a constant friction force of 240 N. He applies a horizontal force of 300 N on the crate. How much work is done on the crate by:

- the warehouse worker
- the net force?

11.3.3 Force-versus-distance graphs

The work done by a force can be calculated from a force-versus-displacement, or force-versus-distance graph. For this to be applicable the force presented in the graph and the displacement must be in the same direction.

The work done is equal to the area under the force-versus-distance graph.

SAMPLE PROBLEM 3

A filing cabinet is pushed in a straight line across the floor of an office during some spring cleaning. The force applied in the direction of its motion and its displacement are recorded in the graph provided. Determine the work done.



THINK

- The work done can be calculated by the area under the graph.
- The area of a trapezium is $\frac{1}{2}(a + b)h$ where a and b are the lengths of the horizontal sides and h is the height.
- State the solution.

WRITE

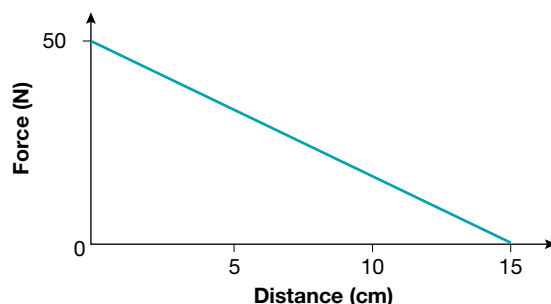
$$W = \text{area under graph}$$

$$\begin{aligned} W &= \frac{1}{2}(3 + 1) 150 \\ &= 300 \text{ J} \end{aligned}$$

300 J of work is done.

PRACTICE PROBLEM 3

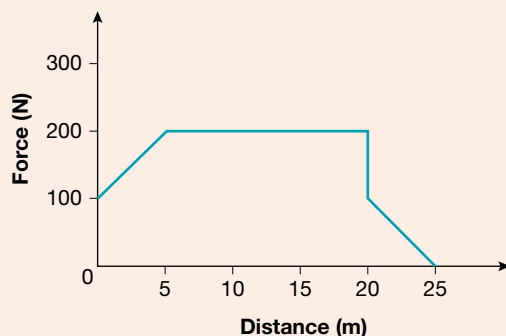
A spring is used in an old fashioned pinball machine to launch the ball from a rest position into the arcade game. The following graph shows the force applied to the ball by the spring during this motion against the distance travelled in the direction of the force. Determine the work done.



11.3 EXERCISE

To answer questions online and to receive **immediate feedback** and **sample responses** for every question go to your learnON title at www.jacplus.com.au.

1. A box is pushed across the floor with force as shown in the following force-versus-displacement graph. Calculate the work done to push the box 25 metres.



2. How much work is done on a 4-kilogram brick as it is pushed a distance of 1.5 metres by a net force of 40 N?
3. Imagine that you are trying to push-start a 2000-kilogram truck with its handbrake on. How much work are you doing on the truck?
4. A toddler swings her fluffy toy by a string around in circles at a constant speed. How much work does she do on the toy in completing:
 - (a) one full revolution
 - (b) half of a full revolution?

studyon

To answer practice exam questions online and to receive immediate feedback and sample responses for every question go to your learnON title at www.jacplus.com.au.

studyON: Practice questions online only

Fully worked solutions and sample responses are available in your digital formats.

11.4 Energy transfers

KEY CONCEPTS

- Investigate and analyse theoretically and practically Hooke's Law for an ideal spring: $F = -k\Delta x$.
- Analyse and model mechanical energy transfers and transformations using energy conservation:
 - changes in gravitational potential energy near Earth's surface: $E_g = mg\Delta h$
 - potential energy in ideal springs: $E_s = \frac{1}{2}k\Delta x^2$
 - kinetic energy: $E_k = \frac{1}{2}mv^2$.

11.4.1 Kinetic energy

Kinetic energy is the energy associated with the movement of an object. By imagining how much energy it would take to stop a moving object, it can be deduced that kinetic energy depends on the mass and speed of the object.

A formula for kinetic energy can be deduced by recalling Newton's First Law of Motion:

Every object continues in its state of rest or uniform motion unless made to change by a non-zero net force.

The kinetic energy of an object can change only as a result of a non-zero net force acting on it in the direction of motion. It follows that the change in kinetic energy of an object is equal to the work done on it by the net force acting on it. If an object initially at rest is acted on by a net force of magnitude F_{net} and moves a distance s (which will necessarily be in the direction of the net force), its change in kinetic energy ΔE_k can be expressed as:

$$\Delta E_k = F_{\text{net}}s$$

The quantity of kinetic energy it possesses is:

$$E_k = F_{\text{net}}s$$

because the initial kinetic energy was zero.

Applying Newton's second law ($F_{\text{net}} = ma$) to this expression:

$$E_k = mas$$

where m is the mass of the object.

The movement of the object can also be described in terms of its initial velocity v and its final velocity u . The magnitudes of the quantities a , s , v and u are related to each other by the equation:

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

If the object acquires a speed v as a result of the work done by the net force:

$$v^2 = 2as \quad \text{since } u = 0$$

$$\Rightarrow as = \frac{v^2}{2}$$

Substituting this into the expression for kinetic energy:

$$\begin{aligned} E_k &= mas \\ \Rightarrow E_k &= \frac{mv^2}{2} \end{aligned}$$

The kinetic energy of an object of mass m and speed $\vec{v}$ can therefore be expressed as:

$$E_k = \frac{1}{2}m\vec{v}^2$$

Note that the momentum ($\vec{p} = m\vec{v}$) is a vector quantity, whereas kinetic energy $E_k = \frac{1}{2}m\vec{v}^2$ is a scalar quantity.

SAMPLE PROBLEM 4

Compare the kinetic energy of an Olympic track athlete running the 100-metre sprint with that of a family car travelling through the suburbs. Assume the athlete is 70 kilograms and travelling at 10 m s^{-1} and the car is 1500 kilograms and travelling at 60 km h^{-1} .

 Teacher-led video: SP4 (tlvd-0096)

THINK

1. Use the estimated mass and speed to calculate the kinetic energy of the athlete.
2. Convert the speed into m s^{-1}
3. Use the estimated mass and speed to calculate the kinetic energy of the family car.
4. Interpret the results.
5. State the solution.

WRITE

$$\begin{aligned} E_k &= \frac{1}{2}mv^2 \\ &= \frac{1}{2} \times 70 \times 10^2 \\ &= 3500 \text{ J} \\ \text{Speed} &\approx 60 \text{ km h}^{-1} \\ &\approx 17 \text{ m s}^{-1} \\ E_k &= \frac{1}{2}mv^2 \\ &= \frac{1}{2} \times 1500 \times 17^2 \\ &\approx 217\,000 \text{ J} \\ \frac{217\,000}{3500} &= 62 \end{aligned}$$

The family car has approximately 62 times more kinetic energy than the athlete.

PRACTICE PROBLEM 4

- a. Calculate the kinetic energy of a 2000-kilogram elephant charging at a speed of 8.0 m s^{-1} .
- b. Estimate the kinetic energy of:
 - i. a cyclist riding to work
 - ii. a snail crawling across a footpath.

SAMPLE PROBLEM 5

A shopper pushes horizontally on a loaded supermarket trolley of mass 30 kilogram with a force of 150 N to move it a distance of 5 metres along a horizontal, straight path. The friction force opposing the motion of the trolley is a constant 120 N. If the trolley starts from rest what is its final speed?

 Teacher-led video: SP5 (tlvd-0097)

THINK

1. The change in kinetic energy of the trolley is equal to the work done on it by the net force acting on it.
2. As the trolley was initially at rest the change in kinetic energy is equal to the final kinetic energy.
3. Use the formula for kinetic energy to calculate the velocity.
4. State the solution.

WRITE

$$\Delta E_k = F_{\text{net}} s$$

$$\begin{aligned} E_k &= F_{\text{net}} s \\ &= 30 \times 5.0 \\ &= 150 \text{ J} \end{aligned}$$

$$\begin{aligned} E_k &= \frac{1}{2} m v^2 \\ 150 &= \frac{1}{2} \times 30 \times v^2 \end{aligned}$$

$$\begin{aligned} v^2 &= \frac{150}{15} \\ &= 10 \\ v &= \sqrt{10} \\ &\approx 3.2 \text{ m s}^{-1} \end{aligned}$$

The trolley's final speed is 3.2 m s^{-1} .

PRACTICE PROBLEM 5

A gardener pushes a loaded wheelbarrow with a mass of 60 kilograms a distance of 4 metres along a straight horizontal path against a constant friction force of 120 N. He applies a horizontal force of 150 N on the wheelbarrow. If the wheelbarrow is initially at rest, what is its final speed?

If the net force is in the opposite direction to that in which the object is moving, the object slows down. For example, the work done by the net force to stop a 70-kilogram athlete running at a speed of 10 m s^{-1} is given by:

$$\begin{aligned} \text{work done by net force} &= \Delta E_k \\ &= 0 - \frac{1}{2} m v^2 \\ &= -\frac{1}{2} \times 70 \text{ kg} \times (10 \text{ m s}^{-1})^2 \\ &= -3500 \text{ J} \end{aligned}$$

The negative sign indicates that the direction of the net force is opposite to the direction of the displacement.

SPEED KILLS

The truth of the slogan 'Speed kills' can be appreciated by comparing the kinetic energy of a 1500-kilogram car travelling at 60 km h^{-1} (16.7 m s^{-1}) with that of the same car travelling at 120 km h^{-1} (33.3 m s^{-1}).

At 60 km h^{-1} , the car's kinetic energy is:

$$\begin{aligned} E_k &= \frac{1}{2} m v^2 \\ &= \frac{1}{2} \times 1500 \text{ kg} \times (16.7 \text{ m s}^{-1})^2 \\ &= 2.1 \times 10^5 \text{ J} \end{aligned}$$

At 120 km h^{-1} , its kinetic energy is:

$$\begin{aligned}E_k &= \frac{1}{2}mv^2 \\&= \frac{1}{2} \times 1500 \text{ kg} \times (33.3 \text{ m s}^{-1})^2 \\&= 8.3 \times 10^5 \text{ J}\end{aligned}$$

In other words, a 100% increase in speed produces a 400% increase in the kinetic energy and therefore four times as much work needs to be done on the car to stop it during a crash with a solid object.

11.4.2 Potential energy

Energy that is stored is called potential energy. Objects that have potential energy have the capacity to apply forces and do work. Potential energy takes many forms.

- The food that you eat contains potential energy. Under certain conditions, the energy stored in food can be transformed into other forms of energy. Your body is able to transform the potential energy in food into internal energy so that you can maintain a constant body temperature. Your body transforms some of the food's potential energy into the kinetic energy of blood, muscles and bones so that you can stay alive and move. Some of it is transformed into electrochemical energy to operate your nervous system.
- Batteries contain potential energy.
- An object that is in a position from which it could potentially fall has **gravitational potential energy**. The gravitational potential energy of an object is 'hidden' until the object is allowed to fall. Gravitational potential energy exists because of the gravitational attraction of masses towards each other. All objects with mass near the Earth's surface are attracted towards the centre of the Earth. The further away from the Earth's surface an object is, the more gravitational potential energy it has.
- Energy can be stored in objects by compressing them, stretching them, bending them or twisting them. If the change in shape can be reversed, energy stored in this way is called **strain potential energy**. Strain potential energy can be transformed into other forms of energy by allowing the object to reverse its change in shape.

11.4.3 Gravitational potential energy

When an object is in free fall, work is done on it by the force of gravity, transforming gravitational potential energy into kinetic energy. When you lift an object, you do work on it by applying an upwards force on it greater than or equal to its weight. Although the gravitational field strength, g , decreases with distance from the Earth's surface, it can be assumed to be constant near the surface. The increase in gravitational potential energy ΔE_{gp} by an object of mass m lifted through a height Δh can be found by determining how much work is done on it by the force (or forces) opposing the force of gravity.

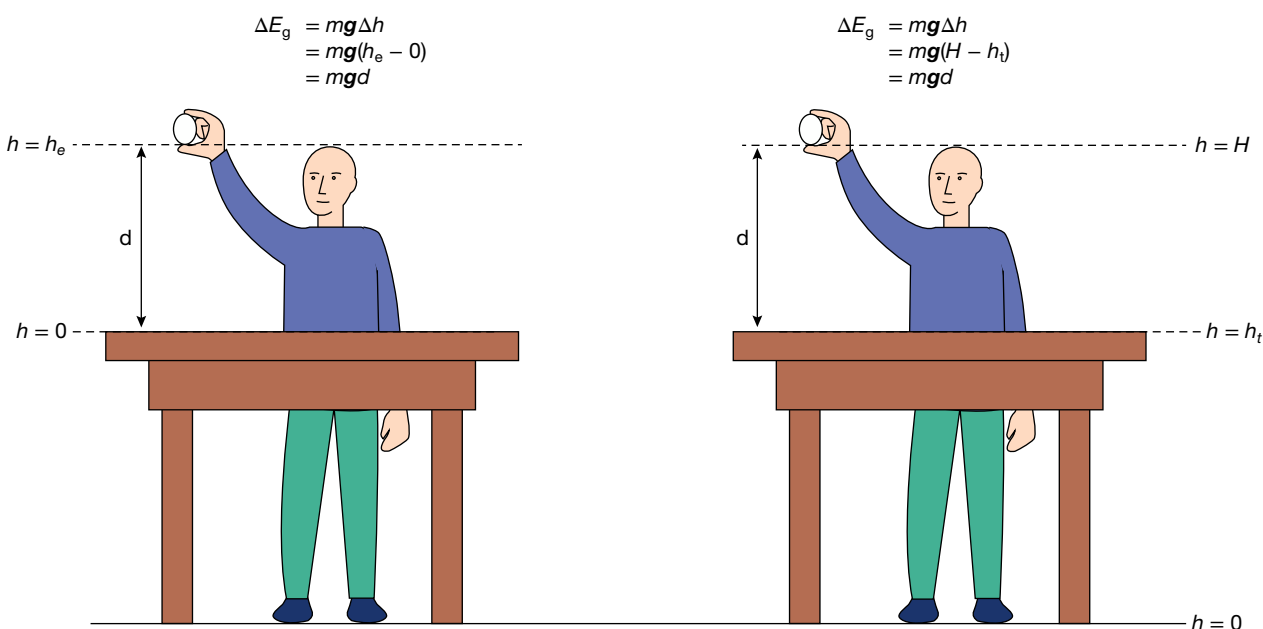
$$\begin{aligned}W &= Fs \\&= mg\Delta h \quad (\text{substituting } F = mg \text{ and } s = \Delta h) \\ \Rightarrow \Delta E_{\text{g}} &= mg\Delta h\end{aligned}$$

This formula only provides a way of calculating *changes* in gravitational potential energy. If the gravitational potential energy of an object is defined to be zero at a reference height, a formula for the quantity of gravitational potential energy can be found for an object at height h above the reference height.

$$\begin{aligned}\Delta E_{\text{g}} &= mg\Delta h \\ \Rightarrow E_{\text{g}} - 0 &= mg(h - 0) \\ \Rightarrow E_{\text{g}} &= mgh\end{aligned}$$

Usually the reference height is ground or floor level. Sometimes it might be more convenient to choose another reference height. However, it is the change in gravitational potential energy that is most important in investigating energy transformations. Figure 11.3 shows that the gain in gravitational potential energy as a raw egg is lifted from the surface of a table is mgd . When the raw egg is dropped to the table, the result will be the same whether you use the height of the table or ground level as your reference height. The gravitational potential energy gained will be transformed into kinetic energy as work is done on the egg by the force of gravity.

FIGURE 11.3 The choice of reference height does not have any effect on the change in gravitational potential energy.



THE FOSBURY FLOP

High jumpers use a technique called the Fosbury Flop that allows them to clear the bar while keeping their centre of mass as low as possible. The gravitational potential energy needed to clear the bar is minimised. Thus, with their maximum kinetic energy at take-off, high jumpers can clear those extra few centimetres.

Incidentally, you might like to estimate just how much energy is needed to clear the bar in the high jump. Start by working out the change in height of an athlete's centre of mass during a jump of about 2 metres.

FIGURE 11.4 The Fosbury Flop places a high jumper's centre of mass below the bar.



11.4.4 Strain potential energy

Work must be done on an object by a force in order to change its strain potential energy. However, when objects are compressed, stretched, bent or twisted, the force needed to change their shape is not constant. For example, the more you stretch a rubber band, the harder it is to stretch it further. The more you compress the sole of a running shoe, the harder it is to compress it further. The amount of strain potential energy gained by stretching a rubber band or by compressing the sole of a running shoe can be determined by calculating the amount of work done on it.

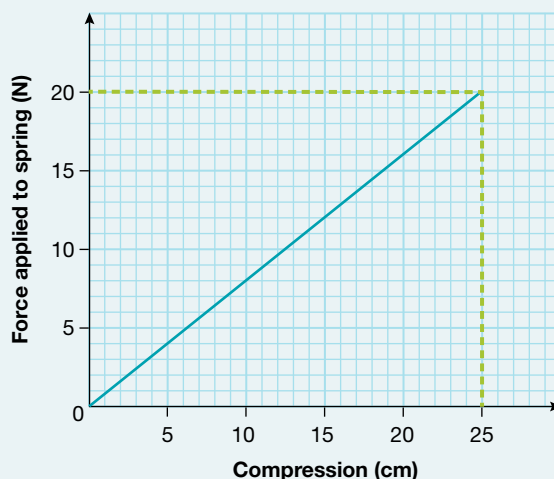
The amount of work done by a changing force is given by:

$$W = F_{\text{av}} s$$

It can be determined by calculating the area under a graph of force versus displacement in the direction of the force. In the case of a simple spring, a rubber band or the sole of a running shoe, the work done (and hence the change in strain potential energy) can be calculated by determining the area under a graph of force versus extension, or force versus compression.

SAMPLE PROBLEM 6

The following figure shows how the force required to compress a spring changes as the spring is compressed. How much strain potential energy is stored in the spring when it is compressed by 25 centimetres?



THINK

1. The amount of strain potential energy added to the spring when it is compressed is equal to the amount of work done to compress it.
2. Work is equal to the area under the graph.
3. State the solution.

WRITE

$$E_s = W$$

$$W = \text{area under graph}$$

$$= \frac{1}{2} \times 20 \times 0.25$$

$$= 2.5 \text{ J}$$

2.5 J strain potential energy is stored in the spring when it is compressed by 25 centimetres.

PRACTICE PROBLEM 6

How much strain potential energy is stored in the spring described in Sample problem 6 when it is compressed by a distance of:

- a. 10 centimetres
- b. 20 centimetres?

Hooke's Law

The spring in Sample problem 6 is an example of an ideal spring. For an ideal spring, the force required to compress (or extend) the spring is directly proportional to the compression (or extension):

$$F \propto \Delta x$$

Where:

F is the force exerted by the spring

Δx is the displacement of the spring.

This relationship is expressed fully by Hooke's Law, which states:

$$F = -k\Delta x$$

where k is known as the spring constant.

The negative sign in Hooke's Law is necessary because the direction of the force applied by the spring is always opposite to the direction of the spring's displacement. For example, if the spring is compressed, it pushes back in the opposite direction. If the spring is extended, it pulls back in the opposite direction.

Hooke's Law is more conveniently expressed without vector notation as:

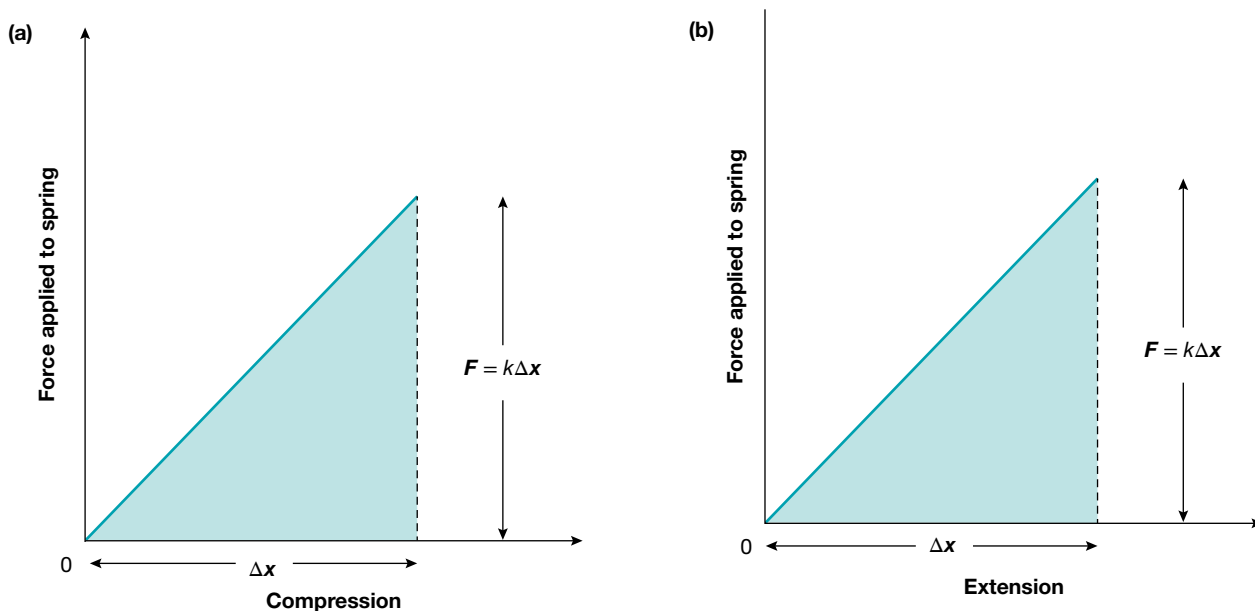
$$\vec{F} = k\Delta\vec{x}$$

Where:

$\vec{F}$ is the magnitude of the force applied by the spring

$\Delta\vec{x}$ is the magnitude of the extension or compression of the spring.

FIGURE 11.5 Graphs showing the force applied by an ideal spring versus (a) compression and (b) extension



The strain energy stored in a spring that is changed in length by $\Delta\vec{x}$, whether it is compressed or extended, is equal to the area under the force-versus-compression graph or the force-versus-extension graph. That is:

$$\begin{aligned}\text{strain potential energy } (E_s) &= \frac{1}{2} \times k\Delta\vec{x} \times \Delta\vec{x} \\ &= \frac{1}{2}k(\Delta\vec{x})^2\end{aligned}$$

SAMPLE PROBLEM 7

A wooden block is pushed against an ideal spring of length 30 centimetres until its length is reduced to 20 centimetres. The spring constant of the spring is 50 N m^{-1} .

- What is the magnitude of the force applied on the wooden block by the compressed spring?
- How much strain potential energy is stored in the compressed spring?
- How much work was done on the spring by the wooden block?

 Teacher-led video: SP7 (tlvd-0099)

THINK

- Recall Hooke's Law.
 - Substitute the values into the equation.
 - State the solution.
- Recall the formula for strain potential energy.
 - Substitute the values into the equation.
 - State the solution.
- The work done on the spring is equal to the elastic potential energy.
 - State the solution.

WRITE

- $F = k\Delta x$
 $\Delta x = 0.30 - 0.20 = 0.10 \text{ m}$
 $= 50 \times 0.10$
 $= 5.0 \text{ N}$
 5 N is applied on the wooden block by the compressed spring.
- $E_s = \frac{1}{2}k(\Delta x)^2$
 $= \frac{1}{2} \times 50 \times 0.10^2$
 $= 0.25 \text{ J}$
 0.25 J of strain potential energy is stored in the compressed spring.
- $W = E_s$
 $= 0.25 \text{ J}$
 0.25 J of work was done on the spring by the wooden block.

PRACTICE PROBLEM 7

- An object hanging from the end of a spring extends the spring by 20 centimetres. The spring constant is 60 N m^{-1} .
 - What upwards force is applied to the object by the spring?
 - How much strain potential energy is stored in the spring when it is extended by 50 centimetres?
 - What is the mass of the object?
- What is the spring constant of the spring described in Sample problem 6?

11.4.5 Conservation of energy

Conservation of energy is a law of the universe. It states that the total energy in an isolated system is constant. Considering the universe is an isolated system, the total amount of energy is constant, meaning energy cannot be created or destroyed.

Energy can, however, be transferred from one form to another. A single bounce of a tennis ball onto a hard surface involves the following mechanical energy transformations.

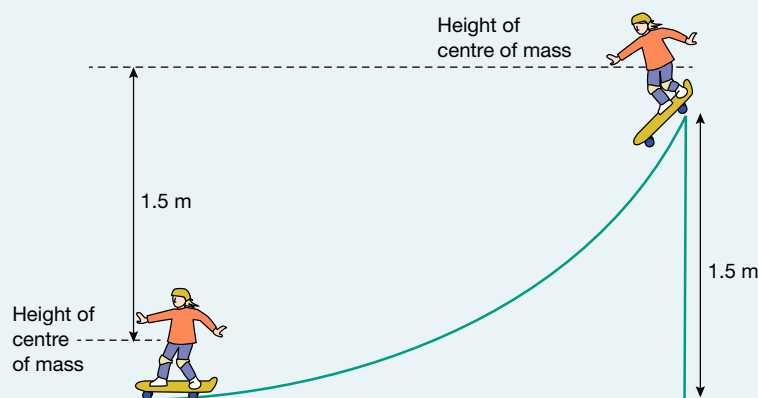
- As the ball falls, the force of gravity does work on the ball, transforming gravitational potential energy into kinetic energy.
- As soon as the bottom of the tennis ball touches the ground, the upwards push of the ground does work on the tennis ball, transforming kinetic energy into strain potential energy. A small amount of gravitational potential energy is also transformed into strain potential energy. This continues until the kinetic energy of the ball is zero.
- As the ball begins to rise and remains in contact with the ground, the upwards push of the ground does work on the tennis ball, transforming strain potential energy into kinetic energy and a small amount of gravitational potential energy until the ball loses contact with the ground.
- As the ball gains height, the force of gravity does work on the ball, transforming kinetic energy into gravitational potential energy.

FIGURE 11.6 Energy is transferred into different forms when a tennis ball is bounced.



SAMPLE PROBLEM 8

A skateboarder of mass 50 kilograms, starting from rest, rolls from the top of a curved ramp, a vertical drop of 1.5 metres (see the following figure). What is the speed of the skateboarder at the bottom of the ramp? (The frictional force applied to the skateboarder by the ramp is negligible.)



 Teacher-led video: SP8 (tlvd-0100)

THINK

1. It can be assumed in this case that the total mechanical energy is conserved. The only transformation that takes place is that from gravitational potential energy to kinetic energy. The gain in kinetic energy of the skateboarder is therefore equal to the magnitude of the loss of gravitational potential energy.
2. Substitute the values into the equation.

3. State the solution.

WRITE

$$\Delta E_k = \Delta E_{gp}$$

$$\frac{1}{2}mv^2 = mg\Delta h$$

$$\Delta E_k = \Delta E_{gp}$$

$$\frac{1}{2}mv^2 = mg\Delta h$$

$$\frac{1}{2} \times 50v^2 = 50 \times 9.8 \times 1.5$$

$$25v^2 = 735$$

$$v^2 = \frac{735}{25}$$

$$v = \sqrt{\frac{735}{25}}$$

$$v \approx 5.4 \text{ m s}^{-1}$$

The speed of the skater at the bottom of the ramp is 5.4 m s^{-1} .

PRACTICE PROBLEM 8

A toy car of mass **0.5 kilograms** is pushed against an ideal spring so that the spring is compressed by **0.1 metres**. The spring constant of the spring is 80 N m^{-1} .

- a. How much strain potential energy is stored in the spring when it is compressed?
- b. After the toy car is released, what will be its speed at the instant that the spring returns to its natural length?

AS A MATTER OF FACT

Kangaroos have huge tendons in their hind legs that store and return elastic potential energy much more efficiently than do those of other mammals of comparable size. This allows them to hop for very large distances without tiring. An adult red kangaroo can jump over obstacles up to 2 metres in height.

A young 50-kilogram kangaroo is capable of storing about 360 J of energy in each of its hind legs. A typical four-legged animal of the same mass stores about 55 J in each of its hind legs while running.

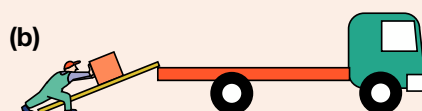
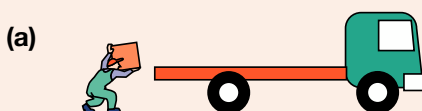
FIGURE 11.7 An adult red kangaroo.



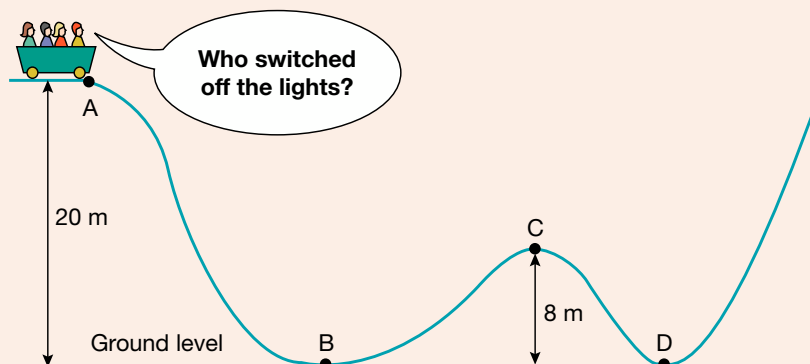
11.4 EXERCISE

To answer questions online and to receive **immediate feedback** and **sample responses** for every question go to your learnON title at www.jacplus.com.au.

- Use the formulae for work and kinetic energy to show that their units are equivalent.
- Estimate the kinetic energy of:
 - a car travelling at 60 km h^{-1} on a suburban street
 - a 58 gram tennis ball as it is returned to the server in a Wimbledon final.
- Estimate the amount of work done on a 58 gram tennis ball by the racquet when the ball is served at a speed of 200 km h^{-1} .
- Estimate the change in gravitational potential energy of:
 - a skateboarder riding down a half-pipe
 - a child sliding from the top to the bottom of a playground slide
 - you at your maximum height as you jump up from rest.
- A truck driver wants to lift a heavy crate of books with a mass of 20 kilograms onto the back of a truck through a vertical distance of 1 metre. The driver needs to decide whether to lift the crate straight up, or push it up along a ramp.

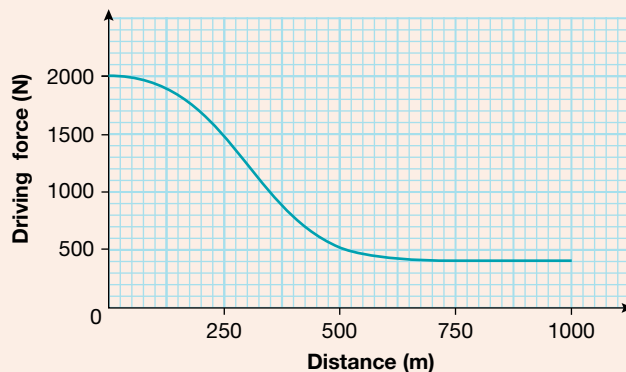


- What is the change in gravitational potential energy of the crate of books in each case?
 - How much work must be done against the force of gravity in each case?
 - If the ramp is perfectly smooth, how much work must be done by the truck driver to push the crate of books onto the back of the truck?
 - In view of your answers to (b) and (c), which of the two methods is the best way to get the crate of books onto the back of the truck? Explain your answer.
- World-class hurdlers raise their centre of mass as little as possible when they jump over the hurdles. Why?
 - Two ideal springs, X and Y, have spring constants of 200 N m^{-1} and 100 N m^{-1} respectively. They are each extended by 20 centimetres by pulling with a hook. For each of the springs, determine:
 - the magnitude of the force applied to the hook
 - the strain potential energy.
 - A tourist on an observation tower accidentally drops her 1.2-kilogram camera to the ground 20 metres below.
 - What kinetic energy does the camera gain before shattering on the ground?
 - What is the speed of the camera as it hits the ground?
 - The following figure shows part of a roller-coaster track. As a fully loaded roller-coaster car of total mass 450 kilograms approaches point A with a speed of 12 m s^{-1} , the power fails and it rolls freely down the track. The friction force on the car can be assumed to be negligible.

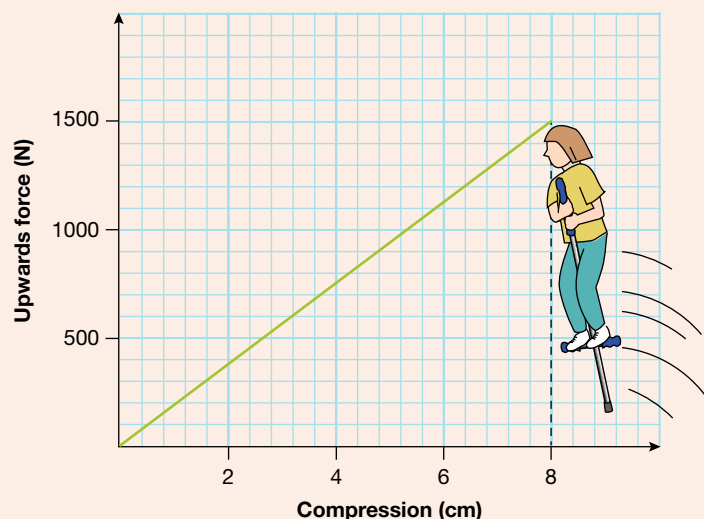


- What is the kinetic energy of the loaded car at point A?
- Determine the speed of the loaded car at each of points B and C.
- What maximum height will the car reach after passing point D?

10. The following graph shows how the driving force on a 1200-kilogram car changes as it accelerates from rest over a distance of 1 kilometre on a horizontal road. The average force opposing the motion of the car due to air resistance and road friction is 360 N.



- (a) How much work has been done by the forward push (the driving force) on the car?
 (b) How much work has been done on the car to overcome both air resistance and road friction?
 (c) What is the speed of the car when it has travelled 1 kilometre?
11. A toy truck of mass 0.5 kilograms is pushed against a spring so that it is compressed by 0.1 metres. The spring obeys Hooke's Law and has a spring constant of 50 N m^{-1} . When the toy truck is released, what will be its speed at the instant that the spring returns to its natural length? Assume that there is no frictional force resisting the motion of the toy truck.
12. A pogo stick contains a spring that stores energy when it is compressed. The following graph shows how the upwards force of a pogo stick on a 30-kilogram child jumping on it changes as the spring is compressed. The maximum compression of the spring is 8 centimetres. Assume that all of the energy stored in the spring is transformed to the mechanical energy of the child. The mass of the pogo stick itself can be ignored.



- (a) How do you know that the spring in the pogo stick is an ideal spring?
 (b) What is the spring constant of the spring?
 (c) How much work is done on the child by the pogo stick as the spring expands?
 (d) What is the kinetic energy of the child at the instant that the compression of the pogo stick spring is zero?
 (e) How high does the child rise from the ground? Assume that the child leaves the ground at the instant that the compression of the pogo stick spring is zero.
13. Describe the mechanical energy transformations that take place when a child jumps up and down on a trampoline.

14. Discuss the mechanical energy transformations that take place when a diver uses a springboard to dive into the water, from the time that the diver is standing motionless on the springboard until the time she reaches her lowest point in the water. Use a graph describing the energy transformations in both the springboard and the diver to illustrate your answer.
15. Discuss the mechanical energy transformations that take place when a skateboard rider gets airborne off the end of a ramp (see the figure on the right).
 - (a) Use a graph to describe the energy transformations that occur during the time interval between starting at one end of the ramp, getting airborne at the other end and returning to the starting point.
 - (b) Explain in terms of the energy transformations how it is possible for the rider's feet to remain in contact with the skateboard while in the air.



studyon

To answer practice exam questions online and to receive immediate feedback and sample responses for every question go to your learnON title at www.jacplus.com.au.

studyON: Practice exam questions online only

Fully worked solutions and sample responses are available in your digital formats.

11.5 Efficiency and power

KEY CONCEPTS

- Calculate the efficiency of an energy transfer system: $\eta = \frac{\text{useful energy out}}{\text{total energy in}}$.
- Analyse rate of energy transfer using power: $P = \frac{E}{t}$.

11.5.1 Efficiency

Along with kinetic energy, gravitational potential energy and strain potential energy are referred to as forms of mechanical energy. Transformation to or from each of these forms of energy requires the action of a force. Of course, if mechanical energy were conserved, a ball would return to the same height from which it was dropped. In fact, mechanical energy is not conserved. During each of the mechanical transformations that occur during a bounce, some of the ball's mechanical energy is transformed to thermal energy of the air, ground and ball, resulting in a small temperature increase. Some mechanical energy is also lost as sound, and as the ball undergoes permanent deformation.

Mechanical energy losses to thermal energy, sound, and so on are largely permanent. It is very difficult to convert this lost energy back into mechanical energy and so it is not considered useful.

The efficiency, η , of an energy transfer is calculated from the ratio:

$$\eta = \frac{\text{useful energy out}}{\text{total energy in}}$$

where η is the Greek letter 'eta'.

SAMPLE PROBLEM 9

A ball dropped from 1.5 metres rebounds to 1.2 metres. What is the efficiency?

THINK

1. Recall the formula for efficiency.
2. Calculate the total energy in.
3. Calculate the useful energy out.
4. Substitute these values into the formula to find the efficiency.
5. State the solution.

WRITE

$$\eta = \frac{\text{useful energy out}}{\text{total energy in}}$$

The total energy in is the initial gravitational potential energy of the ball.

$$\begin{aligned} E_g &= mgh \\ &= mg \times 1.5 \end{aligned}$$

The 'useful energy out' is the gravitational potential energy of the ball at its rebound height of 1.2 metres.

$$\begin{aligned} E_g &= mgh \\ &= mg \times 1.2 \end{aligned}$$

$$\eta = \frac{\text{useful energy out}}{\text{total energy in}}$$

$$= \frac{1.2mg}{1.5mg}$$

$$= 0.8$$

$$= 80\%$$

The efficiency is 80%.

PRACTICE PROBLEM 9

A basketball is pumped up to give an efficiency of 80% when dropped. If this basketball is dropped from a height of 2 metres, to what height does it rebound after the fourth bounce?

11.5.2 Power

Power is the rate at which energy is transferred or transformed.

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

Where:

E = the energy transformed, in joules

t = the time taken, in seconds.

In the case of conversions to or from mechanical energy or between different forms of mechanical energy, power, P , can be defined as the rate at which work is done.

$$P = \frac{W}{\Delta t}$$

Where:

W = the work done, in joules

Δt = the time interval during which the work is done, in seconds.

The SI unit of power is the watt (W), which is defined as 1 J s^{-1} .

The power delivered when a force, F , is applied to an object can also be expressed in terms of the object's speed v .

$$\begin{aligned} P &= \frac{W}{\Delta t} = \frac{Fx}{\Delta t} \\ &= F \times \frac{x}{\Delta t} \\ &= Fv \end{aligned}$$

SAMPLE PROBLEM 10

A student of mass 40 kilograms walks briskly up a flight of stairs to climb four floors of a building, a vertical distance of 12 metres in a time interval of 40 seconds.

- At what rate is the student doing work against the force of gravity?
- If energy is transformed by the leg muscles of the student at the rate of 30 kJ every minute, what is the student's power output?

 **Teacher-led video:** SP10 (tlvd-0102)

THINK

- The work done by the student against the force of gravity is equal to the gain in gravitational potential energy.
 - Recall the formula for power.
- State the solution.

- Recall the formula for power.

- State the solution.

WRITE

- $$\begin{aligned} W &= mg\Delta h \\ &= 40 \times 9.8 \times 12 \\ &= 4704 \text{ J} \\ P &= \frac{W}{\Delta t} \\ &= \frac{4704}{40} \\ &\approx 118 \text{ W} \end{aligned}$$

The student is doing work against the force of gravity at a rate of 118 W.

- $$\begin{aligned} P &= \frac{\text{energy transferred}}{\text{time taken}} \\ &= 30 \text{ kJ min}^{-1} \\ &= \frac{30\,000 \text{ J}}{60 \text{ s}} \\ &= 500 \text{ W} \end{aligned}$$

If energy is transformed by the leg muscles of the student at the rate of 30 kJ every minute, the student's power output is 500 W.

PRACTICE PROBLEM 10

- If all of the 720 J of energy stored in the hind legs of a young 50-kilogram kangaroo were used to jump vertically, how high could it jump?
- What is the kangaroo's power output if the 720 J of stored energy is transformed into kinetic energy during a 1.2 second interval?

WHICH IS EASIER — RIDING A BIKE OR RUNNING?

A normal bicycle being ridden at a constant speed of 4 m s^{-1} on a horizontal road is subjected to a rolling friction force of about 7 N and air resistance of about 6 N . The forward force applied to the bicycle by the ground must therefore be about 13 N . The mechanical power output required to push the bicycle along at this speed is:

$$\begin{aligned} P &= Fv \\ &= 13 \text{ N} \times 4 \text{ m s}^{-1} \\ &= 52 \text{ W} \end{aligned}$$

Running at a speed of 4 m s^{-1} requires a mechanical power output of about 300 W . Even walking at a speed of 2 m s^{-1} requires a mechanical power output of about 75 W .

Riding a bicycle on a horizontal surface is less tiring than walking or running for two reasons.

1. Less mechanical energy is needed. The body of the rider does not rise and fall as it does while walking or running, eliminating the changes in gravitational potential energy.
2. Because the rider is seated, the muscles need to transform much less chemical energy to support body weight. The strongest muscles in the body can be used almost exclusively to turn the pedals.

Once you start riding uphill or against the wind, the mechanical power requirement increases significantly. For example, in riding along an incline that rose 1 metre for every 10 metres of road distance covered, the additional power needed by a 50-kilogram rider travelling at 4 m s^{-1} would be:

$$\begin{aligned} P &= \frac{\Delta E_{\text{gp}}}{\Delta t} \\ &= \frac{mg\Delta h}{\Delta t} \end{aligned}$$

In a time interval of 1 seconds , the vertical climb is $\frac{1}{10}$ of $4 \text{ m} = 0.4 \text{ m}$.

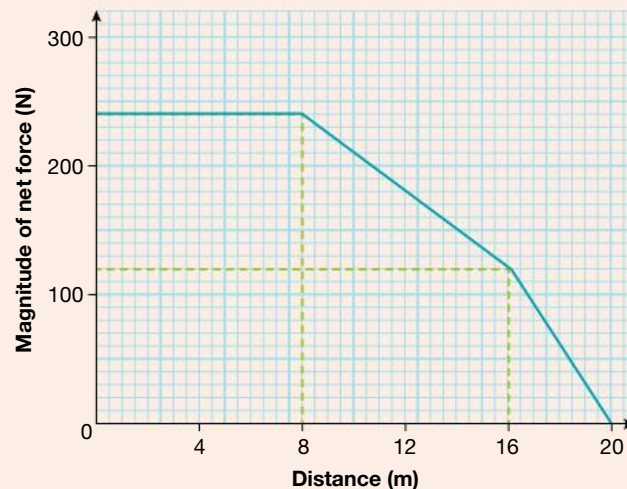
$$\begin{aligned} \Rightarrow P &= \frac{50 \text{ kg} \times 10 \text{ N kg}^{-1} \times 0.4 \text{ m}}{1 \text{ s}} \\ &= 200 \text{ W} \end{aligned}$$

11.5 EXERCISE

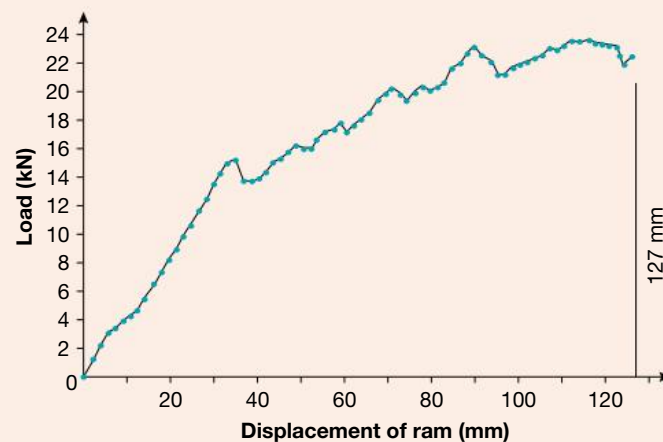
To answer questions online and to receive **immediate feedback** and **sample responses** for every question go to your learnON title at www.jacplus.com.au.

1. When a cricket ball bounces on a hard surface, 32% of the kinetic energy is stored as elastic potential energy. If a 160 gram cricket ball is dropped from a height of 2 metres onto a hard surface, calculate:
 - (a) the kinetic energy of the ball as it hits the ground
 - (b) the maximum amount of elastic potential energy stored in the ball
 - (c) the height to which it will rebound.
2. A car of mass 1500 kilograms travelling at 50 km h^{-1} collides with a concrete barrier. The car comes to a stop over a distance of 60 centimetres as the front end crumples.
 - (a) What is the average net force on the car as it stops?
 - (b) What is the average acceleration of the car and its occupants? Assume that the occupants are wearing properly fitted seatbelts.
 - (c) What would be the average acceleration of properly restrained passengers in a very old car with no crumple zone if it stopped over a distance of only 10 centimetres ? (The maximum magnitude of acceleration that humans can survive is about 600 m s^{-2} .)

- (d) Explain in terms of mechanical energy transformations why the front and rear ends of cars are designed to crumple.
- (e) In a collision with a rigid barrier, would you feel safer in a large or a small car? Use some sample calculations to illustrate your answer.
3. A girl of mass 50 kilograms rollerblades freely from rest down a path inclined at 30° to the horizontal. The following graph shows how the magnitude of the net force on the girl changes as she progresses down the path.



- (a) What is the kinetic energy of the girl after rolling a distance of 8 metres?
- (b) What is the sum of the friction force and air resistance on the girl over the first 8 metres?
- (c) What is the kinetic energy of the girl at the end of her 20-metre roll?
- (d) How much gravitational potential energy has been lost by the girl during her 20-metre roll?
- (e) Account for the difference between your answers to (c) and (d).
4. The following graph shows the results of a roof crush test conducted in the laboratories of the Department of Civil Engineering at Monash University.



- (a) How much work has been done on the roof when the ram has reached its maximum displacement?
- (b) If the car has a mass of 1400 kilograms, from what height would it need to be dropped on its roof to crush it by 127 millimetres?
5. Jo and Bill are conducting an experimental investigation into the bounce of a basketball. Bill drops the ball from various heights and Jo measures the rebound height. They also use an electronic timer with thin and very light wires attached to the ball and to a foil on the floor to measure the impact time. A top-loading balance measures the mass of the ball. What physical quantities can they calculate using these four measurements?
6. A tractor engine has a power output of 80 kW. The tractor is able to travel to the top of a 500-metre high hill in 4 minutes and 30 seconds. The mass of the tractor is 2.2 tonnes. What is the efficiency of the engine?

7. Human muscle has an efficiency of about 20%. Take a heavy mass, about 1–2 kilograms, in your hand. With your hand at your shoulder, raise and lower the mass 10 times as fast as you can. Measure the mass, your arm extension and the time taken, and calculate the amount of energy expended and your power output.
8. A pile driver has an efficiency of 80%. The hammer has a mass 500 kilograms and the pile a mass of 200 kilograms. The hammer falls through a distance of 5 metres and drives the pile 50 millimetres into the ground. Calculate the average resistance force exerted by the ground.
9. Estimate the average power delivered to a 58 gram tennis ball by a racquet when the ball is served at a speed of 200 km h^{-1} and the ball is in contact with the racquet for 4 milliseconds.
10. At what average rate is work done on a 4-kilogram brick as it is lifted through a vertical distance of 1.5 metres in 1.2 seconds?
11. In the sport of weightlifting, the clean-and-jerk involves bending down to grasp the barbell, lifting it to the shoulders while squatting and then jerking it above the head while straightening to a standing position. In 1983, Bulgarian weightlifter Stefan Topurov became the first man to clean and jerk three times his own body mass when he lifted 180 kilograms. Assume that he raised the barbell through a distance of 1.8 metres in a time of 3.0 seconds.
 - (a) How much work did Stefan do in overcoming the force of gravity acting on the barbell?
 - (b) How much power was supplied to the barbell to raise it against the force of gravity?
 - (c) How much work did Stefan do on the barbell while he was holding it stationary above his head?
12. A small car travelling at a constant speed of 20 m s^{-1} on a horizontal road is subjected to air resistance of 570 N and road friction of 150 N. What power provided by the engine of a car is used to keep it in motion at this speed?
13. While a 60-kilogram man is walking at a speed of 2 m s^{-1} , his centre of mass rises and falls 3 centimetres with each stride. At what rate is he doing work against the force of gravity if his stride length is 1 metre?
14. A bicycle is subjected to a rolling friction force of 6.5 N and an air resistance of 5.7 N. The total mass of the bicycle and its rider is 75 kilograms. Its mechanical power output while being ridden at a constant speed along a horizontal road is 56 W.
 - (a) At what speed is it being ridden?
 - (b) If the bicycle was ridden at the same speed up a slope inclined at 30° to the horizontal, what additional mechanical power would need to be supplied to maintain the same speed? Assume that the rolling friction and air resistance are the same as on the horizontal road.

studyon

To answer practice exam questions online and to receive immediate feedback and sample responses for every question go to your learnON title at www.jacplus.com.au.

studyON: Practice exam questions 

Fully worked solutions and sample responses are available in your digital formats.

11.6 Review

11.6.1 Summary

- If the net force acting on a system is zero, the total momentum of the system does not change. This statement is an expression of the Law of Conservation of Momentum.
- If there are no external forces acting on a system of two objects when they collide, the change in momentum of the first object is equal and opposite to the change in momentum of the second object.
- The Law of Conservation of Energy states that energy cannot be created or destroyed.
- Work is done when energy is transferred to or from an object by the action of a force. The work done on an object by a force is the product of the magnitude of the force and the magnitude of the displacement in the direction of the force.
- All moving objects possess kinetic energy. The kinetic energy of an object can be expressed as:

$$E_k = \frac{1}{2}mv^2$$

- The work done on an object by the net force is equal to the object's change in kinetic energy.
- The change in gravitational potential energy of an object near the Earth's surface can be expressed as:

$$\Delta E_g = mg\Delta h$$

where Δh is the object's change in height.

- The change in the strain potential energy stored in an object can be found by determining the area under a force-versus-compression or force-versus-extension graph.
- The force F applied by an ideal spring when it is compressed or extended is proportional to its displacement Δx . This relationship is expressed by Hooke's Law:

$$F = -k\Delta x$$

where k is known as the spring constant.

- The strain potential energy stored in an ideal spring is expressed as $E_s = \frac{1}{2}k(\Delta x)^2$.
- Kinetic energy, gravitational potential energy and strain potential energy are referred to as forms of mechanical energy. During a mechanical interaction, it is usually reasonable to assume that total mechanical energy is conserved.
- The efficiency of an energy transfer is calculated from the ratio:

$$\text{efficiency, } \eta = \frac{\text{useful energy out}}{\text{total energy in}}$$

- Power is the rate at which energy is transferred or transformed. In mechanical interactions, power is also equal to the rate at which work is done.

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

- The power delivered by a force is the product of the magnitude of the force and the velocity of the object on which the force acts.

on Resources

studyon

To access key concept summaries and practice exam questions download and print the studyON: Revision and practice exam question booklet (sonr-0036)

11.6.2 Key terms

Gravitational potential energy is the energy stored in an object as a result of its position relative to another object to which it is attracted by the force of gravity.

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

A **mechanical interaction** is one in which energy is transferred from one object to another by the action of a force.

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

Strain potential energy is the energy stored in an object as a result of a reversible change in shape. It is also known as elastic potential energy.

Work is done when energy is transferred to or from an object by the action of a force. Work is a scalar quantity.

on Resources

 **Digital document** Key terms glossary (doc-32270)

11.6.3 Practical work and investigations

Investigation 11.1

Simulating a collision

Aim: To show that momentum is conserved in a collision in which there are no unbalanced external forces acting on the system

Digital document: doc-31878

Teacher-led video: tlvd-0823



Investigation 11.2

Climbing to the top

Aim: To investigate the difference that extra load makes to the work done against gravity and the power developed

Digital document: doc-31881

Other practical work ideas:

- Investigate the magnetic collision between two air track gliders. **Hint:** Use an ultrasound motion detector or a high-speed digital camera.
- Investigate the force of impact on a bouncing ball.

on Resources



Digital document Practical investigation logbook (doc-32271)

11.6 Exercises

To answer questions online and to receive immediate feedback and sample responses for every question go to your learnON title at www.jacplus.com.au.

11.6 Exercise 1: Multiple choice questions

- Two identical toy cars are travelling directly towards each other at 5 m s^{-1} . They have a head on collision. They are stuck together after the collision. Assume friction is negligible. What is their combined speed after the collision?
 - 0 m s^{-1}
 - 2.5 m s^{-1}
 - 5 m s^{-1}
 - 10 m s^{-1}
- Two physics students, Steve and Terri, are standing at rest next to each other on skateboards. They push against each other and move off in opposite directions. The friction on the floor is negligible. Steve has a mass of 75 kilograms and was moving at a speed of 5 m s^{-1} immediately after he lost contact with Terri. Terri has a mass of 60 kilograms. What is the impulse that Steve exerted on Terri.
 - 15 N s^{-1}
 - 300 N s^{-1}
 - 375 N s^{-1}
 - 6.25 N s^{-1}

3. Trish applies a constant horizontal force of 125 N to push a 95-kilogram rock a distance of 5 metres horizontally across her lawn. Calculate the work done.
- A. 11 875 J
 - B. 625 J
 - C. 59 375 J
 - D. 475 J
4. Emily kicks a football high into the air before she is tackled. The ball strikes the ground at a speed of 25 m s^{-1} . Assuming that the ball is of regulation size and has a mass of 500 grams, calculate its kinetic energy the instant before it struck the ground.
- A. 12.5 J
 - B. 156 J
 - C. 313 J
 - D. 6.25 J
5. Kate creates a toy for her cats to play with by hanging a fluffy object at the bottom of a spring. The spring constant is 5 N m^{-1} . One of the cats is able to stretch the spring by 10 centimetres. How much energy has the cat stored in the spring?
- A. 0.5 J
 - B. 0.05 J
 - C. 0.25 J
 - D. 0.025 J
6. Rohan rides his pushbike home from work. At the end of his journey he has gained 25 metres in altitude. Assuming that his mass is 80 kilograms, determine how much gravitational potential energy he has gained over this journey.
- A. 2000 J
 - B. 19 600 J
 - C. 245 J
 - D. 784 J
7. Louise stretches a spring, causing it to extend in length by 17 centimetres. The spring constant is 125 N m^{-1} . Determine the force that Louise has applied to the spring at this extension.
- A. 21.25 N
 - B. 2125 N
 - C. 7.36 N
 - D. 736 N
8. To assist them in their studies of motion in physics, Grover and Bailey are riding on a roller coaster. The combined mass of the two students and the carriage is 369 kilograms. As part of the ride they stop momentarily at the highest point in the track. The cart then accelerates down a steep slope, dropping 40 metres in vertical height at the end of the slope. What is the total kinetic energy of the cart and students at the end of the slope.
- A. 200 295 J
 - B. 295 200 J
 - C. 648 144 J
 - D. 144 648 J
9. Scott is building a small robot that uses a number of electrical engines to run its wheels and arms. One of the engines is specified to be 90% efficient. If the engine is provided with 42 J of energy to perform a manoeuvre, how much useful energy will it output.
- A. 34 J
 - B. 37.8 J
 - C. 42 J
 - D. 46.7 J

10. Matt is building a wall out of stone. This requires a lot of stone to be lifted into place. Matt lifts a 3.7-kilogram stone 47 centimetres in 0.8 seconds. What is the average rate that he is doing work on the stone during this motion?
- A. 2130 W
 - B. 1704 W
 - C. 21.3 W
 - D. 17 W

11.6 Exercise 2: Short answer questions

1. John is practising for a tennis tournament by hitting a ball against a wall. The ball strikes the wall at 27 m s^{-1} and rebounds in the opposite direction at 19 m s^{-1} . The ball has a mass of 58.5 grams.
 - a. Calculate the change in momentum of the ball.
 - b. Calculate the average force exerted by the wall on the ball during this collision.
2. A large car of mass 1980 kilograms travelling at 11 m s^{-1} collides head on with a small car of mass 970 kilograms. Immediately after they collide, the cars are stuck together and have come to a complete stop. Calculate the speed of the smaller car immediately before the collision.
3. A teacher applies a constant vertical force 40 N to lift a 4-kilogram box of physics exam papers 0.8 metres directly upwards from the floor onto a bench. Assume that the motion is at a constant speed. Calculate the work done by the teacher on the box of exam papers.
4. An Airbus A380 of mass 560 000 kilograms lands on a runway at a speed of 250 km h^{-1} . Determine its kinetic energy at this instant.
5. As part of a practical investigation a physics student hangs various objects on an ideal spring and measures its extension. The spring constant is 90 N m^{-1} . One of the objects that the student hangs on the spring causes it to extend by 12 centimetres.
 - a. What upwards force is applied to the object by the spring?
 - b. What is the mass of the object?
 - c. How much strain potential energy is stored in the spring?
6. A rock climber climbs a cliff, gaining a vertical height of 185 metres above where they started by the end of their climb. Assuming that their mass is 72 kilograms, how much gravitational potential energy have they gained as a result of their climb?
7. A vase of flowers, is at rest 175 metres vertically above the surface of the Earth. It falls freely, smashing onto the ground below. Assume that it has a mass of 420 grams and air resistance is negligible. Considering the instant immediately before it smashes on the ground, determine its:
 - a. kinetic energy
 - b. speed.
8. A car of mass 1500 kilograms is travelling along a level road at a constant speed of 62 km h^{-1} . The driver applies the accelerator and the force on the driven wheels does 550 000 J of work to accelerate the car to a higher speed. Determine what the new speed of the vehicle is.
9. A softball of mass 180 grams strikes a hard stationary surface while travelling at a speed of 23 m s^{-1} . It rebounds in the opposite direction at 10 m s^{-1} .
 - a. Calculate the kinetic energy of the ball before and after this collision.
 - b. Determine the efficiency of the collision.
10. A car travelling at a constant speed of 30 m s^{-1} on a horizontal stretch of highway experiences a combined resistance force of 1150 N from the air and the road. Determine the power that the engine of the car must deliver to the driven wheels to keep it in motion at this constant speed.

11.6 Exercise 3: Exam practice questions

Question 1 (1 mark)

As part of a practical investigation, physics students are measuring the energy transformations of objects sliding down a ramp that they have constructed. A heavy box is allowed to slide down the ramp. The students find that the kinetic energy gained is less than the change in gravitational potential energy. Explain why this is the case. Assume that there are no significant errors in their methodology or measurement.

Question 2 (3 marks)

A runaway tram of mass 26 000 kilograms is travelling at a speed of 54 km h^{-1} when it collides with a stationary tram of mass 35 000 kilograms. After an impact of duration 0.40 seconds the two trams are stuck together and continue to move along the track.

a. Calculate the speed of the trams after the collision.

2 marks

b. Determine the average force acting on the runaway tram during the collision.

1 mark

Question 3 (2 marks)

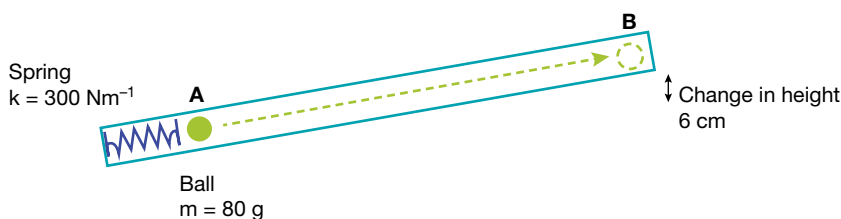
A physics student is waiting tables at a restaurant. They have been doing this work for some time and have perfected the ability to carry a tray of drinks across the room in a purely horizontal motion at a constant speed. Is the student doing work on the tray of drinks during this constant speed motion? Refer to relevant physics principles in your response.

Question 4 (2 marks)

A new energy storage system is proposed as an alternative to using chemical batteries. It stores energy as gravitational potential energy instead. A prototype of this system uses an old mine shaft with a 450-metre vertical drop to reach the bottom. A 2500-kilogram mass is attached to an electrical motor/generator. The mass is lowered to the bottom of the shaft. When there is electricity available it is used to run the motor to raise the mass up. When electricity is needed, the mass is dropped and the motor is used to generate electricity. At peak capacity, the system takes 520 seconds for the mass to travel the entire 450-metre drop. Calculate the power output of the system.

Question 5 (3 marks)

A physics student is investigating the energy transformations involved in the workings of pinball machines. In particular they decide to focus on the launch of the ball. The following is a diagram they made of the key details of the machine.



At the start of the game the spring is compressed by 10 centimetres by the machine and the ball sits motionless against it at point A. When the spring is released it pushes on the ball, transferring its energy to the ball and travels up the machine to point B. At point B the ball has gained 6 centimetres in height. Calculate the speed of the ball when it reaches B. Assume that friction is negligible.

11.6 Exercise 4: studyON topic test online only

Fully worked solutions and sample responses are available in your digital formats.

teachon

Test maker

Create unique tests and exams from our extensive range of questions, including practice exam questions. Access the assignments section in learnON to begin creating and assigning assessments to students.

UNIT 2 | AREA OF STUDY 1 REVIEW

AREA OF STUDY 1

How can motion be described and explained?

OUTCOME 1

Investigate, analyse and mathematically model the motion of particles and bodies.

PRACTICE EXAMINATION

STRUCTURE OF PRACTICE EXAMINATION		
Section	Number of questions	Number of marks
A	20	20
B	4	20
Total		40

Duration: 50 minutes

Information:

- This practice examination consists of two parts. You must answer all question sections.
- Pens, pencils, highlighters, erasers, rulers and a scientific calculator are permitted.
- You may use the VCAA Physics formula sheet for this task.



Resources



Weblink VCAA Physics formula sheet

SECTION A — Multiple choice questions

All correct answers are worth 1 mark each; an incorrect answer is worth 0.

Use the following information to answer questions 1 and 2.

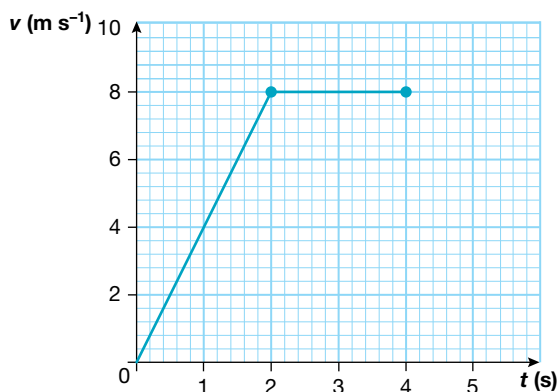
A body travels 25 metres north in a time of 8.0 seconds. It stops for 2.0 seconds, then moves 7.0 metres south in a time of 2.0 seconds.

1. Which of the following is the best estimate of its average velocity?
 - A. 2.7 m s^{-1}
 - B. 1.5 m s^{-1}
 - C. 3.3 m s^{-1}
 - D. 3.5 m s^{-1}
2. Which of the following is the best estimate of its average speed?
 - A. 2.7 m s^{-1}
 - B. 1.5 m s^{-1}
 - C. 3.3 m s^{-1}
 - D. 3.5 m s^{-1}

3. A dodgem car was travelling at 5.0 m s^{-1} south when it collided head-on with another dodgem car, and its velocity changed to 3.0 m s^{-1} north over a time interval of 0.80 seconds. What is the average acceleration of the first dodgem car?
- A. 2.5 m s^{-2} north
B. 2.5 m s^{-2} south
C. 10.0 m s^{-2} north
D. 10.0 m s^{-2} south

Use the following information to answer questions 4 and 5.

The following is a velocity-versus-time graph of a car moving away from a traffic stop.



4. What is the average acceleration of the car in the first two seconds?
- A. 2 m s^{-2}
B. 4 m s^{-2}
C. 6 m s^{-2}
D. 8 m s^{-2}
5. What is the distance covered by the car in the first four seconds?
- A. 24 m
B. 32 m
C. 40 m
D. 48 m
6. Consider the following four descriptions for the motion of a body.
- i. Velocity is positive and acceleration is positive.
 - ii. Velocity is positive and acceleration is negative.
 - iii. Velocity is negative and acceleration is positive.
 - iv. Velocity is negative and acceleration is negative.
- Which of the following best describes the two scenarios in which the body is *slowing down*?
- A. i. and ii.
B. ii. and iii.
C. i. and iii.
D. i. and iv.

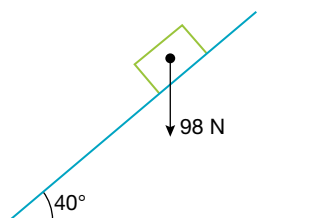
Use the following information to answer questions 7 and 8.

A truck travelling on a road changes its velocity from 3.0 m s^{-1} to 9.0 m s^{-1} and covers a distance of 24 metres during this period of acceleration.

7. What is the magnitude of the truck's acceleration?
 - A. 0.25 m s^{-2}
 - B. 0.50 m s^{-2}
 - C. 1.5 m s^{-2}
 - D. 4.0 m s^{-2}
8. Which of the following is the best estimate for the time taken to accelerate the truck?
 - A. 2 seconds
 - B. 4 seconds
 - C. 6 seconds
 - D. 8 seconds
9. A passenger is not wearing a seatbelt in a car moving forward. The car runs head-on into a barrier and the passenger hits her head against the windscreen in front of her. The best explanation for her motion immediately after the car hit the barrier is which of the following?
 - A. She experienced a force that pushed her forward towards the windscreen.
 - B. She experienced no force on her and kept moving forward.
 - C. She experienced a force from the barrier that pushed her towards the windscreen.
 - D. She experienced no force on her by the barrier but one from the car, which pushed her forwards.
10. A man is in a lift travelling upwards at constant speed. He stands on a spring balance that reads 750 N. What is the magnitude of the force exerted on the man by the floor of the lift?
 - A. Zero
 - B. Slightly less than 750 N
 - C. 750 N
 - D. Slightly more than 750 N
11. A small car of mass 800 kilograms is accelerating at 2.5 m s^{-2} . What is the magnitude of the net force on the car?
 - A. 320 N
 - B. 1200 N
 - C. 1600 N
 - D. 2000 N
12. A truck of mass 3600 kilograms is carrying a load of mass M . A net driving force of 9600 N causes an acceleration of 2.0 m s^{-2} . What is the mass M ?
 - A. 6000 kg
 - B. 4800 kg
 - C. 2400 kg
 - D. 1200 kg
13. A body, J , travelling to the right at a high velocity, collides with a stationary body, K . Which of the following best describes the forces in the interaction between J and K ?
 - A. $\mathbf{F}_{\text{on } J \text{ by } K} = \mathbf{F}_{\text{on } K \text{ by } J}$
 - B. $-\mathbf{F}_{\text{on } J \text{ by } K} = -\mathbf{F}_{\text{on } K \text{ by } J}$
 - C. $-\mathbf{F}_{\text{on } J \text{ by } K} = \mathbf{F}_{\text{on } K \text{ by } J}$
 - D. $\mathbf{F}_{\text{on } J \text{ by } K} - \mathbf{F}_{\text{on } K \text{ by } J} = 0$
14. A window-washer with a mass of 60 kilograms is standing on a platform that is accelerating upwards at a constant rate of 1.2 m s^{-2} . What is the force exerted on the platform by the person?
 - A. 660 N down
 - B. 660 N up
 - C. 588 N up
 - D. 588 N down

Use the following information to answer questions 15 and 16.

A box is at rest on a ramp inclined at 40° to the horizontal, as shown in the following diagram. The force due to gravity is 98 N.



15. What is the magnitude of the normal force that the surface of the ramp is exerting on the box?
 - A. 63 N
 - B. 75 N
 - C. 82 N
 - D. 98 N
16. What is the magnitude of the friction force that the surface of the ramp is exerting on the box?
 - A. 63 N
 - B. 75 N
 - C. 82 N
 - D. 98 N

Use the following information to answer questions 17 and 18.

A jogger with mass of 80 kilograms is moving east at 7 m s^{-1} . He then slows down to a velocity of 2 m s^{-1} east over a period of 2 seconds.

17. Which of the following best describes the change in momentum of the jogger?

A. 560 kg m s^{-1} east	B. 560 kg m s^{-1} west
C. 400 kg m s^{-1} east	D. 400 kg m s^{-1} west
18. What is the magnitude of the average force exerted on the jogger to slow him down?

A. 280 N	B. 200 N
C. 160 N	D. 80 N
19. A ball of mass 0.42 kilograms is at rest on the field. It is kicked and reaches a maximum speed of 13.5 m s^{-1} . What is the work done on the ball when it was kicked?

A. 12 J	B. 24 J
C. 38 J	D. 77 J
20. A spring has an unstretched length of 0.7 metres. After a mass of 2.5 kilograms is attached to it, its length is 1.2 metres. What is the spring constant of this spring?

A. 20 N m^{-1}	B. 35 N m^{-1}
C. 49 N m^{-1}	D. 98 N m^{-1}

SECTION B — Short answer questions

Question 1 (4 marks)

A cyclist is pedalling along a straight stretch of road at a constant velocity of 6.0 m s^{-1} . She then accelerates at a constant rate for 4.0 seconds, reaching a final velocity of 14 m s^{-1} .

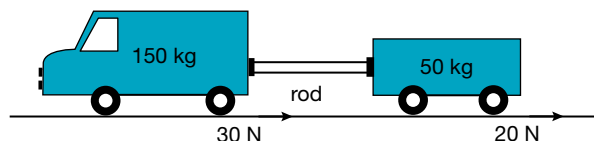
- a. What is the magnitude of the cyclist's acceleration? 1 mark
- b. How far did she travel during the period that she was accelerating? 1 mark

While travelling at 14 m s^{-1} the cyclist applied constant braking, coming to a stop over a distance of 24.5 m.

- c. What is the magnitude of the cyclist's acceleration while she was braking? 1 mark
- d. How long did the bicycle slow down to a stop? 1 mark

Question 2 (6 marks)

A van with mass 150 kilograms tows a small trailer with mass of 50 kilograms. They are connected by a towing rod that can be considered to be massless. The driving force is entirely provided by the electric motor on the van. The total resistive force on the van is 30 N, while the total resistive force on the trailer is 20 N. The van and trailer are accelerating at 1.9 m s^{-2} .



- a. Calculate the net force acting on the van and trailer. 1 mark
- b. Determine the size of the driving force provided by the electric motor on the van. 2 marks
- c. What is the size of the tension force of the rod on the trailer? 3 marks

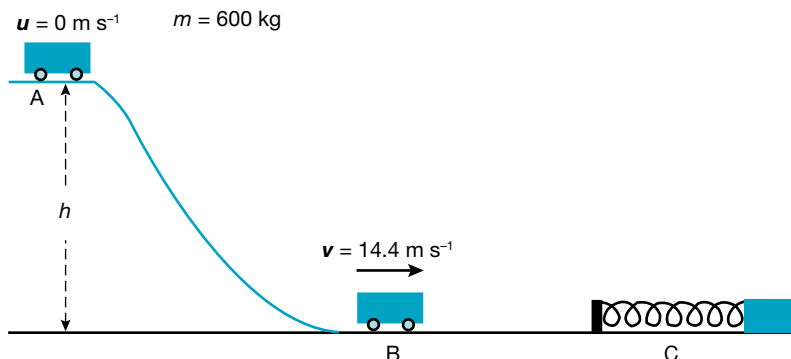
Question 3 (4 marks)

Suzy, an ice skater with a mass of 55 kilograms, is skating at a constant velocity of 4.8 m s^{-1} east. She collides with Kai, another ice skater, who is stationary. They move off together at a constant velocity of 3.0 m s^{-1} east. The collision may be considered as isolated.

- a. What was Suzy's initial momentum before the collision? 1 mark
- b. Considering that the collision is isolated, what is the mass of Kai? 3 marks

Question 4 (6 marks)

A stationary cart, mass 600 kilograms, is at the top of a sloping ramp at point A. It is released and rolls down the ramp and attains its maximum speed of 14.4 m s^{-1} at point B.



- a. Calculate the kinetic energy of the cart at point B. 2 marks
- b. Assuming that friction is negligible and there is no energy lost, what is the height, h , of the ramp? 2 marks
- c. The cart hits a spring at point C, which compresses and slows the cart down to a stop. The spring compresses a distance of 7.40 metres. What is the spring constant of the spring? 2 marks

ASSESSMENT TASK — DATA ANALYSIS

In this task, you will be required to investigate, analyse and mathematically model the motion of particles and bodies.

- A scientific calculator is permitted. You will need graph paper for this task.

Total time: 50 minutes (5 minutes reading and 45 minutes writing)

Total marks: 34 marks

TRACKING THE POSITION OF ATHLETES

The motion of an athlete can be studied using a radar system that can track their position on a course. The data obtained (shown in table 1 below) gives the position of the runner down a straight athletics track in half-second intervals for the first three seconds of the race and one-second intervals thereafter. The athlete is training for a 100-metre race. At time $t = 0$, the athlete is in the starting blocks and the gun goes off.

**USEFUL FORMULAE FOR THIS TASK**

Average speed: $v = \frac{\Delta x}{\Delta t}$

Average acceleration: $a = \frac{\Delta v}{\Delta t}$

Momentum: $p = mv$

Kinetic energy: $E_k = \frac{1}{2}mv^2$

- Use the data in table 1 to plot a distance-versus-time graph.

TABLE 1 Distance versus time

Time (s)	Distance (m)
0.00	0.00
0.50	0.60
1.00	2.40
1.50	5.40
2.00	9.60
2.50	15.0
3.00	21.0
4.00	32.9
5.00	44.7
6.00	56.4
7.00	67.8
8.00	79.0
9.00	89.9
10.0	100.7

2. By taking pairs of data, complete a table for the average speed of the runner for each pair of data points in table 1.

The first data point, in which the average speed of the athlete in the first interval is 1.2 m s^{-1} (determined through dividing the change in distance by the change in time), has been done for you. It occurs at the midpoint in time of the first frame. This will be at $t = 0.25$ seconds.

TABLE 2 Average speed versus time

Time (s)	Average speed (m s^{-1})
0.25	1.20
0.75	
1.25	

3. Using your data from table 2, plot a graph of the athlete's average speed versus time.

Now we are going to find the acceleration of the athlete during the course of the race.

4. Complete table 3 for acceleration versus time. Again, your time should be the midpoint between each set of data points in table 2.

TABLE 3 Acceleration versus time

Time (s)	Average acceleration (m s^{-2})
0.50	

5. Provide a definition of acceleration and explain, using an example from table 3, how you used this definition to determine the average acceleration between two time frames.
6. Plot a graph of the athlete's acceleration versus time.
7. Give a detailed summary of the athlete's motion, making reference to their speed and acceleration during the race.
8. Use your velocity-versus-time graph to estimate the distance run after 7.0 seconds, showing all workings. How does your estimate compare to the data in table 1?
9. By appealing to Newton's Third Law of Motion, explain why the athlete is able to accelerate out of the starting blocks.
10. The mass of the athlete is 75 kg. Draw a free body force diagram to illustrate the three significant forces acting on the athlete during the time they are accelerating. (**Hint:** There is one vertical force, one horizontal force and one force acting on the athlete that has both horizontal and vertical components.)
11. During the period of acceleration, what is the magnitude of the horizontal component of the net force acting on the athlete?
12. From your graph of acceleration versus time, approximately when is the net force acting on the athlete zero?
13. Use your results from one of your graphs to estimate both the momentum and the kinetic energy of the athlete at $t = 4$.



Resources



Digital document School-assessed coursework (doc-32276)

UNIT 2 | AREA OF STUDY 1 OPTIONS

OBSERVATION OF THE PHYSICAL WORLD

The twelve option topics available for selection in Unit 2, Area of Study 2, are all based on a different observation of the physical world. The Option topics 12–23 can be accessed through your digital formats, learnON and eBookPLUS, or you can download a PDF at www.jacplus.com.au.

Students will study only one option topic.

Topic	Option	Outcome
12	What are stars?	Apply concepts of light and nuclear physics to describe and explain the genesis and life cycle of stars, and describe the methods used to gather this information.
13	Is there life beyond Earth's solar system?	Apply concepts of light and atomic physics to describe and analyse the search for life beyond Earth's solar system.
14	How do forces act on the human body?	Analyse the physical properties of organic materials including bone, tendons and muscle, and explain the uses and effects of forces and loads on the human body.
15	How can AC electricity charge a DC device?	Construct, test and analyse circuits that change AC voltage to a regulated DC power supply, and explain the use of transducers to transfer energy.
16	How do heavy things fly?	Apply concepts of flight to investigate and explain the motion of objects through fluids.
17	How do fusion and fission compare as viable nuclear energy power sources?	Apply the concepts of nuclear physics to describe and analyse nuclear energy as a power source.
18	How is radiation used to maintain human health?	Use nuclear physics concepts to describe and analyse applications of electromagnetic radiation and particle radiation in medical diagnosis and treatment.
19	How do particle accelerators work?	Apply the principles related to the behaviour of charged particles in the presence of electric and magnetic fields to describe and analyse the use of accelerator technologies in high energy physics.
20	How can human vision be enhanced?	Apply a ray model of light and the concepts of reflection and refraction to explain the operation of optical instruments and the human eye, and describe how human vision can be enhanced.
21	How do instruments make music?	Apply a wave model to describe and analyse the production of sound in musical instruments, and explain why particular combinations of sounds are more pleasing to the human ear than others.
22	How can performance in ball sports be improved?	Apply concepts of linear, rotational and fluid mechanics to explain movement in ball sports.
23	How does the human body use electricity?	Explain the electrical behaviour of the human body and apply electricity concepts to biological contexts.

Source: VCE Physics Study Design (2016–2021) extracts © VCAA; reproduced by permission.

12 What are stars?

OUTCOME 2.1

Apply concepts of light and nuclear physics to describe and explain the genesis and life cycle of stars, and describe the methods used to gather this information.

12.1 Overview

Numerous **videos** and **interactivities** are available just where you need them, at the point of learning, in your digital formats, learnON, eBookPLUS and at www.jacplus.com.au.

12.1.1 Introduction

Astrophysics is the area of science in which the laws of physics are applied to the universe. It is quite remarkable that we can learn anything about the universe beyond the solar system as most stars are so far away that we cannot observe any of their features — they are mere points of light — and we cannot yet travel to these stars to explore them. If we ever travel to the stars, the journey will take so long that generations will pass before word of the discoveries comes back to Earth. Yet in the past hundred years, astrophysics has flourished and revealed much about our universe. Astrophysicists can now determine what stars are made of, how they generate their energy, their age and distance from us. This topic explores scientist's understanding of stars and how they came to gain this knowledge. We have barely left the surface of the Earth, so how have we gained such understanding?



- 12.1 Overview
- 12.2 BACKGROUND KNOWLEDGE Changing views of the universe
- 12.3 Using electromagnetic radiation to collect information
- 12.4 Spectroscopy and measuring the distances to stars and galaxies
- 12.5 Measuring distances to stars and galaxies
- 12.6 The properties of stars
- 12.7 Nuclear fusion
- 12.8 The Hertzsprung-Russell diagram
- 12.9 Galaxies
- 12.10 Review

The Unit 2, Area of Study 2 Options topics 12–23 can be accessed through your digital formats, learnOn and eBookPLUS, or you can download a PDF at www.jacplus.com.au.

13 Is there life beyond Earth's solar system?

OUTCOME 2.2

Apply concepts of light and atomic physics to describe and analyse the search for life beyond Earth's solar system.

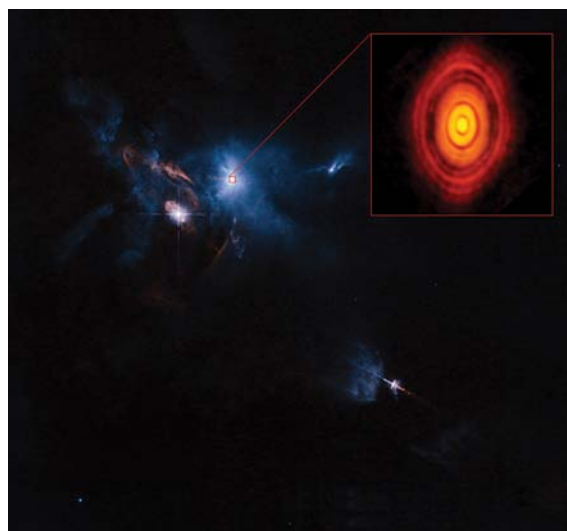
13.1 Overview

Numerous **videos** and **interactivities** are available just where you need them, at the point of learning, in your digital formats, learnON, eBookPLUS and at www.jacplus.com.au.

13.1.1 Introduction

Understanding how life could exist in our universe is the ultimate quest for astronomers. The investigation of our solar system using spacecraft has revealed much new information and stimulated extensive debate on the origins of life on Earth and beyond. But how do we look outside our solar system? How can we discover the composition and origin of other planets and stars when they are too far away to physically visit?

In earlier science studies, you may have discovered that visible light is just a small part of a much bigger electromagnetic spectrum. This spectrum identifies light through different wavelengths and frequencies — that is, light modelled as a wave. This model of light is the key to our understanding of the universe, so it is important to look at what the model tells us.



13.1 Overview

13.2 Spectroscopic analysis of light

13.3 Locating extrasolar planets (exoplanets)

13.4 Conditions for life beyond Earth's solar system

13.5 The search for extraterrestrial intelligence

13.6 Review

The Unit 2, Area of Study 2 Options topics 12–23 can be accessed through your digital formats, learnON and eBookPLUS, or you can download a PDF at www.jacplus.com.au.

14 How do forces act on the human body?

OUTCOME 2.3

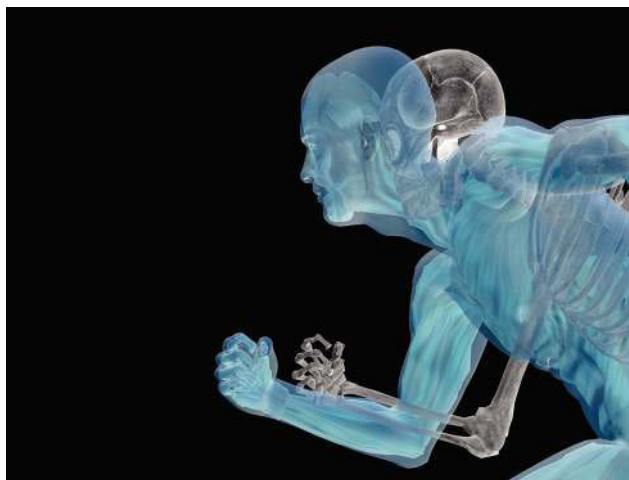
Analyse the physical properties of organic materials including bone, tendons and muscle, and explain the uses and effects of forces and loads on the human body.

14.1 Overview

Numerous **videos** and **interactivities** are available just where you need them, at the point of learning, in your digital formats, learnON, eBookPLUS and at www.jacplus.com.au.

14.1.1 Introduction

We work, we play, we move. Lift an object and you feel it pull on your arm. Throw or catch a ball and you feel it push on your hand. You should also feel something happening inside your body. Perhaps you'll feel a particular muscle when pushing off to run or when jumping to catch a ball. Forces generated by our muscles enable our bones to move relative to each other; that's how we move. This happens when we bend, run or sit, whether we are exercising vigorously, sitting down or turning to look over our shoulder. Even when we are standing still our muscles work to help us keep our balance. Humans must be strong enough to create these internal forces and safely respond to the external forces that act on us. Try to think of your body as a structure made of bone, tendons, muscles and skin. To find out what the body is capable of, we will look at the forces and loads on these structures.



- 14.1 Overview
- 14.2 Forces in the human body
- 14.3 Stress and strain
- 14.4 Elastic and plastic behaviour of materials
- 14.5 Materials for prostheses
- 14.6 Performance of artificial limbs
- 14.7 Review

The Unit 2, Area of Study 2 Options topics 12–23 can be accessed through your digital formats, learnON and eBookPLUS, or you can download a PDF at www.jacplus.com.au.

15 How can AC electricity charge a DC device?

OUTCOME 2.4

Construct, test and analyse circuits that change AC voltage to a regulated DC power supply and explain the use of transducers to transfer energy.

15.1 Overview

Numerous **videos** and **interactivities** are available just where you need them, at the point of learning, in your digital formats, learnON, eBookPLUS and at www.jacplus.com.au.

15.1.1 Introduction

We live in a world surrounded by electronic devices. Many of us feel the need to be connected constantly to the internet and the telephone network. To be connected we need mobile communication devices such as smart phones, tablets and laptops. These devices need batteries to provide electrical energy. Rather than using batteries that are thrown away and replaced, these devices are fitted with rechargeable batteries that need to be recharged from the mains power network.

The mains power network supplies electricity to houses and buildings at 230 V AC (previously, in Australia, this was 240 V AC). Batteries are charged by providing a reverse voltage of 6 V DC.

This topic looks at how to convert a 230 V AC voltage to a DC voltage to charge your devices and keep you connected. It also looks at the use of transducers to transfer energy in long distance telecommunications systems.



- 15.1 Overview
- 15.2 Voltage, current and resistance
- 15.3 Converting AC to DC
- 15.4 Voltage regulators
- 15.5 Transducers and diodes
- 15.6 Data transfer
- 15.7 Review

The Unit 2, Area of Study 2 Options topics 12–23 can be accessed through your digital formats, learnON and eBookPLUS, or you can download a PDF at www.jacplus.com.au.

16 How do heavy things fly?

OUTCOME 2.5

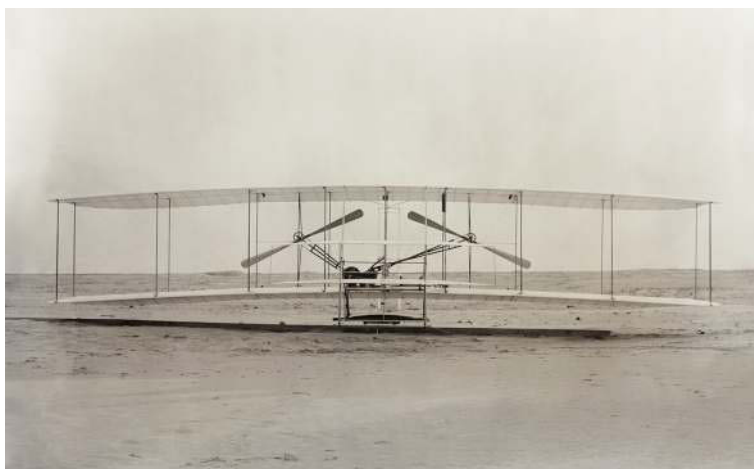
Apply concepts of flight to investigate and explain the motion of objects through fluids.

16.1 Overview

Numerous **videos** and **interactivities** are available just where you need them, at the point of learning, in your digital formats, learnON, eBookPLUS and at www.jacplus.com.au.

16.1.1 Introduction

The science and technology of flight originated over 2000 years ago, when the Chinese began making and experimenting with kites. The idea of people taking to the air was just a dream until the early sixteenth century, when Leonardo Da Vinci produced detailed drawings of flying machines. However, his machines were not built or tested. The first recorded flight driven and controlled by an engine took place in 1903, by the Wright brothers. That first flight followed many experiments with gliders and using a wind tunnel. This topic deals with the study of aeronautics — the science of flight through the Earth's atmosphere.



- 16.1 Overview
- 16.2 Forces acting on an aircraft
- 16.3 Aerodynamic lift
- 16.4 Thrust and drag
- 16.5 Manipulating flight
- 16.6 Controlling an aircraft
- 16.7 Review

The Unit 2, Area of Study 2 Options topics 12–23 can be accessed through your digital formats, learnON and eBookPLUS, or you can download a PDF at www.jacplus.com.au.

17 How do fusion and fission compare as viable nuclear energy power sources?

OUTCOME 2.6

Apply the concepts of nuclear physics to describe and analyse nuclear energy as a power source.

17.1 Overview

Numerous **videos** and **interactivities** are available just where you need them, at the point of learning, in your digital formats, learnON, eBookPLUS and at www.jacplus.com.au.

17.1.1 Introduction

We use energy everyday of our lives. As such, the need for sustainable sources of energy is continually growing. Fission and fusion are two ways of extracting energy from the nucleus of atoms. While the sources of nuclear energy, such as uranium, are classed as non-renewable, they can produce large quantities of energy from very small fuel quantities, making them fairly sustainable. This topic investigates the following methods of nuclear energy production:

1. A heavy nucleus splits into two medium-sized nuclei. This nuclear reaction is called fission.
2. Two very light nuclei are forced together to form one nucleus. This reaction is called fusion.

After studying this topic, you will be able to compare the two reactions and their associated technologies, understanding the benefits and risks associated with nuclear energy production.



17.1 Overview

17.2 Nuclear fusion

17.3 Nuclear fission

17.4 Nuclear bomb design

17.5 Nuclear energy as a power source

17.6 Review

The Unit 2, Area of Study 2 Options topics 12–23 can be accessed through your digital formats, learnON and eBookPLUS, or you can download a PDF at www.jacplus.com.au.

18 How is radiation used to maintain human health?

OUTCOME 2.7

Use nuclear physics concepts to describe and analyse applications of electromagnetic radiation and particle radiation in medical diagnosis and treatment.

18.1 Overview

Numerous **videos** and **interactivities** are available just where you need them, at the point of learning, in your digital formats, learnON, eBookPLUS and at www.jacplus.com.au.

18.1.1 Introduction

The models used by physicists to explain the behaviour of electromagnetic radiation and the nucleus of the atom have provided the basis for huge improvements in medical diagnosis and treatments during the last century. In this topic we will look at how electromagnetic radiation and particle radiation are used in medical imaging and diagnosis.



- 18.1 Overview
- 18.2 Radiation and the human body
- 18.3 The use of radiation in diagnosis and treatment
- 18.4 X-rays in medical diagnosis
- 18.5 Medical imaging with CT, PET, MRI and ultrasound
- 18.6 Review

The Unit 2, Area of Study 2 Options topics 12–23 can be accessed through your digital formats, learnON and eBookPLUS, or you can download a PDF at www.jacplus.com.au.

19 How do particle accelerators work?

OUTCOME 2.8

Apply the principles related to the behaviour of charged particles in the presence of electric and magnetic fields to describe and analyse the use of accelerator technologies in high energy physics.

19.1 Overview

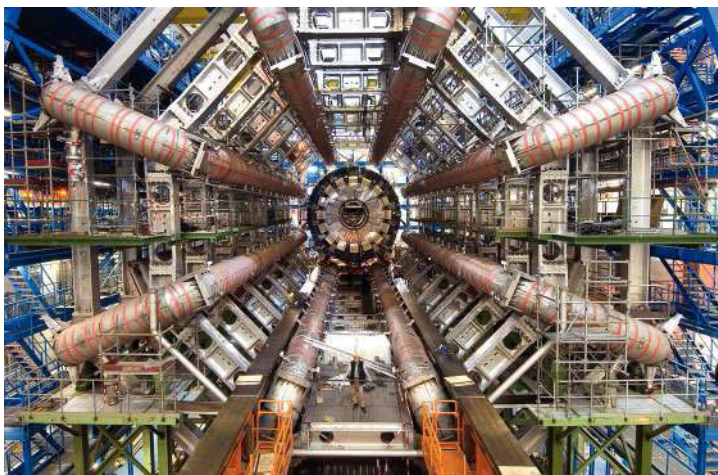
Numerous **videos** and **interactivities** are available just where you need them, at the point of learning, in your digital formats, learnON, eBookPLUS and at www.jacplus.com.au.

19.1.1 Introduction

Following the discovery of radioactivity, the newly identified particles were soon being used as investigative tools. They were fired at targets to see what the targets were made of. Rutherford fired alpha particles at thin gold foil to explore the structure of the atom. He also fired them at nitrogen gas, producing oxygen. Chadwick discovered the neutron by firing alpha particles at beryllium.

These high-speed ‘bullets’ were fired at the nuclei of various atoms to break them apart. By looking at the fragments, an insight into the structure of the atoms and the nucleus and ultimately the structure of the nuclear particles themselves could be achieved.

However, Rutherford, Chadwick and other early researchers were limited to particles from naturally occurring radioactive sources. They soon realised there were three limitations to these natural ‘bullets’, prompting the eventual creation of particle accelerators, which allow for greater control of energies.



19.1 Overview

19.2 Particle accelerators and the production of light

19.3 Accelerator technology and the development of modern particle physics

19.4 Current and future applications of accelerator technology for society

19.5 Review

The Unit 2, Area of Study 2 Options topics 12–23 can be accessed through your digital formats, learnON and eBookPLUS, or you can download a PDF at www.jacplus.com.au.

20 How can human vision be enhanced?

OUTCOME 2.9

Apply a ray model of light and the concepts of reflection and refraction to explain the operation of optical instruments and the human eye, and describe how human vision can be enhanced.

20.1 Overview

Numerous **videos** and **interactivities** are available just where you need them, at the point of learning, in your digital formats, learnON, eBookPLUS and at www.jacplus.com.au.

20.1.1 Introduction

Physics is the field of science that is based on making sense of the physical universe. To do this we use our senses, looking for patterns and connections to evaluate the data they provide. Our sense of sight is one of our most significant. Although it detects only a small part of the electromagnetic spectrum, it provides us with vast amounts of useful information. Our ability to enhance human vision is incredible — glasses and bionic eyes have been designed to treat vision impairment and blindness, and lenses in telescopes and microscopes allow us to see very small and very distant objects. We will explore these amazing innovations further in this topic.



- 20.1 Overview
- 20.2 Behaviour of light
- 20.3 Refraction
- 20.4 Manipulating light for a purpose
- 20.5 Extending vision
- 20.6 Light and the eye
- 20.7 Review

The Unit 2, Area of Study 2 Options topics 12–23 can be accessed through your digital formats, learnON and eBookPLUS, or you can download a PDF at www.jacplus.com.au.

21 How do instruments make music?

OUTCOME 2.10

Apply a wave model to describe and analyse the production of sound in musical instruments and explain why particular combinations of sounds are more pleasing to the human ear than others.

21.1 Overview

Numerous **videos** and **interactivities** are available just where you need them, at the point of learning, in your digital formats, learnON, eBookPLUS and at www.jacplus.com.au.

21.1.1 Introduction

Sound is a form of energy that is created by vibrating objects, with the vibrations moving as a wave through the surrounding medium. The sound you hear is dependent on the nature of these vibrations and the medium through which they travel.

Instruments create sound in a variety of ways, most commonly using strings or hollow tubes to create standing waves. This topic explores the physics of sound and hearing, as well as the production of sound by instruments.



- 21.1 Overview
- 21.2 Sound as a wave
- 21.3 Measuring sound intensity
- 21.4 How does the human ear respond to sound?
- 21.5 How instruments create sound
- 21.6 Characteristics of sound
- 21.7 Review

The Unit 2, Area of Study 2 Options topics 12–23 can be accessed through your digital formats, learnON and eBookPLUS, or you can download a PDF at www.jacplus.com.au.

22 How can performance in ball sports be improved?

OUTCOME 2.11

Apply concepts of linear, rotational and fluid mechanics to explain movement in ball sports.

22.1 Overview

Numerous **videos** and **interactivities** are available just where you need them, at the point of learning, in your digital formats, learnON, eBookPLUS and at www.jacplus.com.au.

22.1.1 Introduction

How can performance in ball sports be improved?
Consider the following questions.

- Is a heavier cricket bat more effective?
- When does a sliding ball begin to roll?
- How can you bend it like Beckham?

The physics of ball games can answer questions such as these. The concepts and principles of mechanics can be applied to any collision with a ball, whether it is with a tennis racket, a golf club, a cricket bat, a hockey stick, your hand or your foot. They can explain the movement of a ball through the air, and the effects of air resistance and spin. In this topic you will learn about the physics behind a variety of ball sports and apply that knowledge to find ways to improve performance.



22.1 Overview

22.2 Collisions and conservation of momentum

22.3 Friction and rolling balls

22.4 Maximising flight

22.5 Review

The Unit 2, Area of Study 2 Options topics 12–23 can be accessed through your digital formats, learnON and eBookPLUS, or you can download a PDF at www.jacplus.com.au.

23 How does the human body use electricity?

OUTCOME 2.12

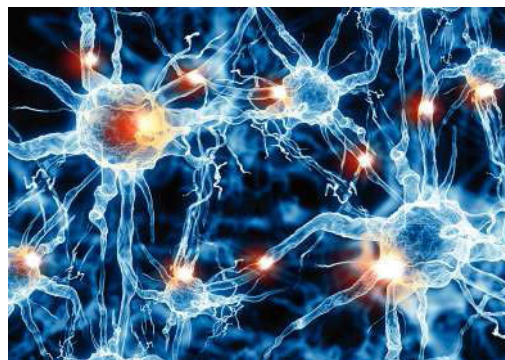
Explain the electrical behaviour of the human body and apply electricity concepts to biological contexts.

23.1 Overview

Numerous **videos** and **interactivities** are available just where you need them, at the point of learning, in your digital formats, learnON, eBookPLUS and at www.jacplus.com.au.

23.1.1 Introduction

Many important discoveries in the history of electricity came from observations of electrical behaviour in animals and humans. There are recorded instances from 46 CE of the use of electric shock therapy to treat headaches. The source of the electric shock was the electric discharge from the tornado fish! In 1781 Luigi Galvani demonstrated that a frog's leg could be made to twitch using electrical energy. Galvani's work inspired Alessandro Volta to further investigate the source of the electrical energy affecting the frog's leg, leading to the development of the first batteries. Thomas Green, an anaesthetist in the late nineteenth century, discovered that he could restart a sedated patient's heart by discharging a 300 V battery across the patient's chest. Today, knowledge of electrical processes in the human body is leading to medical advances in the treatment of paraplegia and degenerative brain and muscle disease.



In this topic you will learn how and why the human body responds to electrical stimuli, and what roles electrical processes perform in essential body systems such as the heart and the nervous system.

23.1 Overview

23.2 Electrical signals in the human body

23.3 Electrical signalling and the nervous system

23.4 The heart as an electrically powered pump

23.5 The effects of electricity applied to the body

23.6 Applications of electricity involving the human body

23.7 Review

The Unit 2, Area of Study 2 Options topics 12–23 can be accessed through your digital formats, learnON and eBookPLUS, or you can download a PDF at www.jacplus.com.au.

24 Practical investigation

Numerous **videos** and **interactivities** are available just where you need them, at the point of learning, in your digital formats, eBookPLUS and learnON at www.jacplus.com.au.

24.1 Overview

24.1.1 Introduction

As part of Area of Study 3 of Unit 2, you will conduct a practical investigation exploring content you have covered this year in Physics. The practical investigation allows you to follow your own interests and passions using scientific method, exploring the answer to questions that are important to you. You will improve your ability to solve problems, use resources and communicate ideas using appropriate physics terminology. These attributes are useful in everyday life and highly valued in the workplace. Being scientific means making use of observations, experiments and logical thinking to test ideas.

FIGURE 24.1 A student conducting a scientific investigation in the classroom



24.1.2 What you will learn

KEY KNOWLEDGE

After completing this topic you will be able to apply the following to practical investigations:

- the physics concepts specific to the investigation and their significance, including definitions of key terms, and physics representations
- the characteristics of scientific research methodologies and techniques of primary qualitative and quantitative data collection relevant to the selected investigation, including experiments (thermodynamics, construction of electric circuits, mechanics), and/or the evaluation of a device; precision, accuracy, reliability and validity of data; and identification of uncertainty
- identification and application of relevant health and safety guidelines
- methods of organising, analysing and evaluating primary data to identify patterns and relationships including sources of error and uncertainty, and limitations of data and methodologies
- observations and experiments that are consistent with, or challenge, current physics models or theories
- the nature of evidence that supports or refutes a hypothesis, model or theory
- the key findings of the selected investigation and their relationship to key physics concepts
- the conventions of scientific report writing including physics terminology and representations, symbols, equations and formulas, units of measurement, significant figures, standard abbreviations and acknowledgment of references.

Source: VCE Physics Study Design (2016–2021) extracts © VCAA; reproduced by permission.

on Resources

 **Digital documents** Key science skills — VCE Units 1–4 (doc-31856)
Key terms glossary (doc-32272)

24.2 Key science skills in Physics

KEY SCIENCE SKILLS

- Develop aims and questions, formulate hypotheses and make predictions.
- Plan and undertake investigations.
- Conduct investigations to collect and record data.

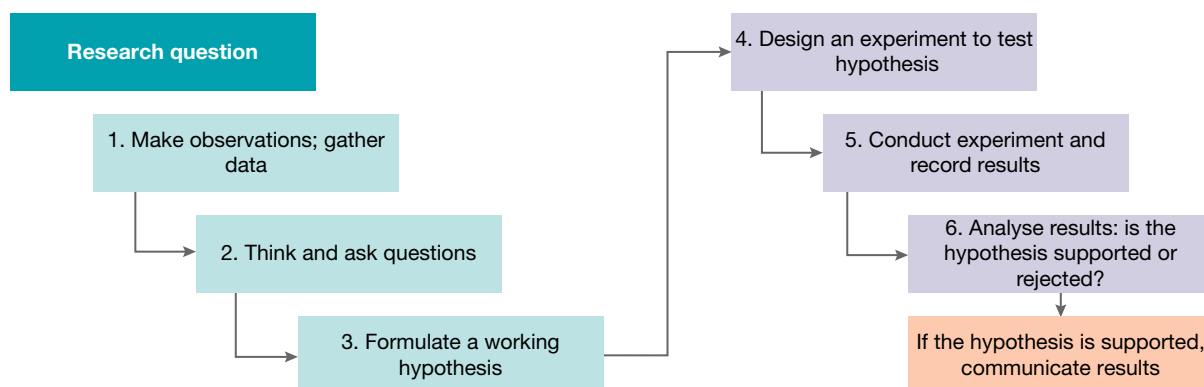
24.2.1 The scientific method: why do we conduct investigations?

Physics relies on formulating and answering questions followed by communication of the findings in order to progress. Scientists work through a series of steps to advance their knowledge as part of this procedure. Experimental and other investigative work is central to this.

Figure 24.2 summarises this process of practical investigations and scientific method.

This investigation will draw upon a number of key skills that you have been developing in Units 1 and 2, and the specific skills in Unit 2, Area of Study 3. As part of this investigation you will be required to produce a report — this is usually in the form of a scientific poster, but your teacher may ask for another format such as a practical report, oral presentation or digital presentation. You will also be required to produce a logbook.

In this investigation, you will have the opportunity to show your skill and imagination in experimental design, display commitment to a task and demonstrate your communication ability in explaining your **results**. You will need to develop a question, plan actions to answer this question, undertake an investigation and interpret the data to form a conclusion. Your investigation will involve two independent variables being explored, one of which must be a continuous variable.

FIGURE 24.2 The scientific method

The investigation will require a significant amount of class time. Your teacher will set aside around two to three weeks for the activity, so some planning and organisation on your part will be needed to achieve a personally satisfying outcome. Table 24.1 will assist with your planning. The timeline may be different depending on your school. Your teacher may also have set checkpoints regarding when you are required to submit work and what specific components need to be included.

TABLE 24.1 Investigation planning with sample schedule

Task	Due date
- Teacher introduces task and expectations. - Brainstorm topics. - Create a choice of topics of investigation.	About two weeks before formal experimentation begins
Return a list of possible topics for approval by teacher, who then provides feedback, recommendations and finally approval.	A few days later
- Submit of a detailed research proposal for your approved topic. - Submit your completed and signed risk assessment.	At the beginning of the week before your experiment begins By the end of the week before your experiment begins
Requested equipment is assembled by the teacher and lab technician.	By the end of the week before your experiment begins
- Investigation begins. - Set up equipment. - Collect preliminary data. - Troubleshoot any issues with equipment. - Collect data and measurements; graph your results and evaluate trends. - Adjust and refine method.	Week 1
- Continue the cycle of measurements and data analysis, leading to a review of progress and more detailed measurements. - Move on to investigating the second continuous independent variable.	Week 2
- Finalise the investigation of the second variable. - Begin preparing your overview of the investigation: summarising your procedure, what you have found out, what difficulties you had and how you addressed them.	Week 3
- Finalise writing the sections of the report and paste them into a poster template. - Submit the logbook and finished report (and poster if required).	Beginning of week 4

24.2.2 Using a logbook

As part of your practical investigation (as well as all practical experiments throughout the year), it is a requirement to keep a logbook.

Usually this logbook is a bound exercise book (however, your teacher may request a digital logbook instead). It is vital to show all aspects of your practical investigation within your logbook using the scientific approach.

The logbook will be assessed by your teacher. You must date all work that is completed in your logbook to show when it was completed and assist in validating your work.

FIGURE 24.3 All observations should be recorded in a logbook.



TABLE 24.2 Components of a logbook

Component of logbook	What to include
Chosen question	Information about your topic, how you chose it and the question you have selected from this
Introductory material	Background data on your topic, diagrams, notes and tables, information about key terms and past experiments that were similar to the one you are conducting
Hypothesis and aim	A clear hypothesis and aim
Methodology	All equipment you plan to use and a clear method you plan to follow, with detailed steps that could be reproducible by someone else
Results	Observations and recorded results, in an appropriate form — tables are particularly useful, can be used to construct graphs
Discussion	Stated results and careful evaluation of results, referring back to hypothesis and question Discussion questions; can be set to help scaffold your thoughts and ideas, or discussion may be more open
Thoughts and questions	Any concerns or questions about the investigation; answers to them should be researched

24.2.3 Developing aims and questions

Coming up with a topic

Your practical investigation will focus on one area of any of the following topics: thermodynamics, electric circuits, matter, motion, astronomy, forces and the human body, AC to DC, flight, nuclear energy and medical physics, light and vision, sound and music, ball games and bioelectricity.

Choosing a topic should not be rushed — it takes time and careful consideration. It is important you don't choose a topic just because it sounds interesting; you should choose one that is reasonable to complete in the provided timeframe and uses the available resources.

The topic of your investigation can come from any of the content you are studying this year, so it may be useful to go back what you have covered and use this to form some ideas.

A good suggestion is to brainstorm a variety of topics as a group. One way to do this is to draw a grid on a large sheet of paper with headings across the top such as: Hobbies and interests, Sports, Science

in the news, Investigations you did in previous years and Course topics. Down the side put types of investigations such as: Investigating the operation of a device or technology, Solving a technological problem, Investigating a physical phenomenon. Brainstorm as many ideas as you can then narrow this down to topics that you want to explore further.

Some topic examples are listed here.

Motion

- The performance of a CD hovercraft
- The impact force on and the energy loss by a bouncing ball
- Motion of a yoyo
- Flight of a table-tennis ball
- The energy delivered by a catapult
- Energy changes on a trampoline (figure 24.4)
- Investigation of the phenomenon that dry sand is soft, wet sand is hard, wetter sand is soft again
- The energy stored in a spiral clock spring
- Maximising the adhesion of Blu-Tack
- Factors affecting the design of a good paddlewheel

FIGURE 24.4 Energy changes on a trampoline



Astronomy

- The resolution of close-spaced objects by the eye
- The field of view of a simple telescope
- The depth of focus of a simple telescope

Forces and the human body

- Effect of force on a bone (beam, cantilever)
- Effect of a twisting force on a bone (figure 24.5)
- The physics of a bicep curl
- The strength of girders of different construction (using balsa wood)
- The strength of human hair

FIGURE 24.5 Broken bones can result from twisting forces



AC to DC

- The design of an AC ammeter
- The value of fins for regulator heat sinks

Flight

- The thrust of a propeller (in air or in water)
- The resistance to water flow of various plumbers' fittings (pipe, bends, etc.)
- The effect of changing the size or shape of the wings of a glider
- Paper plane design (figure 24.6)

Nuclear energy and medical physics

- Variation in range of alpha particles with air pressure
- Variation in range of beta particles in different metals
- Scattering of beta particles back from various substances
- The natural radioactivity of potassium salts
- Reducing background radiation by screening

Light and vision

- Range of wavelengths different people can see
- Contraction of pupil in bright light
- Illumination and the resolution of the eye
- The adaptation to dark of the human eye
- The depth of focus of a microscope
- The resolution of a microscope
- Moiré fringes

Sound and music

- Frequency range of a microphone
- The behaviour of a loudspeaker cabinet at low frequencies
- The frequencies of a stretched wire
- Diffraction of sound waves

Ball games

- The sweet spot of a tennis racquet
- Effect of the mass of a cricket bat on ball speed after impact
- The changeover from sliding to rolling
- Compare static and kinetic friction of running shoes

Bioelectricity

- Variation of resistance between two points on a conducting sheet with different distances
- Resistance between two flat plates in a tank of conducting liquid

A document containing weblinks and many more topics can be found in the Resources tab. Review these lists and see what sparks your interest because choosing a topic that intrigues you will ensure a high level of commitment and a sense of pride in the finished work.

FIGURE 24.6 Designing a paper plane



on Resources

 **Digital document** Investigation topics (doc-16176)

Creating a question

Turning the topic into a question focuses your mind on what you want to discover.

The question needs to be:

- one that can be investigated through scientific method
- practicable — given your knowledge, time and the school resources
- asked in a way that indicates what you will do.

Example of formulating a question from a topic

Topic: Contraction of pupil in bright light

Question:

How quickly does the pupil of the eye contract when the light is made brighter?

Or

Does the contraction of the pupil in bright light differ between individuals?

There are many ways of formulating a question from a topic. Just make sure it is something that can be measured, explored and answered in the scope of your practical investigation.

Developing an aim

Often, developing the **aim** of an investigation is done at the same time as formulating a question from your topic. The aim outlines the purpose or the key objective of the investigation. It outlines what you are trying to achieve in order to answer your question and either support or invalidate your **hypothesis**.

There are two different ways that you can format your aim.

1. To [determine/investigate/compare] how the *dependent variable* is affected by the *independent variable*
2. To [determine/investigate/compare] how the *independent variable* affects the *dependent variable*

Your aim must:

- be no more than two lines
- be linked to your question
- link the independent and dependent variables.

Examples of aims

- To determine the acceleration of objects of different masses due to gravitational field strength
- To investigate momentum transfer involved in collisions between different size objects
- To compare resistors used in parallel and series circuits by determining the overall effective resistance

24.2.4 Formulating hypotheses and making predictions

Formulating a hypotheses is an important step in the **scientific method**.

FIGURE 24.7 Hypotheses are testable explanations for a concept



A hypothesis is a tentative, **testable** and **falsifiable** statement for an observed phenomenon, which predicts the relationship between two variables or predicts the outcome of an investigation. A hypothesis usually predicts the relationship between two kinds of variables: an independent and a dependent variable. Variables will be explored further in subtopic 24.3.

To write a hypothesis, a good tip is to use the following format:

If (statement involving independent variable), then (prediction involving dependent variable) when (change in the independent variable).

Typically, a scientific hypothesis also includes a tentative explanation for the predicted results.

TABLE 24.3 Example of good working hypotheses

IF	THEN	WHEN
<i>If the angle of an incline affects the speed of a small cart</i>	<i>then the speed of the cart will increase and have a greater acceleration</i>	<i>when a steeper incline is used.</i>
<i>If the thickness of a wire affects the current flowing through it</i>	<i>then the resistance will decrease in a circuit</i>	<i>when a thicker wire is used due to an increased area for electrons to flow.</i>

Consider the following statements and decide if each is an example of a well-formatted hypothesis.

Statement 1: The heavier the object, the faster it will fall.

No. This is simply a testable prediction. It does not include a tentative explanation.

Statement 2: If an object has a greater mass, then it will fall faster than other objects.

No. This does not identify a tentative explanation. The statement is a method followed by a predicted outcome.

Statement 3: If an object with a greater mass causes an increased acceleration, then it will fall to the ground when dropped compared to an object with a smaller mass.

Yes. This identifies a tentative hypothesis (explanation) and a predicted outcome by which the hypothesis can be tested.

It is important to note that there are many different writing styles for hypotheses. The way you write your hypothesis will be dependent on the investigation you are conducting.

SAMPLE PROBLEM 1

Polly is putting the kettle on. Polly is very curious about science and wants to see how she can change the speed the water boils. She has heard rumours that salt causes water to boil faster. She has four different types of salt in her house: table salt, sea salt, Himalayan pink salt and chicken salt.

Write an appropriate research question, aim and hypothesis for this scenario.

 **Teacher-led video:** SP1 (tlvd-0107)

THINK

1. Determine the variables to help write an aim, hypothesis and research question.
2. Create a research question based on Polly's problem. Make sure that the question is one that is testable and clearly outlines what is occurring in the investigation.
3. Write an aim, clearly outlining the purpose of the investigation. Be sure to link the independent variable and dependent variable.
4. Write a hypothesis in the 'If ... then' format. Remember, a hypothesis needs to link the independent variable and dependent variable. Your hypothesis may not be correct, but it must be testable. (You may also specify which salt you think would do this best.)

WRITE

The independent variable is the salt type.
The dependent variable is the time it takes for the water to boil.

Does the type of salt added to water affect the time it takes for water to boil?

To determine if different types of salt affect the time it takes for water to boil

If table salt, sea salt, Himalayan salt or chicken salt is added to water, then the time taken for the water to boil will decrease.
(Pure table salt will cause the largest decrease in time.)

PRACTICE PROBLEM 1

Jack wants to know if changing the material of the clothing that Jill is wearing will affect the speed at which she rolls down the hill.

Write an appropriate research question, aim and hypothesis for this scenario.



Resources



Interactivity Formatting a hypothesis (int-7732)

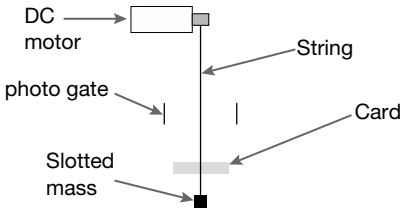
24.2.5 Planning and undertaking experiments

Planning experiments

Once your teacher has approved your topic and you have written a question, aim and hypothesis, it is time to start planning an investigation.

One way that planning may begin is through the use of a practical proposal.

FIGURE 24.8 A practical investigation proposal

Practical investigation proposal	
Name:	Jill
Partner's name: (optional)	Jack
Title of your investigation:	The efficiency of a DC motor
Briefly describe its purpose. (A brief sentence, but needs to be precise)	To investigate how efficiently a DC motor converts electrical energy into gravitational potential energy by raising a mass
Write down three starting questions you want to answer. (To help focus your planning)	What is the most efficient voltage for a given mass? How does this voltage vary with the mass? For a given voltage is there a mass the motor cannot lift? Is the mass raised at a constant speed?
List independent variables, indicating which are continuous and which are discrete, as well as dependent variables. (For your teacher to see if you have thought of all the obvious variables)	Independent: voltage supplied to the DC motor, the mass being raised, the diameter of the spindle about which the string from the mass is wrapped, the type of DC motor (discrete) Dependent: The current drawn by the DC motor, energy supplied to the DC motor, the time for the mass to travel a measured distance, gain in gravitational potential energy
List the physics concepts and relationships that you expect to use in your investigation. (To give your teacher an indication of the extent of your understanding of the topic)	Electric energy consumption, $W = VIt$ Gain in gravitational potential energy = $mg\Delta h$ Efficiency = $\frac{mg\Delta h}{VIt}$
List the equipment and measuring instruments that you plan to use. (For your teacher to see whether you have the right tools for the task)	DC motor with spindle on the shaft Masses — either slotted masses and/or plasticine Light, thin string, possibly with a small card of known length attached near the bottom to trigger a photo gate Variable power supply, voltmeter and ammeter, switch Ruler and balance Timer, preferably electronic, e.g. a photo gate
Sketch your experimental set up. (This will make your first day of investigating smoother, and your teacher may be able to suggest refinements.)	
List the steps in your experimental design. (An important stage in your planning and it will enable your teacher to see if there is anything you have forgotten.)	1. Connect the circuit and attach a mass to the string. Set to a low voltage and turn on the power supply. Adjust arrangement of equipment and voltage and mass values to get a safe set-up that is capable of producing data without damaging the motor. 2. Adjust timer, card and photo gate set-up to produce consistent readings. 3. Set the mass at a known value, set the voltage at a low value, and measure the current and time at least five times. 4. Increase the voltage settings in increments of 1 V and repeat the measurements. Use a voltage divider circuit if in-between voltage values would be useful. 5. Increase the mass progressively and repeat steps 3 and 4 each time. 6. Check for possible intermediate mass values to identify maximum efficiency.
Any special requests (For example, equipment may need to be left set up between classes, or access at lunchtime or after school may be needed.)	None

It is important that your experiment:

- produces results that are reliable, accurate, precise and valid
- clearly shows the link between the dependent and independent variables
- controls variables that are not being tested
- minimises uncertainties and errors where possible
- allows the use of equipment and skills that are cost and time effective
- includes **control group** where possible and numerous **experimental groups**.

Control groups provide a point of comparison for results when the independent variable is not applied. An example of control and experimental groups may occur in a practical exploring the effect of adding resistors in a circuit on the brightness of a light globe. The experimental groups would be trialled with different number of resistors. The control group would be a trial with no resistor in the circuit.

At the end of your planning, you should be able to produce three written documents, which should be in your logbook:

- a risk analysis based on the hazards that you have identified (refer to section 24.6.1 for detail on risk assessments)
- a detailed list of equipment required, along with quantities (refer to section 24.5.3 for detail about different equipment used in Physics)
- an explicit, step-by-step method that takes all of your planning into consideration, including diagrams if relevant.

Conducting investigations

When conducting investigations, it is vital to:

- follow all health and safety protocols
- ensure you know how to use any chosen equipment correctly to minimise errors
- carefully follow your methods; if any changes are required, note these down in your logbook
- ensure you are controlling variables outside your independent variable to keep your results accurate and precise
- clearly record any results obtained, along with the date; this includes any results that did not go according to plan and results of both control and experimental groups
- ensure you carefully pack up equipment after use. If equipment is required to be set up for a few days, make sure it will be in a location where it cannot be affected by other individuals or environmental factors.

It is also recommended, if time allows, that you repeat your experiment to improve accuracy and reliability.

24.2 EXERCISE

To answer questions online and to receive **immediate feedback** and **sample responses** for every question go to your learnON title at www.jacplus.com.au.

1. Using the following topics, create a testable question that could be used for a practical investigation.
 - (a) Exploring the difference in the decrease of water temperature from boiling in an insulated thermos versus a normal mug
 - (b) Comparing the brightness of globes in series and parallel circuits
 - (c) Investigating the time it takes a ping pong ball to fall in normal conditions compared to within a vacuum
2. What is the purpose of a logbook in practical investigations?
3. Which of the following is an acceptable hypothesis?
 - A. Do water and cordial have the same freezing temperature?
 - B. If water has a higher freezing temperature than cordial, then it will change from a liquid to a solid at a faster rate when cooled.
 - C. If the temperature of water decreases, then it will change form into a solid.
 - D. Water will freeze faster than cordial.
4. List the main steps required in planning an investigation.

5. A student has made three parachutes with the same paper, but cut them into three different shapes — a circle, square and triangle. They want to see which stays in the air the longest when dropped from the 20 metres.
- Provide an aim for this investigation.
 - Provide a hypothesis for this investigation.

Fully worked solutions and sample responses are available in your digital formats.

24.3 BACKGROUND KNOWLEDGE Variables

BACKGROUND KNOWLEDGE

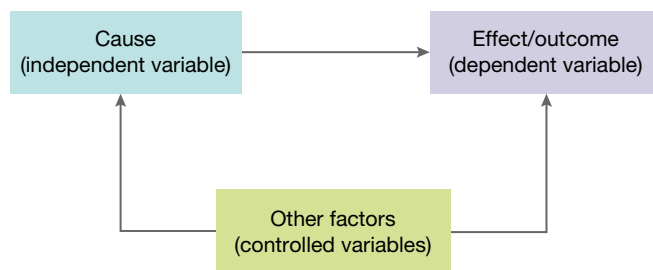
Use this subtopic to review the types of variables.

- Describe and identify independent, dependent and controlled variables.

24.3.1 Types of variables

In an experiment, a variable is any factor that the researcher can control or change or measure. Three kinds of variables are commonly recognised (see figure 24.9). For some variables you will set the value at the start of each experiment; others will be determined by your experiment.

FIGURE 24.9 Diagram showing the relationships between variables in an experiment



- An **independent variable** is a factor that is deliberately manipulated by the investigator and affects the dependent variable. For example, you may be running a simple test to examine the bounce height of different types of balls when dropped from 2 metres. In this case, the independent variable is the type of ball. When graphing results, the independent variable is usually placed on the horizontal axis.
- A **dependent variable** is the factor that the investigator measures. The dependent variable is affected by the independent variable. In the investigation to examine the bounce height of different balls, the dependent variable would be the bounce height. The dependent variable is usually placed on the vertical axis of a graph.
- Controlled variables** are all the other factors that the investigator must maintain at constant values through the course of an experiment. In the bounce height investigation, controlled variables would include the height the ball is dropped from, the instrument used to record data (you wouldn't estimate for one measurement and use a ruler for another) and the surface you dropped the ball on. If these factors are not kept constant, they can confound the experimental results because they can cause changes in the dependent variable. Often controlled variables also include environmental factors such as temperature and humidity, but these are harder to control.

Example of variables

Consider the following example. Allira and Hunter are investigating the effect of paper size on the distance a paper plane can be flown. They are trialling different sizes of paper to explore if a specific paper size allows for the greatest distance travelled.

- **Independent variable.** The factor that is being manipulated is the *size* of paper.
- **Dependent variable.** The factor that is being measured is the *distance* the plane travels.
- **Controlled variables.** Examples include the same type of paper being used, same wind when plane is thrown, same person throwing the paper plane, same folding of the paper plane.

Variables can also be considered as numerical (quantitative) or categorical (qualitative). Refer to section 24.5.2 for further detail on this.

FIGURE 24.10 Different paper sizes being investigated



on Resources

 **Interactivity** Variables (int-7731)

24.3 EXERCISE

To answer questions online and to receive **immediate feedback** and **sample responses** for every question go to your learnON title at www.jacplus.com.au.

1. Describe the difference between a dependent and an independent variable.
2. Why is it important to control variables in an investigation?
3. Belinda and Paul plan to investigate the best way to win a game of tenpin bowling. They are exploring the following variables: (i) the weight of the ball, (ii) the material the ball is made of, (iii) the angle they bowl, (iv) if they hit the bumpers or not, (v) which fingers they use to hold the ball, (vi) the speed they bowl.
 - (a) Describe how you know these variables are independent.
 - (b) Determine for each of these variables if they are numerical (quantities) or categorical (qualities).
 - (c) List as many dependent variables as you can that Belinda and Paul might consider for their investigation, including ones that can be calculated from others.
4. The following table lists two topics with some variables identified. Complete the table for three others.

	Independent variables		Dependent variables
	Numerical	Categorical	
Bouncing basketball	Drop height, pressure of the ball	Surface ball lands on, ball type	Rebound height, impact time, energy loss, change in momentum, average force of impact
(a) Performance of a parachute			
(b) Movement of a ball down a hill			
(c) Ice cube melting			

Fully worked solutions and sample responses are available in your digital formats.

24.4 Concepts specific to investigation, key terms and representations

KEY CONCEPT

- The physics concepts specific to the investigation and their significance, including definitions of key terms, and physics representations.

KEY SCIENCE SKILL

- Communicate and explain scientific ideas.

24.4.1 Concepts specific to investigation

As part of an investigation, it is vital to link key physics concepts that are relevant and clearly explain their significance. This shows your understanding of a topic and allows others who read your report to see the connection between theory and practical applications.

Background information

Concepts should be researched prior to commencing your investigation, recorded in your logbook (and referenced). This background information will also form part of your introduction in your poster.

Concepts that are relevant to your investigation include:

- explanations of key formulae
- definitions of key terms
- detail about the theories being examined
- information about other practical investigations exploring similar concepts.

An example of this may be in an exploration of effective resistance in series and parallel arrangements. In your background information, it is important to explain any findings and experiments about this topic completed in the past, information about its application, information about circuit electricity and resistors, and a description of key formulae relevant to the investigation (such as $R_T = R_1 + R_2 + \dots + R_n$ for series and $\frac{1}{R_T} = \frac{1}{R_1} + \frac{1}{R_2} + \dots + \frac{1}{R_n}$ for parallel).

You should also have clear concepts linked to theory from your background information in your **discussion** section of an investigation.

24.4.2 Key terms

It is vital in practical investigations to define any key terminology.

This can be done in two ways:

- within a report itself
- as part of an appendix or glossary at the end of the report.

Read the following excerpt of an introduction from a scientific report written by a student. This investigation was conducted to examine differences between AC and DC circuits.

Electric current is the movement of charged particles from one place to another. This is usually through the use of negatively charged electrons. Current flows around a circuit.

In this investigation, two types of current in circuits are being explored. Direct current (DC) is when the net flow of charge is in one direction; alternating current (AC) is when charged particles can move in either direction in a circuit.

This student has clearly defined key terms as part of their introduction within their report itself. What terms have they defined?

Read the following excerpt of an introduction from a scientific report written by a different student, conducting the same practical.

In this investigation, **electric current** is being investigated. Two types of current around a circuit are being explored and compared: **direct current (DC)** and **alternating current (AC)**.

Glossary of key terms

Electric current: movement of charged particles from one place to another

Direct current: net flow of charge is in one direction

Alternating current: charged particles can move in either direction in a circuit

In this situation, the student has not defined the terms in their introduction itself, but has bolded key words that later appeared in their glossary.

Both formats are valid methods to define key terms. The method used depends on the format of the report or personal preference. Be sure to check which method is most suitable for the practical investigation you are conducting with your teacher.

24.4.3 Physics representations

A variety of representations are used in physics. This includes the use of models, sketches, graphs, equations, formulae, symbols and diagrams. Additionally, there are many vital conventions related to the use of numerical data including significant figures and scientific notation.

FIGURE 24.11 Representations, such as equations and diagrams, form a vital part of physics reporting.

Handwritten physics derivations for a curved beam under a distributed load q :

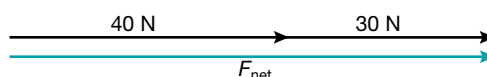
- Deflection: $\frac{-m}{EJ} (1 - \cos \alpha)$, $\frac{m r}{EJ} \alpha$, $A_h = q h$, $A_v = \frac{q h^2}{2 a}$, $D_v = \frac{q h^2}{2 a}$
- Slope: $-q r^2 (1 - \cos \varphi)$, $q r \sin \varphi$, $\frac{q r^4}{EJ} (1 - \cos \alpha)$, $\frac{q r^4}{EJ} (\frac{3 \alpha}{2} - 2 \sin \alpha + \frac{\sin 2 \alpha}{4})$
- Moment: $M_p = \frac{q x^2}{2} + \frac{q y^2}{2} = \frac{q}{2} (x^2 + y^2) = \frac{q r^2}{2} [(1 - \cos \varphi)^2 + \sin^2 \varphi] = q r^2 (1 - \cos \varphi)$
- Fixed-end moments: $\bar{M}_1 = 1 \cdot x = r (1 - \cos \varphi)$, $\bar{M}_2 = 1 \cdot y = r \sin \varphi$, $\lambda = \frac{EJ}{G J_k} \Rightarrow G J_k$

Some examples of representations in physics are outlined below. For whichever topic you choose, it is important to use correct representations for your information. It might be worth going back to that topic and observing how different information is represented.

Vectors

Vectors are commonly used in physics, particularly in the forces topic. A vector has both force and magnitude. We can represent vectors as directed lines, in which the size represents the magnitude and the arrow represents the direction as shown in figure 24.12.

FIGURE 24.12 The use of vectors, showing force and magnitude



In texts vectors often appear in bold italic font (for example, $\mathbf{F} = m\mathbf{a}$, in which $\mathbf{F}$ and $\mathbf{a}$ are vectors). Alternatively, they may be written with a right facing arrow above them as an accent $\vec{F} = m\vec{a}$. This is particularly useful when bold cannot be used to distinguish the vector, such as when handwritten or when all the text is bold.

Electric circuit representations

Many different symbols can be used in electric circuits to show the various components.

In sketches or diagrams of these models, it needs to be clear what component each of these symbols represent.

FIGURE 24.13 Some representations of electric circuit components

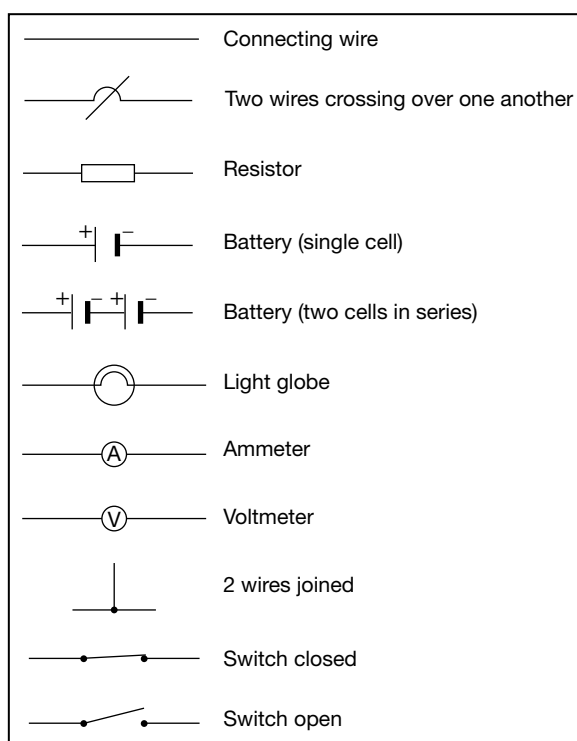
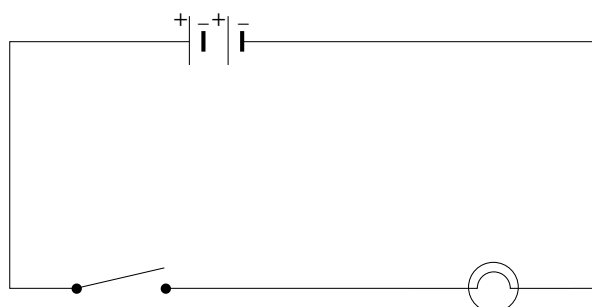


FIGURE 24.14 Representation of a simple electric circuit showing a battery, light globe, switch and connecting wires



Scientific notation

Very large and very small quantities can be more conveniently expressed in scientific notation. In scientific notation, a quantity is expressed as a number between 1 and 10 multiplied by a power of 10.

To write in scientific notation, follow the form $N \times 10^a$, where N is a number between 1 and 10 and a is an integer (positive or negative).

When converting numbers into scientific notation the following steps should be followed.

1. Determine where the decimal point needs to go so that N is between 1 and 10.
2. Count the number of places the decimal point is moved to determine a (the power of 10 or the exponent). If the decimal point was moved to the left, a will be positive, if it was moved to the right, a will be negative.
3. Write the number in scientific notation.

For example, the average distance between the Earth and the moon is 380 000 000 metres. This is more conveniently expressed in scientific notation as 3.8×10^8 m.

In physics, scientific notation is generally used for numbers less than 0.01 and greater than 1000.

Quantities in scientific notation can be entered into your calculator using the EXP, 10^x or $^$ button (depending on the type of calculator you use).

SAMPLE PROBLEM 2

- a. The average distance between Earth and the Sun is 149 600 000 kilometres. Write this in scientific notation.
- b. The mass of a proton is 0.000 000 000 000 000 000 001 67 grams. Write this in scientific notation.

 **Teacher-led video:** SP2 (tlvd-0103)

THINK

- a. 1. Determine the position a decimal point needs to go in order for the number to be between 1 and 10 and remove any 0s that are not between non-zero digits.
2. Determine the exponent by establishing the number of times the decimal point was moved.
If the decimal point was moved to the left, the exponent should be positive, if the number was moved to the right, the exponent should be negative.
3. State the solution.
- b. 1. Determine the position of the decimal point in order for the number to be between 1 and 10 and remove any 0s that are not between non-zero digits.
2. Determine the exponent by establishing the number of times the decimal point was moved.
If the decimal point was moved to the left, the exponent should be positive, if it was moved to the right, the exponent should be negative.
3. State the solution.

WRITE

- a. The decimal point would need to go between 1 and 4 to form 1.496.

The decimal point was moved eight spots to the left so the exponent is 8: 10^8 .

$$1.496 \times 10^8 \text{ km}$$

- b. The decimal point would need to go between 1 and 6 to form 1.67.

The decimal point was moved 24 spots to the right so the exponent is -24 : 10^{-24} .

$$1.67 \times 10^{-24} \text{ g}$$

PRACTICE PROBLEM 2

Express the following quantities in scientific notation.

- a. Diameter of Saturn's rings: 282 000 km
- b. Number of metres that sound travels in one hour: 1 235 000
- c. Uncertainty of a highly precise clock: 0.000 000 000 000 000 003 seconds

24.4 EXERCISE

To answer questions online and to receive **immediate feedback** and **sample responses** for every question go to your learnON title at www.jacplus.com.au.

1. Identify two ways that key terms can be defined in your report.
2. Why are representations useful in scientific reporting?
3. Draw a simple circuit using figures 24.13 and 24.14. Your circuit should contain wires, a single cell battery, a resistor, a light globe and a voltmeter.
4. Express the following quantities in scientific notation.
 - (a) Distance to Pluto from Earth: 7 500 000 000
 - (b) Number of kilometres in a light year: 9 460 730 472 580 km
 - (c) 7.8 millimetres into kilometres: 0.0000078

5. A student is writing a simple report about the addition of two vectors (A and B). Vector A is 8 centimetres long and goes to the right. Vector B is 6 centimetres long and also goes to the right. Adding these vectors gives vector C. This relationship can be expressed as $A + B = C$. Rewrite this using appropriate representations for the vectors, and draw a diagram to represent the addition of the two vectors.

Fully worked solutions and sample responses are available in your digital formats.

24.5 Scientific research methodologies and techniques

KEY CONCEPT

- the characteristics of scientific research methodologies and techniques of primary qualitative and quantitative data collection relevant to the selected investigation, including experiments (thermodynamics, construction of electric circuits, mechanics), and/or the evaluation of a device; precision, accuracy, reliability and validity of data; and identification of uncertainty

KEY SCIENCE SKILLS

- Conduct investigations to collect and record data.
- Analyse and evaluate data, methods and scientific models.

24.5.1 Characteristics of scientific research methodologies

It is important to carefully follow **scientific research methodology** in conducting practical investigations, to ensure that your results are as precise, accurate, reliable and valid. This includes minimising **errors** and **uncertainties** in data in order to draw conclusions in relation to your question.

Each type of research method has its specific purposes, procedures, advantages and limitations. The researcher's choice depends on which method is most appropriate for the specific topic of research interest and hypothesis being tested.

There are different types of scientific inquiry and research methods that can be used, shown in table 24.4.

TABLE 24.4 Types of scientific inquiry methods

Method	Use
Controlled experiment	Determining the relationship between an independent and dependent variable. All other variables are controlled. <i>Example:</i> testing how the size of a parachute affects the rate it falls to the ground
Single variable investigation	Exploring how a variable changes over time and understanding causes of the observations and how other factors affect it <i>Example:</i> investigating how electric fields change over time
Identification	Investigating if objects or events belong into specific sets or are part of new sets <i>Example:</i> exploring if gravity is a contact or non-contact force
Designing	Designing a device using scientific knowledge <i>Example:</i> designing, constructing, testing and evaluating a motor or making a bridge that can hold a maximum mass
Investigating models	Exploring everyday phenomena and collecting evidence to test the model <i>Example:</i> devising an investigation to test Newton's First Law of Motion

24.5.2 Techniques of primary qualitative and quantitative data collection

Data is a set of facts that are collected, observed or generated. Data that you gather may come from **primary sources** or from **secondary sources**. Typically, data that you collect is raw data that must later be analysed and interpreted to produce useful information.

Primary sources of data provide direct or firsthand evidence about some phenomenon. For example, in a practical investigation, your completed logbook will be a primary source of data.

Secondary sources of data are comments on or summaries and interpretations of primary data. Sources of secondary data include review articles in scientific journals, books, newspapers and popular science magazines written as a summary and comment on the research of others.

Qualitative and quantitative data

Qualitative data (or **categorical data**) are expressed in words. They are descriptive and not numerical and can be easily observed but not measured. Bar graphs or pie graphs are often used to display the frequencies of categorical variables. (Graphs are explored in section 24.7.1.)

There are two types of categorical data:

- *Ordinal data* can be ordered or ranked — for example, ionisation energies (first, second, third) or opinion polls (strongly agree, agree, disagree, strongly disagree).
- *Nominal data* cannot be organised in a logical sequence — for example, types of sub-atomic particles (proton, neutron or electron) or the type of surface a ball rolls down.

Quantitative data (or **numerical data**) can be precisely measured and has values that are expressed in numbers. Line graphs or scatterplots are often used to display the frequencies of numerical variables.

There are two types of numerical data:

- *Continuous data* can take any numerical value, such as the release height of a parachute (12.2 m, 16.9 784 m, 1.02 m) or the temperature of an object. These values are usually measured.
- *Discrete data* can only take on set values (integers) that can be counted, such as the number of protons in an atom or the number of electron shells.

FIGURE 24.15 Recording data is vital in investigations.



TABLE 24.5 Examples of data types

Attribute	Qualitative	Quantitative
Length of pendulum	Long	52 cm
Colour	Green	520 nm
Sound	Loud	85 decibels
Speed	Fast	120 kph
Temperature	Hot	100 °C
Gravitational force	Strong	9.8 m s ⁻²

When collecting data, it is vital to consider what is most appropriate for your investigation. Normally, the best evidence is primary quantitative data, and for a majority of your investigations this is what should be collected and recorded as a minimum. However, sometimes an investigation may only allow for the collection of qualitative data. Qualitative data can be subjective — if you record the speed as fast, what does that mean? Be clear and detailed in the data collected, particularly if using qualitative data.

It is also important that results are carefully checked to make sure that recorded data are correct. Many people interpret measurements slightly differently, or use the wrong units, so make sure you are double checking data. All your collected data should be recorded in your logbook, note down all observations (usually in a table) regardless of if you think they are important or not.

24.5.3 Choosing techniques relevant to an investigation

It is important to select techniques that will best suit your investigation.

When selecting appropriate techniques, it is important to ensure that the:

- technique can be performed in an appropriate timeframe
- technique is appropriate to your investigation and serves a purpose to answering the question and supporting or rejected your hypothesis
- data are easily recorded, measured and interpreted, with a particularly emphasis on quantitative data
- technique can be safely performed; this is particularly important in a school where health and safety restrictions are closely regulated
- equipment used in the technique is available and cost effective. If it is not available in a school, can it be used with permission at other locations?
- technique allows for the control of other variables. If there are too many factors that cannot be controlled and will affect results, the technique may not be suitable for an investigation.

Selecting your measuring instruments

You should also consider the most appropriate equipment to use for a particular purpose.

Your school will have a range of measuring instruments. They will vary in precision and ease of use.

You won't always need to use the most accurate instrument. A simple instrument that allows for quick measurements will be enough more often than not. Sometimes a simple stopwatch is just as good as an electronic timer and a voltmeter may compare well to a very accurate multimeter.

Some instruments that you might consider are listed, categorised according to what they measure. There are many more devices you may choose to use.

FIGURE 24.16 Different types of measuring equipment vary in precision



Mass

- Slotted masses of known mass (figure 24.17). Simple to use and accurate. It comes only in multiples of a set weight, for example, 50 grams.
- Beam balance (figure 24.18). Accurate with a large range of values; can be time consuming to measure several masses. Not used as often, but a good option particularly if object is quite heavy.

FIGURE 24.17 Slotted masses



FIGURE 24.18 Beam balance



- Spring balance (figure 24.19). Quick to use, covers a large range of masses but not very accurate.
- Top loading balance (figure 24.20). Very accurate, very good for small masses and simple to use. With equipment set up above the balance, it can be used to measure small variations in attractive and repulsive forces such as magnetic force, electric force and surface tension. If the balance sits on a laboratory jack, force against distance can be easily measured.

FIGURE 24.19 Spring balance



FIGURE 24.20 Top loading balance



Length

- Metre ruler. Accurate, good for a range of distances and can be read to about 0.5 millimetres.
- Laboratory jack. For fine adjustment of height.
- Vernier calliper (figure 24.21). For precision measurement of short distances, such as in determining the refraction of light through a prism. Takes some time to learn how to use.
- Micrometer (figure 24.22). For precision measurement of thicknesses. Takes some time to learn how to use and can be easily damaged.

FIGURE 24.21 Vernier calliper

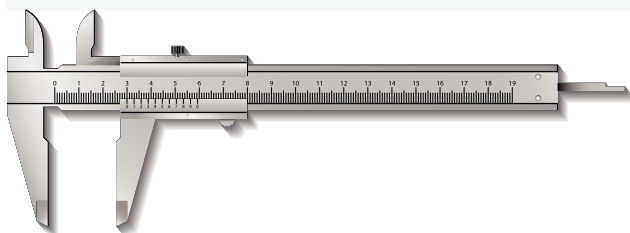


FIGURE 24.22 Micrometer



Time

- Stopwatch. Simple to use, accurate down to your response time, not reliable for short time intervals.
- Electronic timer. Requires some instruction, very accurate, best suited for short time intervals and can be used with electrical contacts and photogates.

Temperature

- Glass thermometer. Very easy to use, but often work for set temperatures only (will not work if temperature is too high or too low). They are not as precise due to limited number of markings.
- Digital thermometers. Very easy to use and give more precise measurements, however, can be easily affected by external air temperature if used incorrectly.

Motion

- Ticker timer (figure 24.23). Simple to use, however, limited in accuracy. Works best with objects moving over a short distance. Can be time consuming to analyse.
- Air track (figure 24.24). Very accurate, particularly if used with photogates, very effective in studying collisions. Takes some time to set up, but data collection is very efficient once done.

- Ultrasonic motion detector (figure 24.25). Quite accurate, useful with real motions, creates large amounts of data which means data analysis can be time consuming.
- Video with analysis software. Quite accurate. Requires some setting up, data obtained from software, data analysis can be time consuming. Free video motion analysis software are Tracker and PhysMo. Digital cameras, such as GoPros, with high-speed video are useful for measurement of short, fast events.

FIGURE 24.23 Ticker timer



FIGURE 24.24 Air track



FIGURE 24.25 Ultrasonic motion detector



Electrical

- Meters: voltmeters (figure 24.26), ammeters, galvanometers. Easy to set up but care is needed to ensure the meter is wired into the circuit correctly, otherwise the meter can be damaged. Large range of values, usually analogue displays.
- Multimeters (figure 24.27). Easy to set up. More tolerant of incorrect use but can be damaged if incorrectly connected to a high current. Large range of values, usually digital displays.

FIGURE 24.26 Voltmeter



FIGURE 24.27 Multimeter



Specialist equipment

You may also have access to some specialised equipment that you can use in your practical investigation. These are unlikely to be available in a general school laboratory, however, it is important to note that the following equipment is all highly accurate and precise. Discuss with your teacher if any of these are available for use at your school or nearby. Alternatively, you may wish to explore these as a point of discussion in relation to uncertainties and possible errors in the data and results you obtained.

- Cathode-ray oscilloscope (CRO) (figure 24.28). Even though the CRO is basically a visual voltmeter, it is a versatile instrument. It can measure both constant and varying voltages. The sweep of the trace across the screen can be used to measure time intervals of the order of millionths of a second.
- Data loggers. There are sensors now available for most physical quantities, such as temperature, pressure, light intensity, motion, force, voltage, current, magnetic field, ionising radiation. The recording of data by these sensors for later analysis greatly facilitates practical investigations.
- Apps. There are increasing numbers of apps that perform measurement functions. The accuracy of each needs to be confirmed before being used in a formal investigation, but it is an area worth exploring. Some sources include Physics Toolbox and Sensor Kinetics.

FIGURE 24.28 Cathode-ray oscilloscope



24.5.4 Precision, accuracy, reliability and validity

For your investigation, it is important to carefully consider the data you obtain and the confidence you can have in the conclusions drawn. Understanding the precision and accuracy of your data are important to ensure your findings are both reliable and valid.

Precision

Precision refers how close multiple measurements of the same investigation are to each other. Results that are precise may not be accurate. It is often difficult to have completely precise results due to random error.

Table 24.6 shows two investigations by different students measuring the height a tennis ball bounces upon being dropped from a height of 1 metre. Student 1's investigation is more precise as the range of their data is smaller compared to that of student 2.

TABLE 24.6 Two investigations measuring the height a tennis ball bounces

Investigation by student 1		Investigation by student 2	
	Height of bounce (cm)		Height of bounce (cm)
Trial 1	39.3	Trial 1	39.3
Trial 2	39.4	Trial 2	42.2
Trial 3	39.3	Trial 3	31.4
Trial 4	39.2	Trial 4	35.3
Trial 5	39.0	Trial 5	45.2

FIGURE 24.29 Results vary in precision when measuring the height of a tennis ball.



Accuracy

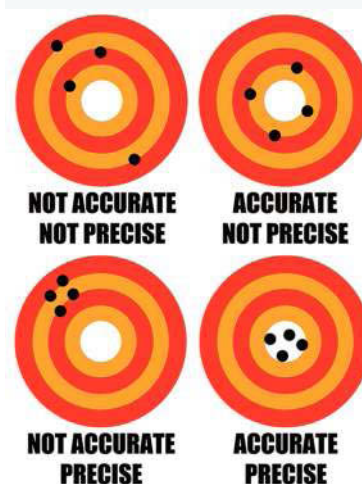
Accuracy refers to how close an experimental measurement is to a known value. If an archer is accurate, their arrows hit close to the target. Another example is in the experimental calculation of gravity, which is known to be 9.8 m s^{-2} on Earth.

Table 24.7 shows two investigations by different students to determine the acceleration of gravity from a simple pendulum by determining the length of the pendulum and time of oscillation. Values for gravity were then calculated. Student 1's investigation is more accurate, as their results had a much smaller deviation from the expected result of 9.8 m s^{-2} .

TABLE 24.7 Two investigations to determine the acceleration of gravity from a simple pendulum

Investigation by student 1		Investigation by student 2	
	Calculation of g		Calculation of g
Trial 1	9.85 m s^{-2}	Trial 1	12.59 m s^{-2}
Trial 2	9.75 m s^{-2}	Trial 2	12.62 m s^{-2}

FIGURE 24.30 Comparing precision and accuracy



Both accuracy and precision are vital in investigations. In table 24.7, student 1 has the most accurate result, with a value closest to 9.8 m s^{-2} , however, student 2 has the most precise results. In order to obtain the best experimental data, we want results that are both accurate and precise.

SAMPLE PROBLEM 3

Students conducted an experiment to determine the temperature of a substance as it changed from a solid to a liquid (melting point). They repeated the experiment four times and achieved the following results.

- Student 1: 56.5 °C; 58.0 °C; 60.0 °C; 55.0 °C
- Student 2: 60.5 °C; 61.0 °C; 60.5 °C; 62.0 °C
- Student 3: 56.5 °C; 58.5 °C; 57.0 °C; 56.0 °C

Students were then provided with the exact value of the melting temperature of the substance, which was found to be 56.48 °C.

- Which student had the least accurate data?
- Which student had the least precise data?
- Was the student with the most precise data also the student with the most accurate data? Explain your answer.

 Teacher-led video: SP3 (tlvd-0218)

THINK

- Review what accuracy means.
 - Explore the data of the three students.
 - Determine which student had the least accurate data.
- Review what precision means.
 - Explore the data of the three students.
 - Determine which student had the least precise data.
- Identify the students with the most accurate and most precise data.
 - State the solution.

WRITE

- Accuracy refers to how close a measurement is to a known value.
Student 1 had data 1.48 °C lower and 3.52 °C higher than the actual data.
Student 2 had data that was up to 5.52 °C higher.
Student 3 had data that was 0.48 °C lower and 2.02 °C higher.
Student 2 had the least accurate data, as their values were the furthest from the actual value.
- Precision refers to how close multiple measurements of the same investigation are to each other.
Student 1 had a data range of 5.0 °C.
Student 2 had a data range of 1.5 °C.
Student 3 had a data range of 2.5 °C.
Student 1 had the least precise data.
- Using the results from parts (a) and (b) it can be seen that student 3 had the most accurate data and student 2 had the most precise data.
The student who had the most precise data was not the same student who had the most accurate data. Students may have measurements very close together (precise), but they may not be accurate. This may be due to errors in the measuring device or interpretation of the melting point. Data may also be accurate without being precise; that is, close to the target but with inconsistent readings. For reliable and valid results, data should be both accurate and precise.

PRACTICE PROBLEM 3

Students conducted an experiment to determine the temperature of a substance as it changed from a liquid to a gas. They repeated the experiment four times and achieved the following results.

- Student 1: 85.4 °C; 92.0 °C; 82.0 °C; 75.5 °C
- Student 2: 83.5 °C; 85.0 °C; 85.5 °C; 86.5 °C
- Student 3: 85.5 °C; 90.0 °C; 89.5 °C; 81.0 °C

Students were then provided with the exact value of the boiling temperature of the substance, which was found to be 85.4 °C.

- a. Which student had the least accurate data? b. Which student had the least precise data?
c. Was the student with the most precise data also the student with the most accurate data?

Explain your answer.

Reliability

Reliability refers to whether another researcher could repeat your investigation by following your method and obtain similar results. As well as this, the more times an experiment is replicated, the more reliable the results are considered to be.

Experiments that are reliable shouldn't just be able to be carried out by the investigator, but also by the third party. The investigation should be reproducible, with the same results obtained by an individual who repeats the investigation in the same conditions using the same methodology. If a test is reliable, it usually has both accuracy and precision, as errors are reduced through repetition.

Validity

The **validity** of data refers to the credibility of the research results from experiments or from observations. Validity factors in both experimental design and implementation. Experiments that are valid usually are using the results from one manipulated variable, where other variables are controlled. Valid experiments also have minimised factors such as experimental bias.

Validity applies more to Biology and Psychology, where precise measurement is more difficult and there is a higher risk of bias on the part of the researcher. In Physics and Chemistry, the variables are quantifiable and physically measurable.

If your experimental method clearly relates to the purpose of the investigation and you take care to be precise in your measurements and thorough in your analysis, your results should be valid and meaningful.

Validity can be:

- *internal*. The focus is on whether the results can be believed and if they have been affected by factors that were unsuccessfully controlled: did the experiment measure the variable that was being examined in the experimental question and outlined in the hypothesis?
- *external*. The focus is on whether the results obtained in a sample are indicative of the results expected for the entire population. This can be reduced by removing bias and using a large and random sample.

Measurements that are valid must also be reliable, and therefore must have accuracy and precision.

24.5.5 Identification of uncertainty

Uncertainty is acknowledging that no matter how precise an instrument might be, there is a limit to that precision. The uncertainty is a range within which a measurement lies. An error bar is a way of representing that uncertainty graphically.

Every instrument has a limit to how precisely it measures. The scale or digital display imposes a constraint on how many digits you can record. Further information about uncertainty and errors will be covered in section 24.7.4.

For example, there are both errors and uncertainties associated with using thermometers. Two individuals may look at this and not get the exact same result. The results may not be identical between two different thermometers. The thermometer only gives measurements to the accuracy of 1 °C and not decimal values.

FIGURE 24.31 Thermometers can have issues with precision and accuracy.



24.5 EXERCISE

To answer questions online and to receive **immediate feedback** and **sample responses** for every question go to your learnON title at www.jacplus.com.au.

1. Distinguish between validity and reliability.
2. Is it essential that the results of an experiment can be replicated in order for the experiment to be considered reliable? Explain your answer.
3. Give an example of when results would not be considered reliable.
4. List two procedures that could adversely affect the internal validity of an experiment.
5. Explain how an experiment can be reliable but not valid, whereas an experiment that is valid must also be reliable.
6. Explain, with examples, the difference between precision and accuracy.
7. Give an example of a strength and a weakness of quantitative and qualitative data.
8. Describe why primary data is often stronger evidence than secondary data.

Fully worked solutions and sample responses are available in your digital formats.

24.6 Health and safety guidelines

KEY CONCEPT

- Identification and application of relevant health and safety guidelines.

KEY SCIENCE SKILL

- Comply with safety and ethical guidelines.

24.6.1 Health and safety guidelines

Part of the enjoyment of a practical investigation is that the topic may be unconventional or use an innovative method. Such situations, however, can present some risk, so special care needs to be taken to ensure yourself and others are safe.

General safety rules

Some general safety precautions will help to ensure that you and others are not injured in the laboratory.

- Wear protective clothing. This might include laboratory coat, safety glasses and gloves.
- Be aware of the position of safety equipment such as fire blanket, fire extinguisher, safety shower and eyewash.
- Ask if you are unsure how to operate equipment or how to use apparatus.
- Read labels carefully to confirm contents.
- Clean and return all equipment to the correct places.
- Check for the correct disposal of equipment and chemicals, including damaged equipment (i.e. broken glasswear).
- Read instructions carefully before commencing an experiment.
- Prepare a risk assessment for required chemicals and equipment.
- Do the investigation as outlined in your approved plan. Don't vary your plan without approval from your teacher.
- Don't do experimental work unsupervised unless you have prior approval from your teacher.
- When first setting up electrical experiments, ask your teacher to check the circuit.
- Don't interfere with the equipment set-up of others.

It is important to address health and safety concerns through the use of a **risk assessment**.

An example of a risk assessment is shown in figure 24.32. Risk assessments may also be created online using various websites.

FIGURE 24.32 Risk assessment

RISK ASSESSMENT

ACTIVITY	Energy transferred by an electric current			
SUMMARY OF EXPERIMENT				
AIM	To calculate how much energy is transformed from electrical potential energy into the internal energy of a load			
METHOD	1. Find the mass of the copper vessel in the calorimeter. 2. Add 100 mL of water to the vessel. 3. Note the initial temperature of the water. 4. Connect the circuit as shown in the diagram. 5. Set the power supply on 6 V and close the switch. Start the stopwatch. 6. Record the current passing through and the voltage drop across the calorimeter. 7. Agitate the water with the stirrer until the temperature of the water reaches a value 10 °C above its initial value. 8. Open the switch and stop the stopwatch.			
PROTECTIVE MEASURES				
GLASSES	GLOVES	DUST MASK	LAB COAT	FUME HOOD
X			X	
SAFETY INFORMATION				
CHEMICAL				
Water				
Hazards • Temperature of water will increase during this investigation, which may lead to burns.		Safety precautions • Use hot hands or metal tongs when handling hot water vessel. • Allow water to cool before packing away equipment.		
EQUIPMENT				
Wire				
Hazards • Wire may be use as a restraint. • Wire may be wrapped around neck, which may lead to strangulation.		Safety precautions • Only provide enough material for the investigation. • Ensure cotton or wire is not wrapped around students.		
EQUIPMENT				
Power supply				
Hazards • If cable or power supply is not properly maintained, it may lead to electric shock or electrocution. • Water may splash up onto power supply, leading to electric shock.		Safety precautions • Regularly inspect for damage, particularly around cords or outlets and get tagged and tested. • Ensure water is kept away from power supply.		
EQUIPMENT				
Thermometer				
Hazards • There is a risk of glass breakage, especially if there are chips or cracks present. • Some thermometers contain mercury, so if a thermometer breaks, toxic mercury is released.		Safety precautions • Wear gloves, safety glasses and a lab coat. • Try to substitute mercury thermometer with alcohol thermometer.		
CONCLUSION				
• Ensure all equipment has been maintained and checked for damage before use. • Allow equipment to cool before packing away.				
Signed: _____		Date: _____		

A risk assessment is a procedure for identifying hazardous chemicals, what the risks are and how to work safely with them. Table 24.8 lists the usual requirements for a written risk assessment. This assesses potential hazards with equipment being used and standard handling procedures to ensure health and safety of individuals and the environment.

TABLE 24.8 Requirements for a written risk assessment

Outline of investigation	Title, date and location of task
Summary of method	Brief list of steps indicating how the chemicals and equipment will be used
Equipment/chemicals used	List of materials used in the experiment
Equipment/chemical risk and hazards	List of hazards associated with the equipment
Risk control measures	General precautions taken to limit risks

Risk assessments should also take into consideration correct disposal of equipment and chemicals to adhere to safety and bioethical guidelines. Many chemicals are harmful to the environment, so correct disposal is paramount. While chemicals on their own are not used often in practical investigations in Physics, it is still important to understand their disposal. Batteries, for example, can corrode or sustain damage and chemicals within them may leak.

24.6.2 Ethics

Ethics relate to acceptable and moral conduct — this does not apply only to scientific investigations, but many aspects of life, determining what ‘right’ and what is ‘wrong’.

Science interacts with ethics in several ways, including:

- the way an experiment is conducted
- confidentiality around research
- conflicts with religious and personal beliefs.

Ethical standards and considerations also apply to any type of research or data collection method involving people (or animals).

Due to the nature of practical investigations in physics, ethical considerations usually are not a factor. However, it is an important consideration to take into account, as situations may arise when data collection involves humans. For example, you may be conducting surveys on issues regarding the greenhouse effect and climate science. The confidentiality of individuals who provide responses needs to be considered and permissions gained.

It is important to be mindful of individuals’ personal beliefs. For example, many individuals are opposed to experimentation on animals. This is an ethical consideration that needs to be evaluated and understood when teaching and reporting on these topics.

FIGURE 24.33 Ethics are about the idea of moral choice.



24.6 EXERCISE

To answer questions online and to receive **immediate feedback** and **sample responses** for every question go to your learnON title at www.jacplus.com.au.

1. Identify possible hazards with the following equipment:
 - (a) battery
 - (b) light globe used in a circuit
 - (c) Bunsen burner
 - (d) beaker
 - (e) thermometer.
2. Provide two examples of when ethics may be important in a physics investigation.
3. List five purposes of a risk assessment.
4. What other things do you think should be added to a risk assessment?
5. Draw a plan of your laboratory and label the positions of safety equipment.

Fully worked solutions and sample responses are available in your digital formats.

24.7 Methods of organising, analysing and evaluating primary data

KEY CONCEPT

- Methods of organising, analysing and evaluating primary data to identify patterns and relationships including sources of error and uncertainty, and limitations of data and methodologies.

KEY SCIENCE SKILLS

- Conduct investigations to collect and record data.
- Analyse and evaluate data and methods.

24.7.1 Organising primary data

Scientists gather raw data from their observations. Data must be recorded at the time in a suitable form, for example, text entries, sketches, tables and diagrams in logbooks or in field notebooks. These may be supplemented by audio and video recordings.

Using tables

Tables should be used when you initially record data and help separate and organise your information.

All tables should:

- have a heading
- display the data clearly, with the independent variable in the first column and the dependent variable in later columns
- include units in the column headings and not with every data point
- be easy to read. If a table becomes too complicated, it is better to break it down into a number of smaller tables
- use appropriate significant figures (or decimal places) that are consistent across data sets (for example, if one data point is 2.5, the other data point cannot be just 1, it should be 1.0).

FIGURE 24.34 Using logbooks is an easy way to record data.



FIGURE 24.35 Format of a scientific table

Always include a title for your table.

Temperature of the Earth at different depths

Include the measurement units in the headings.

The column headings show clearly what has been measured.

Use a ruler to draw lines for rows, columns and borders.

Enter the data in the body of the table. Do not include units in this part of the table.

Depth (km)	Temperature (°C)
0	15
1	44
2	73
3	102
4	130
5	158
6	187
7	215
8	242

Using graphs

Presenting results as a graph makes it easier to see patterns and trends in your data, allowing more accurate result analysis.

When drawing graphs:

- Decide on the type of graph to be used. Different types of information are better suited to different types of graphs. When one piece of data is qualitative, a pie, column or bar graph is better; however, if they are both quantitative, a line graph or scatterplot (or scattergram) is preferred.
- Include a title; this should link the dependent and independent variables that are shown in the graph.
- The independent variable should be on the horizontal (x) axis and the dependent variable on the vertical (y) axis in most graph types (excluding pie graphs).

- Axes should be ruled and each should be clearly labelled. Those displaying numerical variables should have a clearly marked scale and units.
- Make sure your scale is suitable and the numbered are evenly distributed.
- For continuous variables, it is often appropriate to draw a line (or curve) of best fit. This is a smooth curve or line that passes as close as possible to most of the plotted points.
- Include the origin, the zero value for the variables, on both axes.
- Include error bars to show uncertainty, particularly vertical error bars.

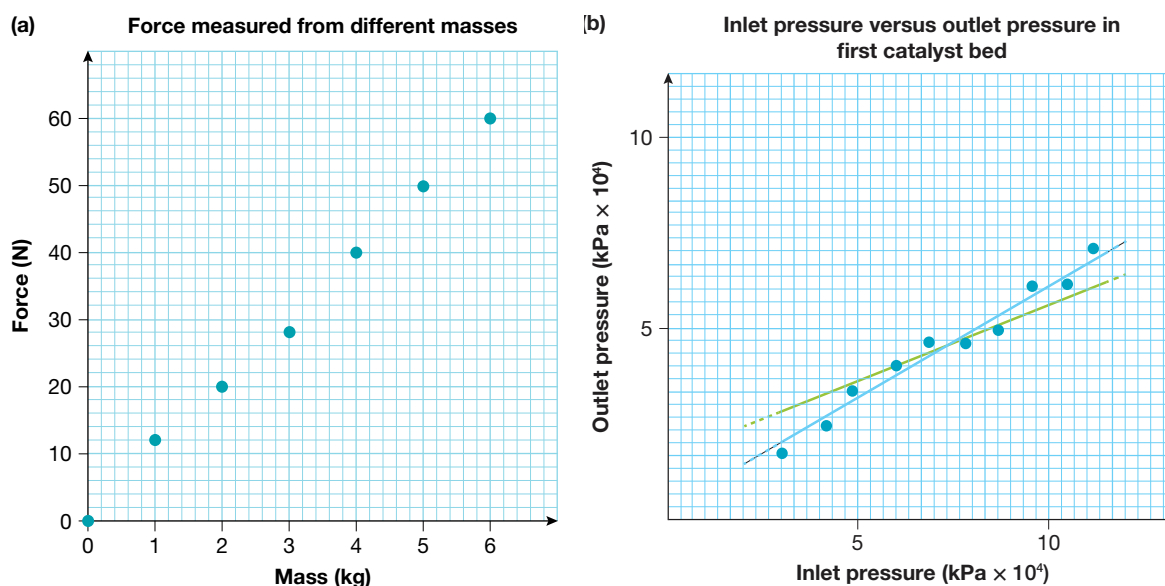
The most common representations include:

- scatterplots
- line graphs
- histograms
- bar/column graphs.

Scatterplots

Scatterplots require both sets of data to be numerical or quantitative. Each dot represents one observation, recorded in regards to the independent and dependent variable. A scatterplot can easily show trends between data sets and correlations can be seen.

FIGURE 24.36 Example of (a) scatterplot and (b) scatterplot with a line of best fit

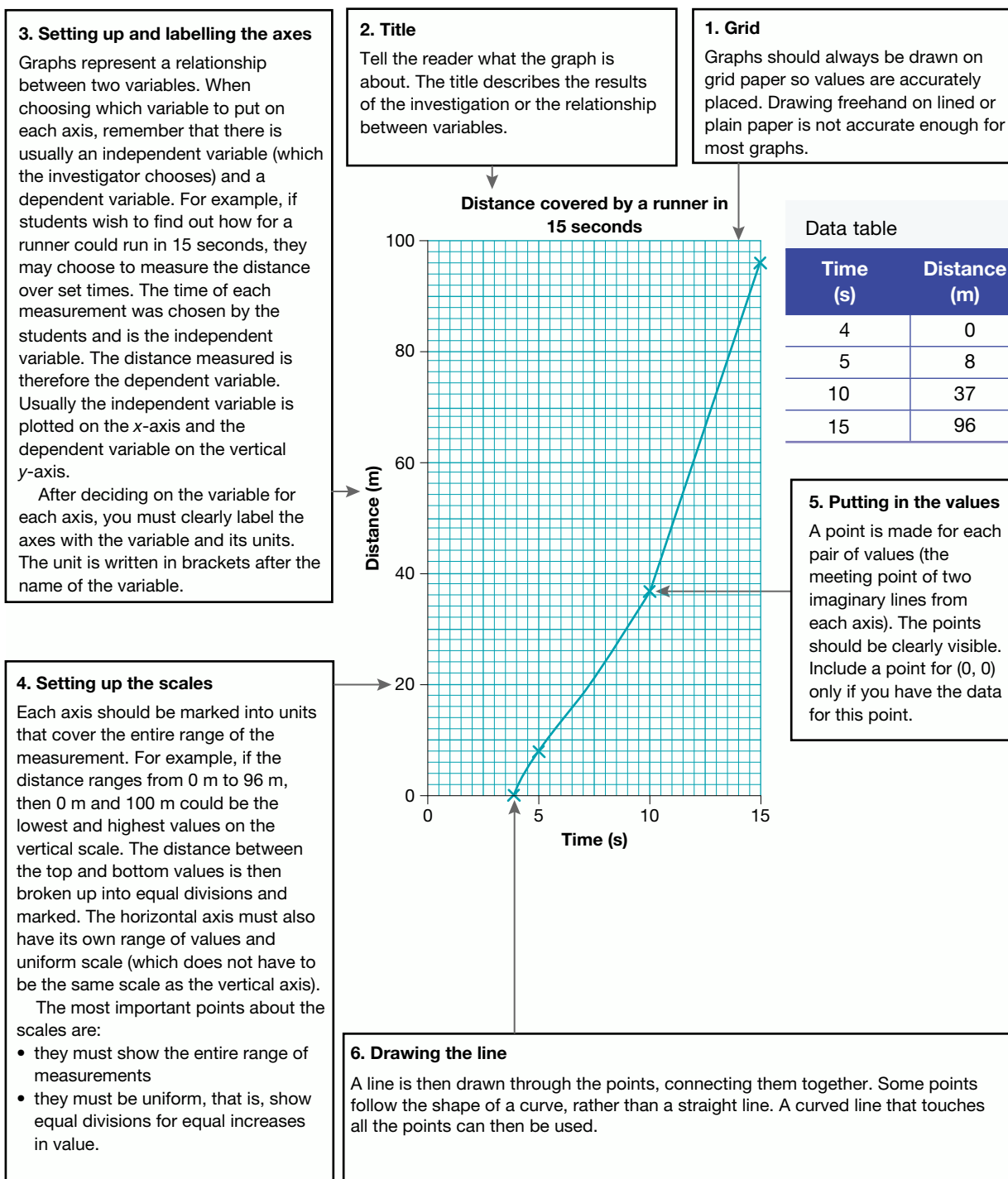


A **line of best fit** can be used to show the general trend of data and provides a quick summary of a relationship. The line of best fit doesn't need to pass through each data point but should be as close as possible to them. This can be seen in figure 24.36b, in which A is a better line of best fit, despite not going through all points. As a general rule, try to have as many data points above your line as you have below. Don't assume your line must pass through the origin (0, 0). A line of best fit does not always need to be a line, but may instead be a curve, or show an exponential relationship.

Line graphs

In a **line graph**, a series of dots represents the values of a variable and the dots are joined using a straight line (this is different to a line of best fit, which shows a general relationship and does not have to go through each point). Line graphs are often used to show changes over a continuous period of time, or over space. In particular, line graphs can identify patterns, trends and turning points in a dataset. Line graphs are sometimes curved rather than straight point to point.

FIGURE 24.37 Setting up a line graph

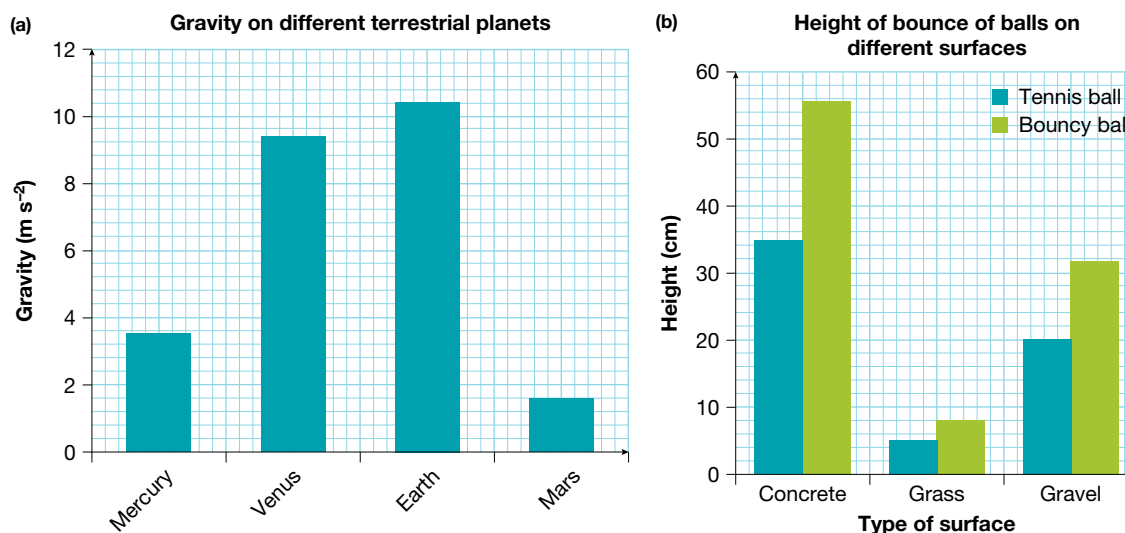


Bar graphs

Bar graphs are often used when one piece of data is qualitative and the other is quantitative. The bars are separated from each other. The horizontal or x-axis has no scale because it simply shows categories. The vertical or y-axis has a scale showing the units of measurements.

Bar graphs can also be used to compare two sets of data by using side-by-side bars, as shown in figure 24.38b.

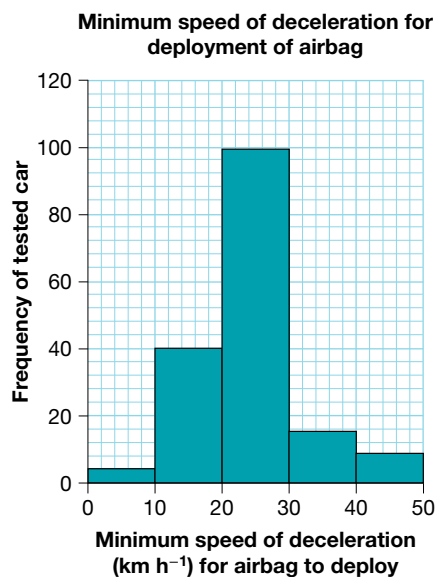
FIGURE 24.38 Bar graphs: (a) showing differences in gravity of the four terrestrial planets and (b) comparing the height of bouncing balls on different surfaces



Histograms

A **histogram** is a special kind of bar graph, showing continuous categories. The bars are not separated, unlike in a bar graph. Histograms are often used when examining frequency. In figure 24.39, the exact values cannot be determined, as data are displayed in intervals. For example, it can be seen that there were 40 cars that had a speed between 10–20 km h^{-1} . We do not know what specific values these are.

FIGURE 24.39 Histogram showing speed deceleration for airbag deployment of 166 tested cars



Using Microsoft Excel

The Excel spreadsheet is a very useful tool to the experimenter. It can:

- store your measurements. Make sure you save your data every few minutes and do a backup every day
- calculate any derived physical quantities, such as speed and acceleration of a parachute or the percentage of energy lost by a bouncing ball. The 'Fill down' command is a time saver
- be a powerful graphing tool, but must be controlled by the user. You will have to select the graph and choose what aspects of your graph you want to show and what scale on the axis you want, what you want to label your axis and whether you want the data displayed on the graphed points
- generate a line of best fit. If you right-click on any data point, a window pops up with the option 'Add Trendline'. This is the Excel command to create a line of best fit. Once selected, you have several choices. If your graph looks like a straight line, choose 'Linear'
- create error bars (however, all error bars are usually the same for each data point, rather than calculated separately).

FIGURE 24.40 Excel is a useful data tool.



on Resources

 **Interactivity** Selecting a graph (int-7733)

24.7.2 Analysing primary data

When analysing primary data, it is important to explore trends and patterns that can be seen.

This may include asking questions such as:

- Is there a clear positive or negative correlation in data? (Positive correlation is when one variable increases in response to another increasing.)
- Are there any **outliers** (unusual data)?
- What results would you expect for specific data that you didn't observe experimentally?
- Can you calculate the average for your data? Does this differ for the median or the mode?

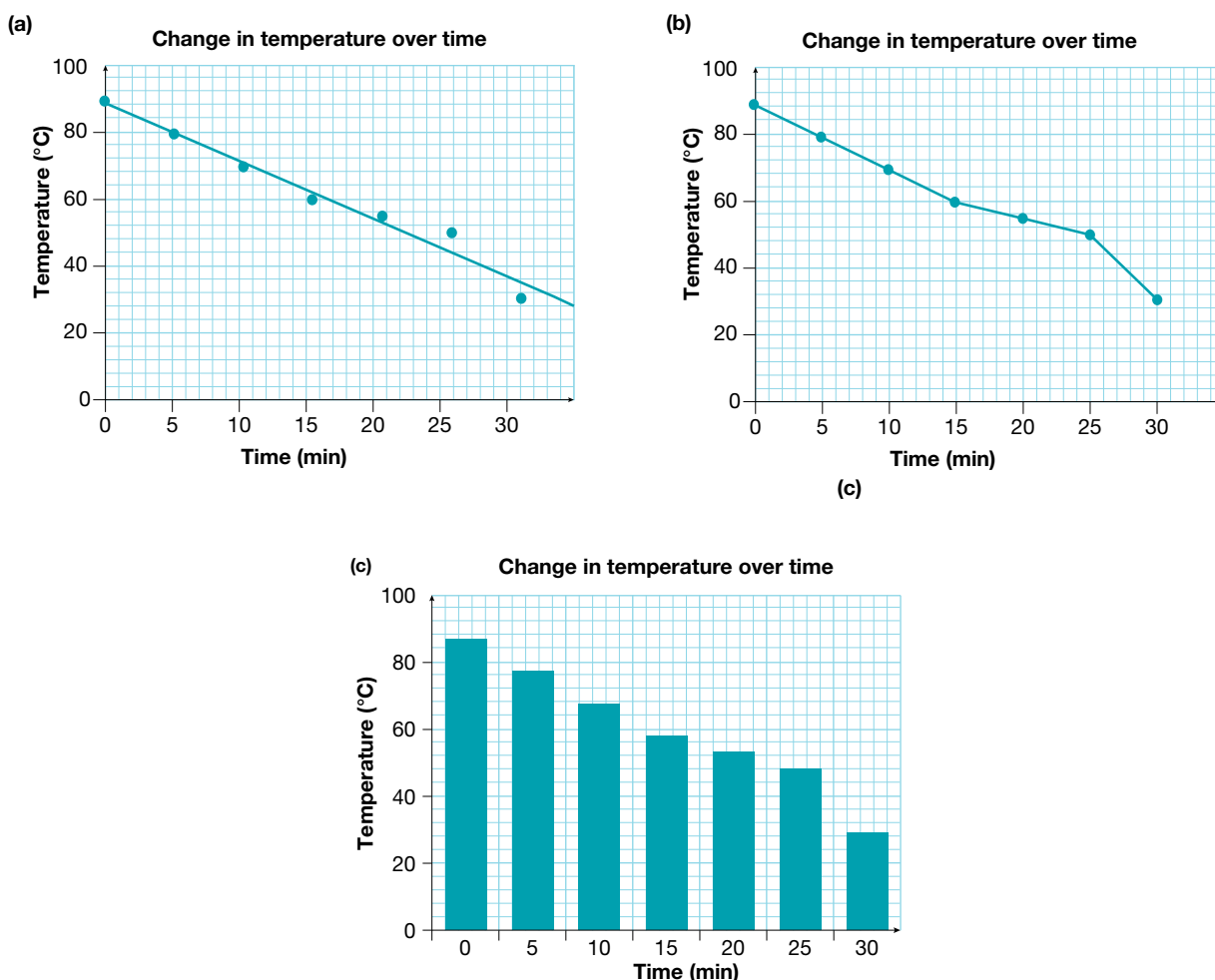
Analysis of your data often depends on the type of graph selected, as it alters the way that trends and patterns can be seen.

For example, the graphs in figure 24.41 show the same data presented in three ways.

If you were analysing the data from each of the three graphs, the following information may emerge.

- *Graph (a).* There is a clear downwards trend (or negative correlation) in the data, as temperature decreases over time. However, the temperature at 25 minutes is slightly higher than the expected pattern based on trends and the temperature at 30 minutes is slightly lower than expected.
- *Graph (b).* There is a clear downwards trend in data, as temperature decreases over time. The rate of temperature drop slows after 15 minutes, before the rate increases again between 25 and 30 minutes.
- *Graph (c).* There is a clear downwards trend in data, as temperature decreases over time. The temperature is lowest at 30 minutes, where it is half the temperature seen at 15 minutes.

FIGURE 24.41 Various graphs showing temperature change over time: (a) scatterplot using a line of best fit, (b) line graph and (c) bar graph



It is clear that from analysing data, the type of graph is quite important in interpreting it. In this case, the data represented in graphs (a) and (b) is far more powerful than graph (c). Regardless, it is important to note any clear trends and patterns seen in the data and any outliers that can be seen. Outliers, which are unusual results that lie well outside the patterns or trends observed, should be accounted for and analysed, but are often not included when calculating averages. However, it is important to consider why outliers occurred.

Graph analysis can also be used to predict and make assumptions about data that was not gathered experimentally. This can be through interpolation (predicting data points within the data set that were not measured) or extrapolation (predicting data points outside data set based on predicted relationship).

Based on the graphs in figure 24.41 you might estimate:

- the temperature at 35 minutes
- the temperature at 13 minutes
- the time that the temperature was 45 °C.

The prediction you get may vary greatly between all the graphs, so it is important to carefully consider which you use. Table 24.9 shows the varying predictions obtained from the different graphs in figure 24.41.

FIGURE 24.42 Outliers in data are unusual results.

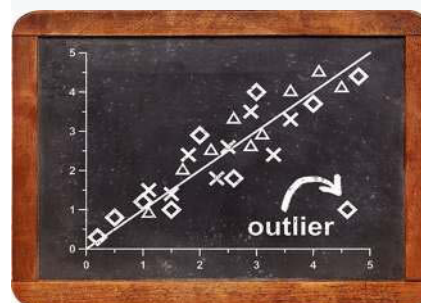


TABLE 24.9 Analysing data from different graph types

	Graph (a)	Graph (b)	Graph (c)
Temperature at 35 minutes (°C)	25	15	20
Temperature at 13 minutes (°C)	65	62	66
Time the temperature was 45 °C (minutes)	24	27	26

Direct variation

When analysing data, you may find that a change in one variable results in a change in the other by the same proportion. This is known as being directly proportional and is a way to describe and analyse the data. Consider, for example, the relationship described by the equation $y \propto x$. This type of relationship is known as a direct variation. The relationship can be written as:

$$y = kx$$

where k is a constant of proportionality.

The ratio $\frac{y}{x}$ is constant; that is, if x is doubled, y doubles, if x is tripled, y triples, if x is halved, y halves.

Many relationships in physics involve direct variation or direct proportion. For example, the power, P , delivered to an electric appliance is directly proportional to the voltage, V , across it and the current, I , passing through it. In symbols:

$$P \propto VI$$

If either V or I are doubled, P changes by the same proportion — that is, it doubles. If both V and I are doubled, P changes by a factor of four.

When one quantity is directly proportional to the reciprocal of another, the relationship is defined as an inverse variation. For example, the electrical resistance, R , of a length of wire is directly proportional to the reciprocal of the cross-sectional area, A , of the wire. In symbols:

$$R \propto \frac{1}{A}$$

$$\Rightarrow R = \frac{k}{A}$$

where k is a constant of proportionality.

R is said to be inversely proportional to A . The product of R and A is constant. If A is doubled, R is halved. If A is tripled, R is divided by three. If A is halved, R doubles.

24.7.3 Evaluating primary data

When you evaluate data, it is important to link back to the initial question.

- Does the data provide an answer to the question of your investigation?
- Does the data support or refute your hypothesis?
- If there were any outliers, errors or uncertainty in your data, why may these have occurred?
- Does your data link to correctly supported models and theories?
- Are there further improvements that you could make to improve your data in future investigations that may reduce errors or limitations?

It is important when evaluating data that you can explain and justify this in relation to your question.

For the data in figure 24.41, two examples of two students evaluating data are as follows.

Student 1. It can be seen from the results that temperature decreased.

Student 2. From the table, it is clear that temperature decreases over time, dropping from an initial temperature of 90 °C to a final recorded temperature of 30 °C. While there is a clear trend in

temperature decreasing over time, the rate of decrease was inconsistent, particularly between 25 and 30 minutes. This may be due to a decrease in external air temperature, causing the rate of heat loss through convection to change.

It is clear that student 2 had a better grasp on evaluating the data, being able to describe trends and a link to theory. What else should they add?

24.7.4 Sources of uncertainty and error

As mentioned in section 24.5.5, uncertainty is a range within which a measurement lies. Errors, on the other hand, are differences between a measurement taken and the true value that is expected. Errors lead to a reduction in the accuracy of the investigation.

Several sources of error can be identified in an investigation:

- **Systematic errors** are errors that affect the accuracy of a measurement, that cannot be improved by repeating an experiment. They are usually due to equipment or system errors. They produce measurements that are consistently too high or too low, for example:
 - instrumental errors that arise because an instrument, such as a weighing balance is uncalibrated and incorrectly set to zero
 - errors that arise because of malfunctions, such as a power outage, that affect the conditions under which an experiment is being conducted.
- **Random errors** are chance variations in measurements that affect the precision of measurements and are always present in measurements of continuous data. An example of a random error is an error of judgement when reading the smallest division on the scale of a measuring instrument, such as a ruler. Unlike systematic errors, this can usually be resolved with repetition of measurements.

It should be noted that so-called ‘human errors’ are not errors but are mistakes that result from carelessness. Examples include gross misreading of an instrument and writing the wrong result in your logbook, such as 40 instead of 4.0.

Measuring errors and uncertainties

Reading rulers

A metre ruler has lines to mark each millimetre but there is space between these lines. You could measure a length to the nearest millimetre but because of the space between the lines, if you look carefully, you can measure to a higher precision. You can measure to the nearest 0.5 millimetre.

The best estimate for the length of the red line in figure 24.44 is 2.35 centimetres. The actual length is closer to 2.35 centimetres than it is to either 2.30 centimetres or 2.40 centimetres. The measurement of 2.35 centimetres says the actual length is somewhere between 2.325 and 2.375 centimetres (0.025 cm lower than and higher than the recorded measurement of 2.35 cm).

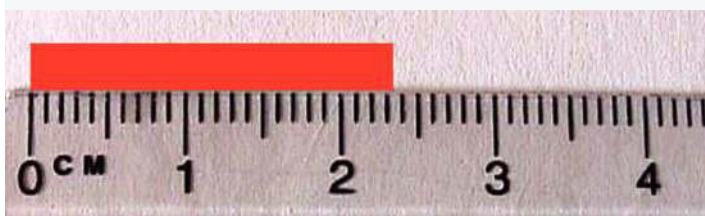
The way to write this is:

The length of the red line = 2.35 ± 0.025 cm

FIGURE 24.43 Liquids should be measured from the bottom of the dip (meniscus) to avoid errors.



FIGURE 24.44 Errors in rulers



The 0.025 represents the tolerance or uncertainty in the measurement (half of the precision that can be recorded). It is important to note that the tolerance will depend on the ruler- sometimes you may not be able to determine if a measurement is halfway between two points, so your uncertainty will be larger.

Reading top-loading balances

Consider the scales shown in figure 24.45. The reading on these digital scales may be 8.94 grams. This means the mass is not 8.93 grams nor 8.95 grams. The actual mass is somewhere between 8.935 and 8.945 grams. We can also calculate this uncertainty by calculating half of the smallest unit that can be recorded. For the scales, the smallest unit that can be recorded is 0.01 g, so the uncertainty is half of this (0.005 g). The way to write this is:

$$\text{The mass} = 8.94 \pm 0.005 \text{ g}$$

FIGURE 24.45 Top-loading balances measure to a certain number of significant figures.



FIGURE 24.46 What is the tolerance in these measuring instruments?



SAMPLE PROBLEM 4

- Record the reading on the scales shown in figure 24.46a including the tolerance (uncertainty).
- Record the reading on the thermometer shown in figure 24.46b including the tolerance (uncertainty).

Teacher-led video: SP4 (tlvd-0104)

THINK

1. Determine the reading on the scale.
2. Determine the range of the measurement.
3. Determine the tolerance.
One way to calculate this is half of the smallest unit that can be measured.
4. State the solution.

WRITE

- 128.93
The measurement can be between 128.925 and 128.935.
0.01 g is smallest measurement possible.
 $\frac{0.01}{2} = 0.005 \text{ g}$
The mass is $128.93 \pm 0.005 \text{ g}$.

- b. 1. Determine the reading on the thermometer.
2. Determine the range of the measurement.
In this case, you can tell if the thermometer is in 0.5 increments due to the gaps in the thermometer, so our range is smaller.
3. Determine the tolerance.
One way to calculate this is half of the smallest unit that can be measured (our smallest unit is 0.5).
4. State the solution.

b. 47 °C

The measurement can be between 46.75 and 47.25.

0.01 g is smallest measurement possible.

$$\frac{0.5}{2} = 0.25$$

The temperature is 47 ± 0.25 °C.

PRACTICE PROBLEM 4

- a. Record the reading on scales including the tolerance (uncertainty) that show a reading of 0.12.
- b. Record the reading on scales including the tolerance (uncertainty) that show a reading of 0.195.

Repeated measurements

Measurements of independent variables are usually precise and careful, so one measurement should be enough. However, measurements of the dependent variables are often prone to some variation.

Whether the variation is caused by the human reaction time when using a stopwatch, judging the rebound height of a basketball or in the case of the parachute, the unpredictable way the canopy will open each time, each reading may be different. It is sensible to take several readings to obtain an average. You would expect that at least three measurements would be needed, and possibly five, but more than five is generally unnecessary. For example, if your partner dropped the basketball from a height of 80 centimetres and you judged the rebound height of the ball for five trials as 68 cm, 69.5 cm, 68.5 cm, 68.5 cm and 69.5 cm. The average is 68.8 centimetres.

Graphing error bars

To represent the measure of uncertainty we use errors bars. The measurement is shown in as the middle dot and error bars are added based on the degree of uncertainty, as shown in figure 24.47.

Calculating error

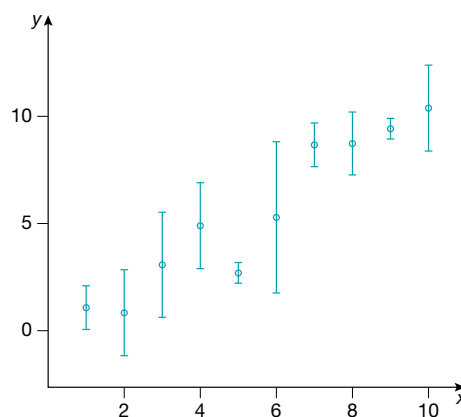
Working out the size of an error bar takes more effort. If the two pieces of data are 69 ± 1 cm and 80 ± 0.3 cm, we can just add the uncertainties to get ± 1.3 cm, but that doesn't make sense when the calculated value is 0.86. Dividing the uncertainties would produce another unusual result.

The method used is to first express the uncertainty for each data value as a percentage. For example:

$$\text{Percentage error of } 69 \pm 1 \text{ cm} = \left(\frac{1}{69}\right) \times 100 = 1.4\%$$

$$\text{Percentage error of } 80.0 \pm 0.3 \text{ cm} = \left(\frac{0.3}{80}\right) \times 100 = 0.4\%$$

FIGURE 24.47 Error bars



Now add the two percentage errors together:

$$\text{Total percentage error} = 1.4\% + 0.4\% = 1.8\%$$

Next use this total percentage error to find the error in the calculated answer.

$$\text{Error} = 0.86 \times 1.8\% = 0.016, \text{ which would be rounded to one digit as } 0.02.$$

The full calculated answer would now be 0.86 ± 0.02 .



Resources



Video eLesson Calculating error (eles-2560)

24.7.5 Limitations of data and methodology

The data that is gathered from the experimental results will have **limitations**. Limitations arise from several sources that can affect the quality of the data:

- Experiments create artificial situations that do not necessarily represent real-life situations.
- While every effort may be made to identify controlled variables and keep them constant throughout the course of an experiment, it is not always possible to identify and control every one of this type of variable.
- The degree on which results obtained in the laboratory can be generalised to other situations and applied in the real world is limited.

It is important to consider limitations when analysing data and drawing conclusions from data.

Limitations should be factors that are out of your control but need to be discussed in regards to how they might affect your results. As part of your practical investigation, you need to clearly outline limitations and suggest improvements to the method or data collection to avoid these.

24.7 EXERCISE

To answer questions online and to receive **immediate feedback** and **sample responses** for every question go to your learnON title at www.jacplus.com.au.

1. Describe the difference between a random and systematic error and provide two examples of each.
2. List two ways that you can minimise uncertainty in an investigation.
3. Identify which graph type would be most appropriate for the following investigations. Justify your choice.
 - (a) Calculating the height of a rocket over time
 - (b) Determining the volume of an airbag upon crashing in six different brands of car
 - (c) Measuring the surface area of a melting ice cube every minute for 20 minutes
 - (d) Showing the frequency of goals scored out of 200 attempts for 1000 students
4. Using the following data, construct an appropriate graph.

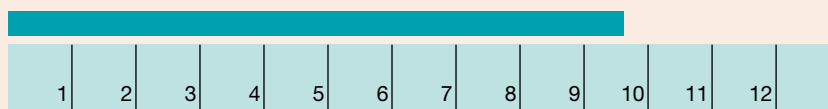
Time (mins)	Height of candle (cm)
0	32 cm
5	29 cm
10	25 cm
15	23 cm
20	19 cm
25	15 cm

Once you construct the graph, analyse and evaluate the data shown.

5. Describe how an outlier should be treated in analysing and evaluating data.

6. Determine the length of each line in the following diagram, showing the tolerance (error) in each case.

(a)



(b)



(c)



7. The power delivered to an electrical device is directly proportional to the voltage across the device and the electric current flowing through the device. If the power delivered to the device is initially 20 W, what will it be if:
- the voltage is tripled
 - the current is doubled
 - the voltage and electric current are both tripled
 - the voltage is doubled and the current is halved?

Fully worked solutions and sample responses are available in your digital formats.

24.8 Models and theories to understand observed phenomena

KEY CONCEPT

- Observations and experiments that are consistent with, or challenge, current physics models or theories.

KEY SCIENCE SKILL

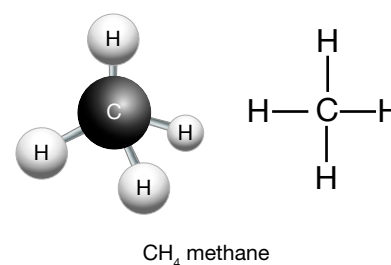
- Analyse and evaluate scientific models.

As well as data limitations, limitations exist in the models and theories that we use in physics. It is important to be able to use models and theories to allow us to understand a variety of observed phenomena, but also to understand the limitations and the idea that they may change as more observation and research is conducted.

24.8.1 Models

Models are representations of ideas, phenomena or scientific processes. They can be physical models, mathematical models or conceptual models. Models can provide an explanatory framework that explains observed phenomena and helps with the understanding of abstract concepts. In physics, many concepts are hard to visualise, so models help contextualise the idea on a smaller and simpler scale.

FIGURE 24.48 Different models of methane, a gas involved in the greenhouse effect. How do you think this differs from a 'real' methane molecule?



While they are very useful, models have their limitations:

- Because of the complexity of the processes, models cannot include all the details of the processes or the things that they represent.
- Models are necessarily approximations of the real world; for example, we can use Newton's law of motion to make predictions about motion, however, this model cannot be used in certain conditions, particular at very high speeds and therefore predictions would not always match what happens in the real world.
- Models often have limits in their accuracy and are often simplified and stylised, for example, a ball-and-stick model of methane (see figure 24.48) is useful but is a very highly simplified and stylised representation that reduces bonds to sticks and atoms to solid balls.
- Models are based off current observations and knowledge at the time. This means that they aren't definite and can change as observations allow for different ideas to come to light.

Models are constantly being refined as new information becomes available. One model that has continuously changed is that of the atom.

FIGURE 24.49 A model showing the Higgs boson particle (known as the god particle)

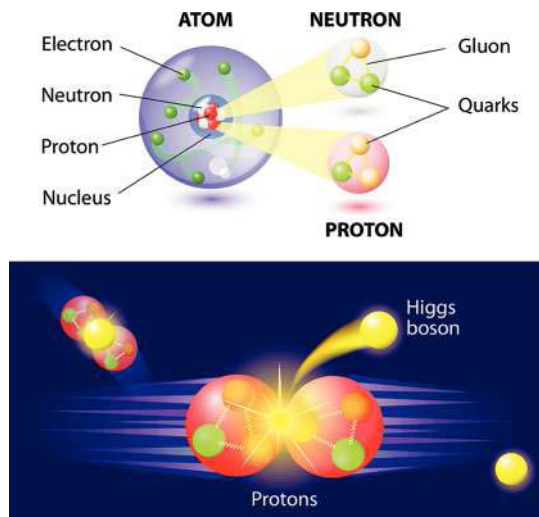
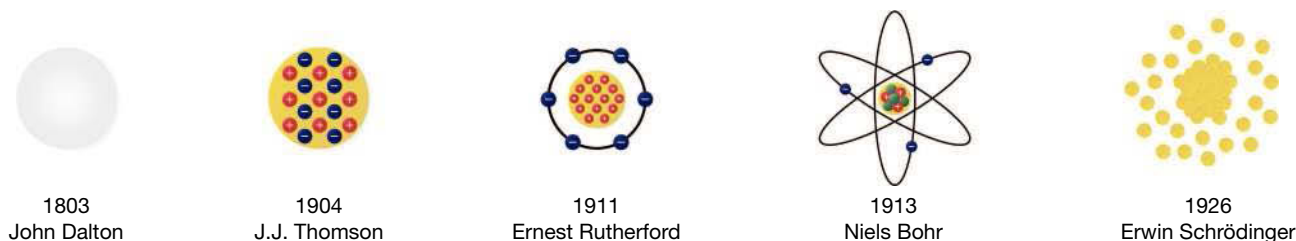


FIGURE 24.50 Various models of the atom including John Dalton's model and J.J. Thomson's Plum Pudding model



24.8.2 Theories

A **theory** is a well-supported explanation of a phenomena. It is based on the interpretation of facts that have been obtained through investigations, research and observations.

There are limitations that can exist with theories, such as:

- There is often a reliance on theories rather than observations made during practical investigations. Often, theories are treated as perfect, when in fact they can be disproven as new observations and evidence come to light.
- Theories often rely on a very specific set of conditions to be met. For example, Newton's laws of motions cannot be used at very small scales or very high speeds.
- Often a phenomenon needs to be described using multiple theories. Sometimes, aspects of theories may have some contradictions to each other.

Theories can change overnight or take a very long time to change. Theories that were once popular and well accepted may be discarded when too much evidence builds up against them. They are replaced by a theory which better fits the observations.

Some examples of theories that have been superseded by other theories are:

- miasma theory of disease — the idea that diseases were caused by bad air
- that the Sun and planets orbit the Earth (geocentrism)
- Flat Earth theory.

Another example of changing theories is seen in astrophysics, where some of Newton's theories (and Einstein's theory of relativity) are being contested.

A new theory known as Modified Newtonian

Dynamics (MoND) has new predictions about the universe, particularly around dark matter and astronomy.

FIGURE 24.51 The Flat Earth theory has been replaced with the idea that the Earth is spherical.



TABLE 24.10 The changing theories in astrophysics

1933	Fritz Zwicky coins the term 'dark matter' to describe unseen mass or 'gravitational glue' in galaxy clusters.
1978	Astronomers show that many galaxies are spinning too quickly to hold themselves together unless they are full of dark matter.
1983	Mordehai Milgrom publishes a modified gravity theory called MoND. It explains why galaxies don't fly apart without using dark matter, but remains at odds with Einstein's relativity.
1990s	Studies of galaxies and galaxy clusters show that their gravity bends light more strongly than is expected without dark matter. MoND researchers start devising improved theories to explain extra light bending.
1994	Jacob Bekenstein and Roger Sanders prove that any theory that resolves the light-bending issue and meshes MoND with relativity must involve at least three mathematical fields.
2000	New data on the cosmic microwave background reinforce the standard, dark matter picture of the universe.
2004	Jacob Bekenstein devises a version of MoND that is consistent with relativity.
2005	Constantinos Skordis and others show that relativistic MoND provides a good fit to the microwave background data.

Refinements to existing theories come about in a number of ways:

- carefully planned laboratory-based or field-based experiments designed to support or refute a particular hypothesis
- critical reinterpretation of previously accepted facts, producing a new framework
- collection and analysis of new data
- identification and exploration of patterns or anomalies
- new technologies that allow for changes to understanding and more depth of knowledge.

24.8 EXERCISE

To answer questions online and to receive **immediate feedback** and **sample responses** for every question go to your learnON title at www.jacplus.com.au.

1. Describe three ways that models can be useful.
2. Describe three limitations of models.

3. What is the difference between a model and a theory?
4. How can theories help us understand phenomena?

Fully worked solutions and sample responses are available in your digital formats.

24.9 Nature of evidence and key findings of investigations

KEY CONCEPT

- The nature of evidence that supports or refutes a hypothesis, model or theory.
- The key findings of the selected investigation and their relationship to key physics concepts.

KEY SCIENCE SKILLS

- Analyse and evaluate data, methods and scientific models.
- Draw evidence-based conclusions.
- Communicate and explain scientific ideas.

24.9.1 Nature of evidence: supporting or refuting a hypothesis, model or theory

Evaluating a hypothesis, model or theory uses the evidence from the results obtained in an investigation. In your investigation, it is important to understand how to best use evidence in order to correctly support or refute your hypothesis.

Evidence can be strong or weak, as summarised. It is vital that the evidence you choose allows the provision of strong and clear conclusions.

Strong evidence should:

- be based on facts derived from studies with high validity and minimal bias
- use data to support conclusions
- clearly link to the aim and hypothesis of an experiment
- be obtained from an investigation that has a reproducible and reliable method.

If the prediction from your hypothesis was validated by your experimental results, you should evaluate your hypothesis as ‘supported’ and if your hypothesis was not supported by results, it is termed as ‘rejected’ or ‘disproven’. This is a reminder that a scientific hypothesis can be disproven, but can never be proven true — it can only be supported. This is because the nature of evidence is that as new technologies and information becomes available, evidence can change and be interpreted in different ways. This may than disprove a previously made hypothesis.

TABLE 24.11 Examples of results that can support or disprove a hypothesis

Observation	Hypothesis	Test of hypothesis	Result	Conclusion
The phone is not charging.	The charger is faulty.	Use a different charger.	The phone still does not charge.	Hypothesis disproved
The globe in the circuit is not working.	The power pack is faulty.	Replace with a new power pack.	Light globe turns on.	Hypothesis supported
The reading on the voltmeter is below zero.	The wires are the wrong way.	Swap the wires.	The reading is now above zero.	Hypothesis supported

24.9.2 The key findings of investigations

In your investigation, you would have written a question and a hypothesis, created a clear reproducible methodology, and collected and analysed data.

From this point, it is then important to determine the key findings of your investigation.

Your key findings should include:

- information about the data obtained in the practical investigation and any patterns and trends
- the relationship of your findings to physics concepts including thermodynamics, matter, motion and electric circuits
- an answer to the question of your investigation.

For example, your question may have been, ‘How does mass affect the change of temperature of gold?’ and you may have obtained the results shown in figure 24.52.

Your key findings that you should include in the discussion, may be as follows:

It is expected that based on the formula $q = mc\Delta T$, in which q is the heat energy, m is the mass, c is the specific heat and ΔT is the change in temperature, that increasing the mass of gold would increase the heat energy required.

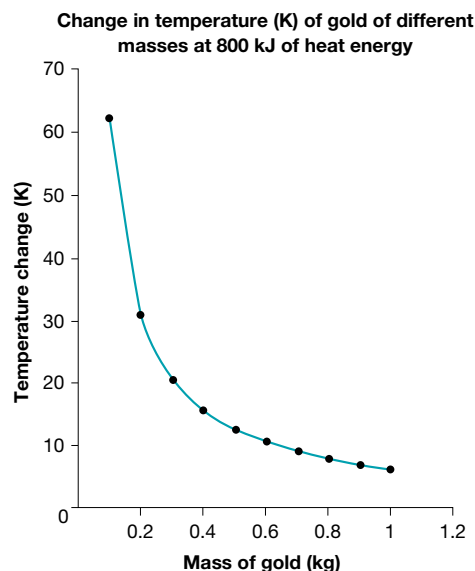
In this situation, the heat energy and specific heat are controlled across all experiments, with the mass being the independent

variable. By rearranging the equation to $\Delta T = \frac{Q}{mc}$, it can be

seen that the change in temperature is inversely proportional to the mass as an object. Therefore, increasing the mass would lead to a reduction in the change in temperature.

From the investigation, it can be observed that the mass of gold does have an impact on the change in temperature as observed in the graph in figure 24.52, however, this relationship is not linear. This supports the hypothesis of this investigation.

FIGURE 24.52 Exploring the impact of different masses on temperature change



24.9 EXERCISE

To answer questions online and to receive **immediate feedback** and **sample responses** for every question go to your learnON title at www.jacplus.com.au.

1. Why do we only say that we ‘support’ a hypothesis rather than ‘prove’ it?
2. Provide three examples of strong evidence.
3. Describe what key findings you should communicate in a discussion.
4. Why is it important to show the relationship of your results to concepts such as waves, fields and motion?

Fully worked solutions and sample responses are available in your digital formats.

24.10 Conventions of scientific report writing and scientific poster presentation

KEY CONCEPT

- The conventions of scientific report writing including physics terminology and representations, symbols, equations and formulas, units of measurement, significant figures, standard abbreviations and acknowledgment of references.

KEY SCIENCE SKILL

- Communicate and explain scientific ideas.

24.10.1 Conventions of report writing

It is vital in scientific report writing to follow the protocols of scientific written communication (see table 24.12).

TABLE 24.12 Aspects of a written report

Section	Description
Title	A precise and complete description of what you investigated
Abstract	An optional section, used to outline the key findings and information
Introduction	A paragraph explaining the relevant physics and background concepts and relationships and how they apply to this investigation. It should explore any prior investigations conducted on this topic. This should also include a clear aim and hypothesis.
Methodology	A detailed section that describes your selection of equipment and measuring instruments, and your step-by-step method. This may include diagrams and photos. Refer to how you controlled variables, achieved the desired accuracy and overcame, avoided or anticipated difficulties. It should be clear enough for someone else (at your level) to repeat your experiment. Do not forget to highlight how the relevant ethical and safety concerns have been addressed. This section is often detailed in your logbook and summarised in your final report.
Results (and observations)	A clear representation of your results includes your data and graphs. If there is too much data, then refer to your logbook for the full set. Make sure you present your results in an organised and clear manner, following accepted conventions (such as numbered sequentially). Make sure you include the appropriate units and use the correct number of significant figures. Try to organise this in such a way that any patterns or relationships start to become obvious, thus making it easier to analyse in the discussion. Show sample calculations if required.
Discussion	A detailed analysis and evaluation of your results. How does your data support your initial intentions and link to relevant physics concepts? What trends and relationships are apparent as a result of your investigation? How much is your analysis limited by uncertainties? Were there any outliers in your investigation and how were they treated? What limitations and sources of error were present in your investigations and how would you improve this in future repetitions? What would the next steps in the investigation be if you had more time?
Conclusion	A paragraph relating to the aim and based entirely on the evidence obtained in the experiment. It should state whether the hypothesis is supported, summarising the meaning of your results in response to your question. No new information should be included.
References and acknowledgements	A list of the sources of any content you include that is not your own original work. Unaltered tables, diagrams and graphs are examples that fit this description, as are direct quotes. In your introduction, you may have mentioned previous work that your investigation is based on. This also needs to be acknowledged, along with any sources that inform your discussion of concepts and theory in a more general sense. This section is not counted in your final word count.

Remember, your teacher will also mark both your scientific report (or poster) and the work in your logbook, so make sure that all required work is there. You may have some of the above information that only appears in your logbook; some that appears in both and some that only appears in your report. Your logbook and report are all part of practical investigation skills.

Some other things that are important to a scientific report:

- Try to avoid subjective language — where possible, use third-person language and write in past tense.
- Don't just record the data you believe supports your hypothesis, you should also include any errors, uncertainties and outliers.
- If you used any calculations, show your workings.
- Use subheadings throughout your report. Make it clear to read.
- Provide headings for all graphs, tables and figures and label them sequentially (graph 1, graph 2, etc.).

24.10.2 Terminology and representations

It is important throughout your report to use clear and concise terminology relevant to the related physics concept. The use of key terms was covered previously. In addition, physics representations are required to be accurate and use common conventions. These representations were discussed in 24.4.3. There may be other representations used that are appropriate to your specific investigation. These should be used consistently in both your logbook and your poster.

24.10.3 Symbols

Table 24.13 lists some commonly used symbols in physics. Many of these are from the Greek alphabet.

TABLE 24.13 Some common symbols used in physics

Symbol	Name	Representation
λ	Lambda	Wavelength (nm)
α	Alpha	Type of particle
β	Beta	Type of particle
γ	Gamma	Type of particle
τ	Tau	Torque (in forces) or time constant (in electricity)
η	Eta	Efficiency
ϵ	Epsilon	Strain (in Young's modulus) or electromotive force (emf)
σ	Sigma	The uniaxial stress (in Young's modulus)
θ	Theta	Angle
ω	Omega	Angular frequency
Δ	Delta	Change in variable
$\perp$		Perpendicular to
$\propto$		Proportional to

Due to the sheer quantity of variables we have to represent, it is important to note that the capital and lowercase letter usually represent different things. For example, t represents time, and T represents temperature (or may be used to represent the orbital period). Factors such whether a symbol is in bold, italics or a roman typeface also affect their meaning. Additionally, sometimes the same symbol is used to represent different variables.

μ for example, can be used to represent:

- mean in statistics
- micro in measurement
- coefficient of friction.

It is important to carefully use the correct symbol in your report to minimise confusion. It is important to know various symbols, including those used in equations.

24.10.4 Equations and formulas

During your exam, you will be provided with a formula sheet for your reference.

When provided these in your scientific investigation, it is important to:

- define all variables
- provide any figures for constants (for example Planck's constant).

Some key formulas in Physics are as follows.

Thermodynamics

- First law of thermodynamics: $Q = U + W$
- Raise of temperature of a substance: $Q = mc\Delta T$
- Raise the state of a substance: $Q = mL$
- Wien's law: $\lambda_{\max} T = \text{constant}$
- Stefan-Boltzmann Law: $P \propto T^4$

Electric circuits

- Electric current: $I = \frac{Q}{t}$
- Potential difference: $V = \frac{E}{Q}$
- Power: $P = \frac{E}{t} = VI$
- Resistance in series: $R_T = R_1 + R_2 + \dots + R_n$
- Resistance in parallel: $\frac{1}{R_T} = \frac{1}{R_1} + \frac{1}{R_2} + \dots + \frac{1}{R_n}$
- Resistance: $I = \frac{V}{R}$
- Power: $P = VI$

Matter

- Conservation of mass: $E = mc^2$

Motion

- Formulas for constant acceleration:
 - $v = u + at$
 - $v^2 = u^2 + 2as$
 - $s = \frac{1}{2}(u + v)t$
 - $s = ut + \frac{1}{2}at^2$
 - $s = vt + \frac{1}{2}at^2$
- Momentum to linear motion: $p = mv$
- Change in momentum: $F_{\text{net}} = \frac{\Delta p}{\Delta t}$
- Force due to gravity: $F_g = mg$
- Acceleration: $a = \frac{F_{\text{net}}}{m}$
- Torque: $\tau = r_{\perp} F$
- Work: $W = FS$
- Hooke's law: $F = -k\Delta x$

- Changes in gravitational power: $E_g = mg\Delta h$
- Transfer in potential energy in springs: $E_s = \frac{1}{2}k\Delta x^2$
- Transfer in kinetic energy: $E_k = \frac{1}{2}mv^2$
- Rate of energy transfer: $P = \frac{E}{t}$
- Efficiency of an energy transfer system: $\eta = \frac{\text{useful energy out}}{\text{total energy in}}$
- Impulse in an isolated system: $I = \Delta p$

24.10.5 Units of measurements

In Physics, it is vital to use the correct unit of measurement for accurate and clear scientific communication.

Prefixes

TABLE 24.14 Prefixes for units of measurement

Pico (p)	Nano (n)	Micro (μ)	Milli (m)	Centi (c)	Deci (d)	Kilo (k)	Mega (M)	Giga (G)
10^{-12}	10^{-9}	10^{-6}	10^{-3}	10^{-2}	10^{-1}	10^3	10^6	10^9

These values are off the base or SI unit, which does not have a prefix (for example, metre, seconds, grams). These have the value of 10^0 or 1. All other prefixes are compared to this base unit.

Understanding different prefixes allows the correct units to be used in practical investigations and allows for easy conversion between different units.

The following formula is used when converting between units:

$$\frac{\text{initial unit (10}^n\text{)}}{\text{new unit (10}^n\text{)}} \times \text{value}$$

SAMPLE PROBLEM 5

Convert:

- 12.412 millilitres to microlitres
- 26 153 milligrams to decigrams
- 8.7 metres to nanometres.

 **Teacher-led video:** SP5 (tlvd-0105)

THINK

1. Determine the conversion between the units.
 - Multiply by the value to be converted.
 - Add the new unit.
 - State the solution.
1. Determine the conversion between the units.

WRITE

- $$\frac{\text{millilitres}}{\text{microlitres}} = \frac{10^{-3}}{10^{-6}} = 10^3$$

$$10^3 \times 12.412 \text{ mL} = 12\,412$$

$$12\,412 \mu\text{L}$$

12.412 millilitres equals 12 412 microlitres.
- $$\frac{\text{milligram}}{\text{decigram}} = \frac{10^{-3}}{10^{-1}} = 10^{-2}$$

2. Multiply by the value to be converted. $10^{-2} \times 26\,153 \text{ mg} = 261.53$
 3. Add the new unit. 261.53 dg
 4. State the solution. $26\,153 \text{ milligrams equals } 261.53 \text{ decigrams.}$
- c.** 1. Determine the conversion between the units.
We use 10^0 for metres as it is our standard unit, so is equal to 1.
- $$\frac{\text{metre}}{\text{nanometre}} = \frac{10^0}{10^{-9}} = 10^9$$
2. Multiply by the value to be converted. $10^9 \times 8.7 \text{ m} = 8700\,000\,000$
 3. Add the new unit (round if required) $8700\,000\,000 \text{ nm}$
 4. State the solution. $8.7 \text{ metres equals } 8700\,000\,000 \text{ nanometres.}$

PRACTICE PROBLEM 5

Convert:

- a. 7823 decigrams into kilograms
- b. 213 microlitres into picolitres.

SI units of measurement

SI units or *Système Internationale* is our metric system of measurements, that is internationally standardised.

TABLE 24.15 Common SI units used in Physics

Quantity	Unit	Symbol
Length	Metre	m
Mass	Kilogram	kg
Time	Second	s
Temperature	Kelvin	K
Electric current	Ampere	A
Energy	Electron volt	eV

For units named after an individual, such as André-Marie Ampère, Lord Kelvin and Sir Isaac Newton, the symbol (or first letter of the symbol) is capitalised. However, when the full word is written out it is not capitalised. For example, 60 A would be written as 60 amperes.

Derived units

Derived units are units of measurements derived from the SI units. Table 24.16 shows some commonly used derived SI units.

Speed is another example of a quantity that is measured in derived SI units. The SI unit of speed is the metre per second, written as m/s or m s^{-1} .

Derived units are often expressed with negative indices. For example, the unit of speed is usually expressed as m s^{-1} rather than m/s. This is because:

$$\begin{aligned}
 1 \text{ m/s} &= 1 \text{ m} \times \frac{1}{\text{s}} \\
 &= 1 \text{ m} \times 1 \text{ s}^{-1} \\
 &= 1 \text{ m s}^{-1}
 \end{aligned}$$

TABLE 24.16 Common derived units used in Physics

Quantity	Unit	Symbol	Unit in terms of other units
Force (F)	Newton	N	kg m s^{-2}
Energy and work (E and W)	Joule	J	N m
Pressure (p)	Pascal	Pa	N m^{-2}
Power (P)	Watt	W	J s^{-1}
Electric charge (q)	Coulomb	C	A s
Voltage (V)	Volt	V	J C^{-1}
Resistance (R)	Ohm	Ω	J C^{-1}
Radiation dose	Sievert	Sv	J kg^{-1}
Temperature	Celcius	$^{\circ}\text{C}$	273.15 K

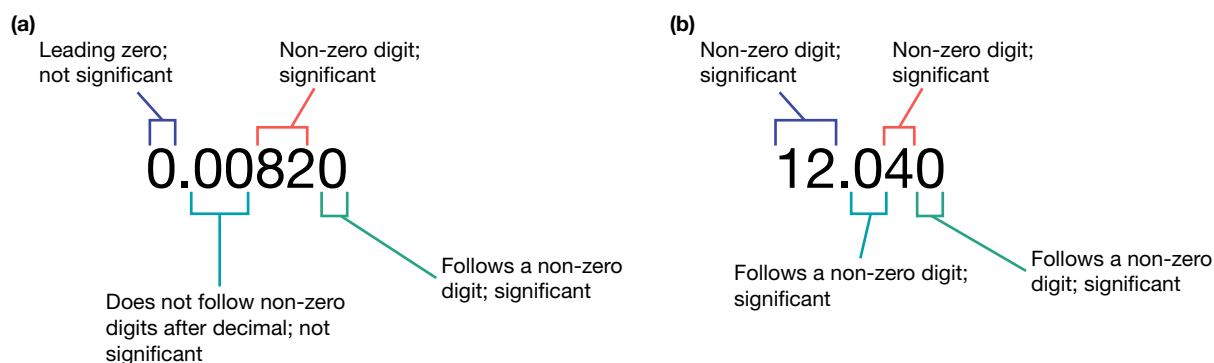
24.10.6 Significant figures

There is a degree of uncertainty in any physical measurement. The uncertainty can be due to human error or to the limitations of the measuring instrument.

In most physical measurements, the last significant figure shows a small degree of uncertainty. For example, the length of an Olympic competition swimming pool is correctly expressed as 50.00 m. The last zero has a small degree of uncertainty.

Two simple rules can be used to help you decide if zeros are significant.

- Zeros before the decimal point are significant if they are between non-zero digits. For example, all of the zeros in the numbers 4506, 27 034 and 602 007 are significant. The numbers therefore have four, five and six significant figures respectively. The zero in the number 0.56 is not significant.
- Zeros after the decimal point are significant if they follow a non-zero digit (or a 0 that follows a non-zero digit). For example, in the number 28.00, the two zeros are significant. The number has four significant figures. However, in the number 0.0028, the zeros are not significant. They do not follow a non-zero digit and are present only to indicate the position of the decimal point. This number therefore has only two significant figures. The number 0.002 80 has three significant figures (the last zero is significant as it follows a non-zero digit).

FIGURE 24.53 Examples of significant figures: (a) three significant figures, (b) five significant figures

Working with significant figures

When multiplying or dividing, the answer is written to the least number of significant figures in the initial values provided. For example, if you travelled a distance of 432 metres in a car for 25 seconds, your average speed would be given by:

$$\begin{aligned}\text{average speed} &= \frac{\text{distance travelled}}{\text{time taken}} \\ &= \frac{432 \text{ m}}{25 \text{ s}} \\ &= 17.28 \text{ m s}^{-1}\end{aligned}$$

The result should be rounded off to two significant figures as this is the least significant figure we were given and can be confident to determine the distance and time, and should be expressed as 17 m s^{-1} .

When adding or subtracting, the answer is written to the least number of decimal places in the initial values provided. For example, if you travelled three consecutive distances of 63.5, 12.2517 and 32.78 metres, the total distance travelled would be given by:

$$\begin{array}{r} 63.5 \text{ m} \\ + 12.2517 \text{ m} \\ + 32.78 \text{ m} \\ \hline 108.5317 \text{ m} \\ = 108.5 \text{ m} \end{array}$$

The result should be rounded off to one decimal place as the minimum number of decimal places used in the data is one (in the distance of 63.5 metres).

SAMPLE PROBLEM 6

In determining the density of a particular liquid, a student measured the volume of a sample as 8.3 millilitres. She then weighed the same sample and obtained a mass of 7.2 136 grams. Calculate the density to the correct level of significant figures.

 **Teacher-led video:** SP6 (tlvd-0106)

THINK

1. Determine the number of significant figures you have been provided.
2. Determine the least number of significant figures; this is what your answer will be in.
3. Calculate the density.
4. Round down to the appropriate number of significant figures.
5. State the solution.

WRITE

7.2 136 = five significant figures
8.3 = two significant figures

Two significant figures

$$\text{density} = \frac{\text{mass}}{\text{volume}}$$

$$\text{density} = \frac{7.2\ 136}{8.3} = 0.8\ 691$$

Round 0.8 691 to two significant figures
= 0.87 g mL⁻¹

The density is 0.87 g mL⁻¹.

PRACTICE PROBLEM 6

In determining the density of a particular liquid, a student measured the volume of a sample as 21.1 millilitres. She then weighed the same sample and obtained a mass of 9.762 grams. Calculate the density to the correct level of significant figures.



Resources



Video eLesson Determining significant figures (eles-2559)

24.10.7 Standard abbreviations

Often, it is appropriate to abbreviate terms rather than writing it out in full on each appearance, which can make a report bulky and hard to follow.

Some common abbreviations used in Units 1 and 2 Physics:

- AC: alternating current
- DC: direct current
- LPG: liquefied petroleum gas
- LED: light-emitting diode
- CT: computed tomography
- PET: positron emission topography.

For other words that can be abbreviated, either the full word needs to be shown, or the meaning of the abbreviation needs to be acknowledged.

This is done by clearly showing the full term the first time the abbreviation is used. In subsequent uses, the abbreviation alone may be used.

An example of this is:

In direct current (DC) the current applied only flows in one direction. Portable electronic sources, such as laptops and mobile phones, use DC.

24.10.8 Acknowledgement of references

In-depth scientific reports require a depth of research for concepts relating to an investigation.

This may be:

- using other sources for definitions and background material
- finding examples of similar investigations
- research on the obtained results to link to scientific understanding.

If you use any material that is the work of another person, you *must* acknowledge its source. Do not claim it as your own work. Acknowledgments come in two formats: a short version when it occurs in the body of your poster or report and a longer version when it occurs in the Reference and Acknowledgments section at the end of your poster or scientific report.

There are many ways to make such acknowledgments and various institutions and publications often use different systems. Details of these systems can be found online and can be quite complicated. You should check with your teacher as to how this is expected to be done.

Acknowledging sources within your report: in-text referencing

An in-text reference is a shortened abbreviated form of a reference and should be used in the body of your report in the location in which the sourced information is referred to. This is used not just for direct quotes, but also for tables, images and any information that has been paraphrased.

There are numerous ways to do this and it depends on what style you are using, so again, check with your teacher.

Author-date system

This style of in-text referencing is more commonly used, particularly in the APA and Harvard styles of referencing (the two styles most commonly used in science). As well as the shortened in-text referencing, a full reference is included in the reference list.

Text that has been sourced has the in-text at the end of the information being used. This may be in the middle of a sentence as seen here.

... over the past 10 years, the number of eligible children has increased (Kringle, 2008) and a need has therefore developed for sleighs to travel faster to meet the required delivery schedule. More efficient fuels are required for this purpose.

Tables, diagrams, graphs, and so on that are being inserted without being substantially altered can often be acknowledged by stating the details directly underneath them as shown in table 24.17.

TABLE 24.17 Energy content of commonly available sleigh fuels

Fuel	Energy content (kJ L ⁻¹)
Rudolphene	45
Polar plus	29
Super sleigh	53

(Claus, 2016, p. 45)

Notes

- If an online article is undated, put (n. d.) in place of the date.
- If there is no author listed, use the title in place of the author's name.
- If there are up to three authors, list them all.
- If there are more than three authors, only use the name of the first author and follow it by the phrase 'et al.' (meaning 'and others').
- If you quote directly from an author or cite a specific idea or piece of information from the source, you need to include the page number of the quote in your in-text reference.

Footnotes system

This style of in-text referencing is usually used in the Chicago and Vancouver style of referencing.

In this style, the citation is should below, which a superscript number showing the point in which a reference have been used.

... over the past 10 years, the number of eligible children has increased⁵ and a need has therefore developed for sleighs to travel faster to meet the required delivery schedule. More efficient fuels are required for this purpose.

⁵ Kringle, K. (2008). *Journal of Polar Transport*, vol. 34, p. 356.

In the footnotes section of the page (depending on the format of the report) the work is referenced with the corresponding number, and then again included in the reference list.

Acknowledging sources at the end of your report: Reference list

At the end of a scientific report or poster, a reference list is included.

In your reference list, references should be listed alphabetically. If the footnotes version of in-text referencing was used, references should be listed in order of footnote number.

The following provides examples of the use of Harvard style in creating references.

Book

Author surname(s), initial(s) (Year published). *Title*. Edition (if applicable). Place of publication, publisher.

Example:

Langley, P & Jones, M (2013). *The search for Richard III: The king's grave*. London, John Murray.

Do not use et al. in your reference list. This is only appropriate in your in-text referencing.

Journal

Author surname(s), initial(s) (Year published). *Title of article*. Title of Journal. Volume number. Page numbers.

Example:

Boiero, D & Bagaini, C (2018). *S-wave splitting intensity analysis and inversion*. Geographical Prospecting. Vol. 67(2). 362–378.

If available, you may also include the DOI (digital object identifier) after the page numbers. A DOI is a permanent identifier for a journal article and is often used in place of a URL.

TV programs

Title of program (date) (TV program) Channel identification.

Example:

Gene editing made simple (2016), Four Corners, ABC Sydney.

Websites

Author surname(s), initial(s) (Year published). *Title of page*. Name of website, date and URL of retrieval

Example:

Fein, B 2011, 'The Patriot Act is at war with the constitution', The American view: God, family, republic, accessed 8 November 2011, <http://archive.theamericanview.com/index.php?id=1770>

24.10.9 Presenting a scientific poster

Your logbook will form a key part of your assessment. You will also be required to deliver a scientific report. This may be in the form of a poster, oral communication or digital communication as selected by your teacher.

A sample format of the poster is shown in figure 24.54, but similar sections will be found in other reports.

FIGURE 24.54 Format of scientific poster

SCHOOL LOGO/ OTHER IMAGE	TITLE The question under investigation with a clear link to the independent and dependent variables	NAME
INTRODUCTION • Aim • Hypothesis • Purpose of the investigation • Background information	RESULTS/OBSERVATIONS • Presentation of collected data/evidence in an appropriate form to illustrate trends, patterns and/or relationships • This may include graphs, images and tables with clear headings	CONCLUSION • Conclusion that provides a response to the question referring to the aim and hypothesis
METHODOLOGY • Summary of the materials and method used that can be authenticated by logbook entries • Information about the choice of equipment and how variables were controlled • Identification and management of relevant risks, including health, safety and ethics	DISCUSSION • Analysis and evaluation of primary data — does it support your initial intentions and relevant theory • Identification of outliers and their subsequent treatment • Discussion of sources of error • Identification of limitations in data and methods and suggested improvements • Linking of results to relevant physics concepts • What would the next steps in the investigation be?	REFERENCES/ ACKNOWLEDGEMENTS • Referencing and acknowledgement of all quotations and sourced content from your poster

Jacaranda
A Wiley Brand

24.10.10 Practical investigation checklist

- ☐ Your name, the title and the aim/hypothesis are listed.
- ☐ An introduction describes the purpose and outlines the investigation in a logical and concise manner. Key terms are defined and variables are stated clearly. Relevant theory is addressed.
- ☐ The method is outlined clearly in step form including a consideration of ethics, health and safety. A risk assessment is provided.
- ☐ Your logbook contains dates, headings and complete records.
- ☐ Any abbreviations are explained.
- ☐ Results are presented in an organised way, in a table if possible. All relevant measurements are recorded with appropriate accuracy and units.
- ☐ Observations are clear and concise, as are all diagrams, graphs and tables used.
- ☐ Any calculations are shown.
- ☐ There is a concise summary and interpretation of key findings, including trends and any unexpected results with connection to theory.
- ☐ The experimental design is evaluated and possible improvements are included.
- ☐ There are suggestions for future investigations.
- ☐ The conclusion concisely summarises how your results support or contradict your original hypothesis.
- ☐ All sources are acknowledged and references correctly cited.
- ☐ The use of key terms, symbols and equations is appropriate.

A poster or other form of scientific report should address the all sections in your logbook without going into too much detail. For example, you would display only a subset of the data to convey your findings and accuracy, often as a graph.

24.10 EXERCISE

To answer questions online and to receive **immediate feedback** and **sample responses** for every question go to your learnON title at www.jacplus.com.au.

1. Convert the following units to the SI base unit shown.
 - (a) 2487 mA (to A)
 - (b) 0.871 km (to m)
 - (c) 684 μs (to s)
2. Convert the following to the unit shown.
 - (a) 0.652 kV (to mV)
 - (b) 487 234 μs (to ms)
3. Describe the following aspects of a scientific report.
 - (a) Introduction
 - (b) Discussion
 - (c) Conclusion
4. Write a reference in Harvard style for this textbook. Show both the in-text referencing and the full reference for the reference list.
5. How many significant figures are in the following?
 - (a) 1289.2
 - (b) 0.08 234
 - (c) 0.8 003
 - (d) 121.400
6. Calculate the following and express in the appropriate number of significant figures.
 - (a) The total length of three pieces of wire of 1.82 m, 0.1 m and 9.13 m
 - (b) The area of a rectangular building that is 12.2 m by 11 m

Fully worked solutions and sample responses are available in your digital formats.

24.11 Review

24.11.1 Summary

- It is important to choose a topic that allows for the development of a question and observations to be made.
- An aim is a one- to two-sentence outline of the purpose the investigation, linking the dependent and independent variables.
- A hypothesis is a tentative, testable and falsifiable statement for an observed phenomenon and acts as a prediction for the investigation.
- Part of scientific method or process is in designing an experiment, conducting the experiment and analysing the results.
- Variables are factors that an investigator can control, change or measure. An independent variable is manipulated by the investigator (e.g. the type of ball used). A dependent variable is measured by the investigator and is influenced by the independent variable (e.g. how high a ball bounces). A controlled variable is one that is kept the same in an investigation. There are usually numerous controlled variables in an experiment (e.g. the surface the ball bounces on, the size of ball and the height the ball is initially dropped from). It is important to control variables in order to examine one independent variable at a time to better understand the relationship to the dependent variable.
- Key terms can be defined as part of a scientific report or in a glossary. Key terms that are selected should be those that are vital to understand the investigation.
- There are various representations used in Physics, including symbols, models, equations and formulas. Understanding various representations helps make communication easier and clearer.
- Primary sources of data are direct or firsthand evidence, often gained through practical investigations. Data can be quantitative (numerical) or qualitative.
- It is vital to carefully choose the best techniques and equipment for an investigation. These should be precise, accurate and easy to conduct and use within a school environment.
- In an investigation, it is vital to consider the accuracy, precision, reliability and validity. The best designed experiments are accurate, precise, reliable and valid, while minimising errors and uncertainties.
 - Accuracy is how close a measurement is to a known value (like hitting the target on a bullseye).
 - Precision is how close multiple measures are to each other (like hitting a 6 on a target three times in a row).
 - Reliability shows that if an experiment is replicated (by oneself or another researcher), the results should be similar.
 - Validity is how much credibility can be given to the results: do the results measure what they intended to and back up their claims?
- Both errors and uncertainty can affect the results gained. Errors are a measurement of the difference between a measured value and the true value (the accuracy), whereas uncertainty limits precision and the range of values that can be measured.
- In an investigation, care must be taken to follow ethical, health and safety guidelines. Ethics are involved in moral conduct, in particular when humans and animals are involved as test subjects. This does not tend to be an issue in Physics compared with Biology and Psychology.
- Health and safety is often evaluated using a risk assessment, where different hazards are analysed and safety requirements are made.
- Data can be organised in a variety of ways, including through the use of tables and graphs. Scatterplots and line graphs are used when both variables are quantitative. Bar graphs are used when one piece of data is qualitative and the other is quantitative. Histograms are used when intervals and frequency are being explored.
- It is important to choose an appropriate type of organising data in order to analyse trends, patterns and relationships. Graphs can be used to predict data outside of the investigated set.

- When evaluating data, it is important to link this to scientific concepts, models and theories, link it back to your aim and hypothesis, describe trends and patterns, and identify any outliers or limitations.
- Models represent ideas, phenomena or scientific processes. They can be physical models, mathematical models or conceptual models. Limitations of models include an oversimplification of concepts, an inability to be completely accurate and being specific to a set of conditions, which may or may not reflect the real world.
- Theories are well-supported explanations of phenomena. Similar to models, they are often oversimplifications of concepts, specific to a set of conditions and subject to change as new information becomes available.
- Evidence can be used to support or reject a hypothesis. A hypothesis is not stated to be confirmed or proven true as new evidence may come to light which later leads to its rejection.
- When reporting key findings, it is important to provide information about the data obtained in the practical investigation and any patterns and trends, show the relationship of your findings to physics concepts including waves, fields or motion and provide an answer to the question of your investigation.
- Both your logbook and scientific poster are forms of scientific reporting and combine for your mark for Unit 2 AOS 3.
- Components required in a scientific report include a title, date, name, introduction, aim, hypothesis, methodology (method and materials), results, discussion, conclusions and references.
- A variety of key symbols, formulas, equations, terminology, representations and abbreviations are used in physics and are required for effective communication.
- All sourced information must be correctly and clearly referenced using a style such as Harvard or APA.
- Your poster will not have every piece of information that your logbook will, but will show the important and key points that will allow for a clear understanding of your investigation.

24.11.2 Key terms

Accuracy relates to how close an experimental measurement is to a known value.

The **aim** is a statement outlining the purpose of an investigation, linking the dependent and independent variables.

In a **bar graph** data are represented by a series of bars. They are usually used to when one variable is quantitative and the other is qualitative.

Categorical data, also known as qualitative data, has labels or names rather than a range of numerical quantities.

A **control group** is not affected by the independent variables and is used as a baseline for comparison.

Controlled variables those that are kept constant across different experimental groups.

The **dependent variable** is the variable that is influenced by the independent variable. It is the variable that is measured.

The **discussion** is a detailed area of a report in which results are discussed, analysed and evaluated, relationships to concepts are made, errors, limitations and uncertainties are assessed and suggestions for future improvements are made.

An **error** is the difference between a measurement taken and the true value that is expected. Errors lead to a reduction in the accuracy of the investigation.

Ethics are related to acceptable and moral conduct determining what is 'right' and what is 'wrong'.

The **experimental group** is the group exposed to the independent variable.

Falsifiable means that there has to be a way to prove the hypothesis wrong.

In a **histogram** data are sorted in intervals and frequency is examined. This is used when both pieces of data are quantitative. All columns are attached in a histogram.

A **hypothesis** is a tentative, testable and falsifiable statement for an observed phenomenon and acts as a prediction for the investigation.

The **independent variable** is the variable that is changed or manipulated by an investigator.

Limitations are factors that have affected the interpretation and/or collection of findings in a practical investigation.

In a **line graph** points of data are joined by a connecting line. These are used when both pieces of data are quantitative (numerical).

The **line of best fit** is a trend line that is added to a scatterplot to best express the data shown. These are straight lines and are not required to pass through all points.

A **model** is a representation of ideas, phenomena or scientific processes; can be a physical model, mathematical model or conceptual model.

Numerical data, also known as quantitative data, involves numbers and can be measured or counted.

Outliers are results that are a long way from other results and seen as unusual. They should be accounted for and analysed, but are often not included when calculated averages.

Precision is how close multiple measurements of the same investigation are to each other.

A **primary source** is direct or firsthand evidence about some phenomenon.

Qualitative data are categorical data that examines the quality of something (e.g. colour, gender) rather than numerical values.

Quantitative data are numerical data that examines the quantity of something (length, time).

Random errors are chance variations in measurements.

Reliability relates to whether another researcher could repeat the investigation by following the same method and obtain similar results.

Results is a section in a report in which all data obtained is recorded. This is usually in the form of tables and graphs.

A **risk assessment** is a document that examines the different hazards in an investigation and suggested safety precautions.

In a **scatterplot** two quantitative variables are plotted as a series of dots.

Sometimes referred to as scientific process, the **scientific method** is the procedure that must be followed in scientific investigations, which consists of questioning, researching, predicting, observing, experimenting and analysing.

The **scientific research methodology** is the principles of research based on the scientific method.

A **secondary source** comments on or summaries and interpretations of primary data.

Systematic errors are those that affect the accuracy of a measurement, that cannot be improved by repeating an experiment. They are usually due to equipment or system errors.

Testable means that a hypothesis can be easily tested by observations and/or investigations.

A **theory** is a well-supported explanation of a phenomena, based on facts that have been obtained through investigations, research and observations.

An **uncertainty** limits the precision of equipment, it is a range within which a measurement lies.

Validity relates to the credibility of the research results from experiments or from observations. Validity shows how much results measure what they intending to and how well they show the claims they make.



Resources



Digital document Key terms glossary (doc-32272)

24.11 Exercises

To answer questions online and to receive **immediate feedback** and **sample responses** for every question go to your learnON title at www.jacplus.com.au.

24.11 Exercise 1: Multiple choice questions

1. Rani conducted an investigation to test the effect of the brand of tennis racquet on the speed of a serve.

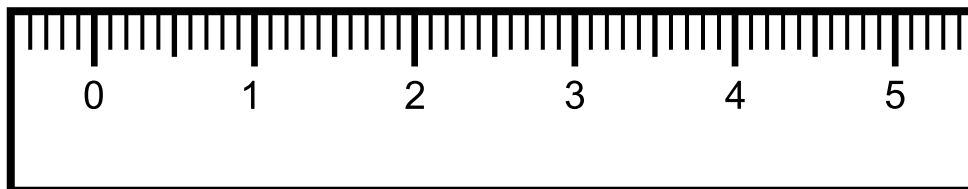
In this investigation, what is the speed of the serve?

- A. A dependent variable
 - B. An independent variable
 - C. A controlled variable
 - D. A control group
2. Students were conducting an investigation to explore the voltage in an electric circuit using both a voltmeter and a digital multimeter.

Each measurement was taken three times using a voltmeter and recorded by the student. A digital multimeter was also used.

Student	Recorded voltage recorded on voltmeter			Digital multimeter reading
	Measurement 1	Measurement 2	Measurement 3	
Steph	12.50	12.25	13.50	11.23
Alex	10.50	10.50	10.25	11.25
Caitlin	11.25	10.75	10.75	11.00
Simonne	12.25	11.75	10.50	12.28

- A. Steph had the least precise measurements.
 - B. Alex had the most precise measurements.
 - C. Caitlin had the least accurate measurements.
 - D. Simonne had the most accurate measurements.
3. In physics, what does the symbol Δ represent?
- A. Force
 - B. Proportional to
 - C. Change in quantity
 - D. Torque
4. What would the measure of uncertainty be in the following ruler?



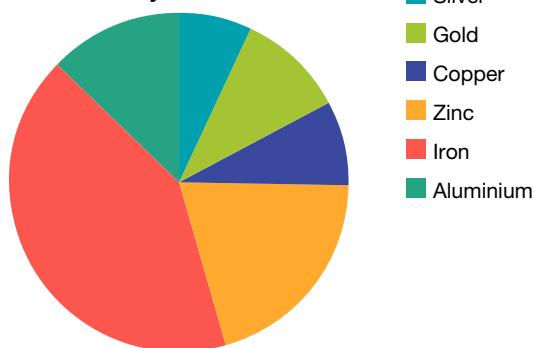
- A. 0.5 cm
- B. 0.1 cm
- C. 0.05 cm
- D. 0.025 cm

5. Which of the following is correct in relation to systematic errors?
- They can affect the accuracy of a reading.
 - They can be caused by human fault.
 - They can be improved by repeated an experiment.
 - They can be caused by deliberate changing of the results due to bias.
6. Melissa was investigating the resistance of different types of metal. The results of her investigation are as follows.

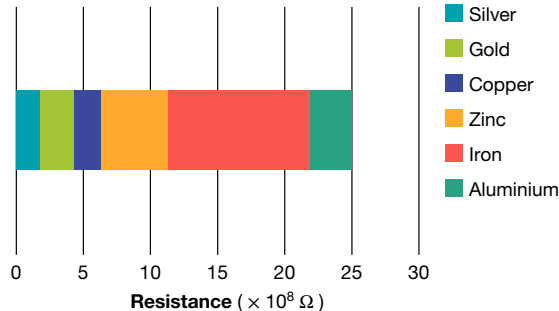
Type of metal	Resistance ($\times 10^{-8} \Omega$)
Silver	1.78
Gold	2.51
Copper	2.03
Zinc	5.03
Iron	10.42
Aluminium	3.12

Which of the following graphs is most appropriate to show and analyse trends in the data from question 3?

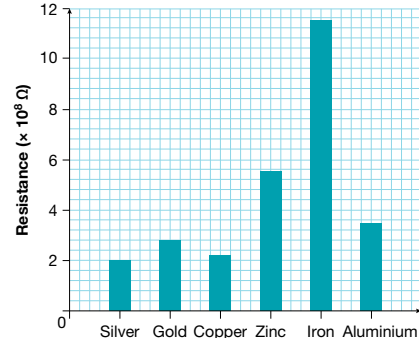
A. Resistivity of different metals



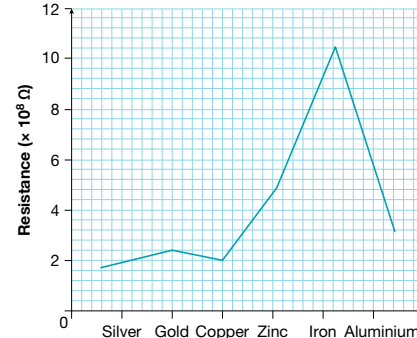
B. Resistivity of different metals



C. Resistivity of different metals



D. Resistivity of different metals



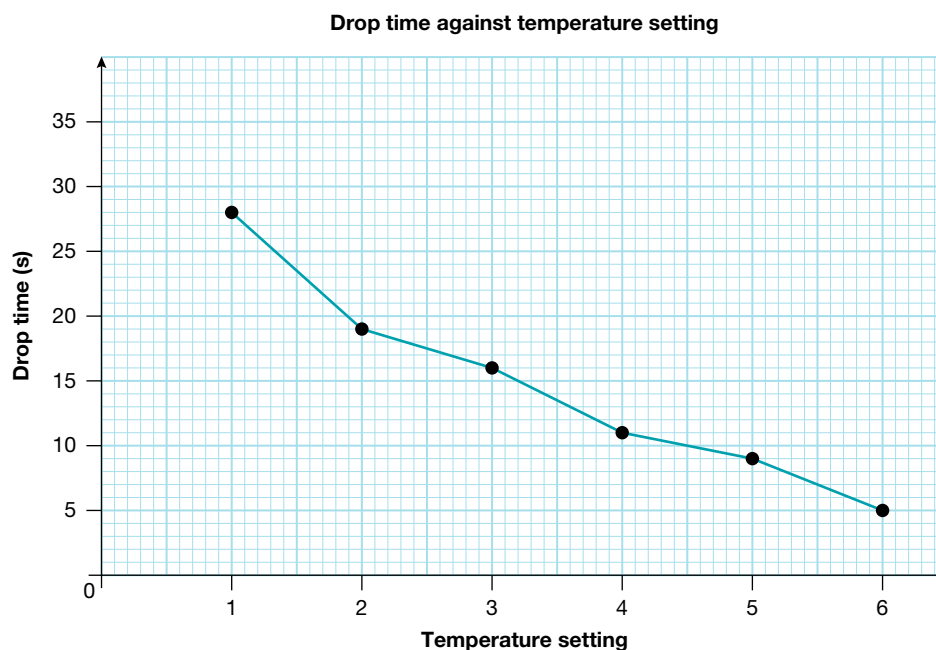
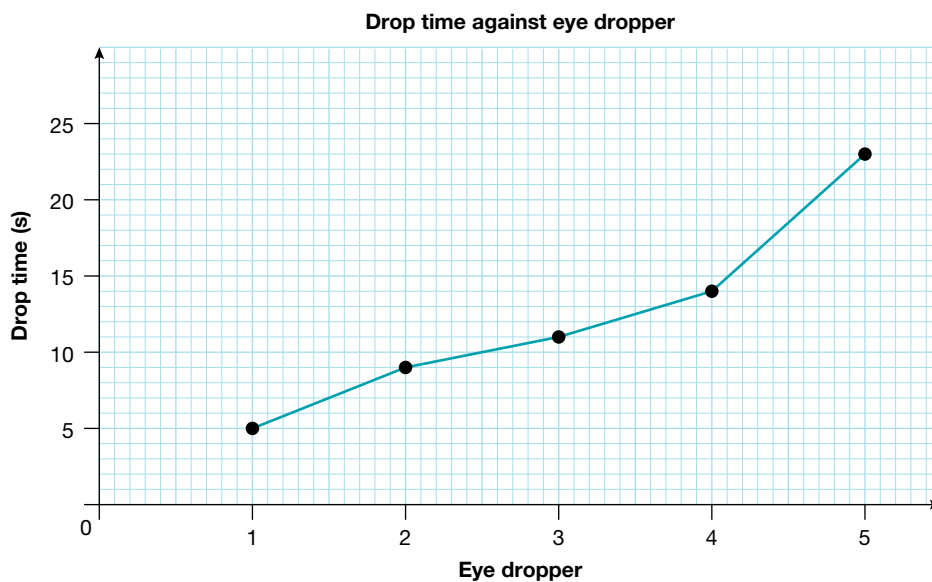
7. What is the difference between an aim and hypothesis?
- The aim of an experiment is a statement, but the hypothesis is a question.
 - The aim includes the dependent and independent variables, but a hypothesis doesn't.
 - The aim explains the expected data, but the hypothesis explains how you will get the data.
 - The aim outlines the purpose of the investigation, but the hypothesis is a testable prediction.

8. Olivia and Vanessa both ran a lap of a 400-metre track. On a very close finish, it was found that Vanessa was 874 milliseconds faster than Olivia.
Which of the following is correct about her result?
- A. It is equal to 874 000 microseconds.
 - B. It contains 2 significant figures.
 - C. It can be written as 87.4×10^{-2} milliseconds.
 - D. It can be shortened to 874 μs .
9. Theories are which of the following?
- A. Concepts that were once accurate, but have now been rejected
 - B. Diagrammatic representations of abstract concepts
 - C. Ideas that are unable to be rejected due to the amount of evidence they have
 - D. Well supported ideas where evidence has been gained from investigations, research and observations
10. In order to identify hazards and outline safety requirements in an experiment, what is it important to complete?
- A. Hazard form
 - B. Repeatable methodology
 - C. Risk assessment
 - D. Project proposal

24.11 Exercise 2: Short answer questions

1. An investigation was conducted to observe the differences in voltage between a series and parallel circuit.
 - a. Identify two pieces of quantitative data that you could record and measure.
 - b. What instruments, if any, would you need to make these observations?
 - c. Identify two pieces of qualitative data that you could observe.
 - d. What instruments, if any, would you need to make these observations?
2. Identify a key difference between the members of the following pairs.
 - a. Independent and dependent variables
 - b. Qualitative and quantitative data
 - c. Control group and experimental group
 - d. Primary and secondary sources of data
 - e. Uncertainty and error
3. In an investigation conducted in class, Ben recorded a voltage of 0.01 430 V.
 - a. How many significant figures does this recorded voltage have?
 - b. Write this voltage in scientific notation.
4. Chris observes that when a droplet of water falls on a hot plate, it fizzes and shoots around the plate for some time. The droplet slowly gets smaller and finally disappears to nothing. Chris decides to investigate how long the droplet lasts and how that might be affected by the temperature of the hot plate and the size of the droplet.

The equipment used was a hot plate, several droppers and a stop watch. The time was measured three times for each eye dropper and for six different temperature settings. The middle reading of the three readings was plotted, as shown on the following graphs.



- a. Write an aim for this investigation.
- b. List the variables in Chris's investigation. For each variable, indicate whether it is an independent or dependent variable, and for each independent variable, indicate whether it is a continuous variable or a discrete variable. Give a reason for each answer.
- c. Write a conclusion for this investigation.
- d. A number of limitations may be identified in this investigation. Discuss these limitations and suggest some suitable improvements. Your discussion could address the following: selection of variables, experimental design, scientific method, data analysis, interpretation of results.
- e. Suggest another independent variable.
- f. Suggest a method for estimating the size of a water droplet.

5. Ammie conducted an experiment to explore how temperature affects the speed of sound travelling through the air. Her data are shown in the following table.

Temperature ($^{\circ}\text{C}$)	Speed (m s^{-1})
0	329
10	335
20	340
30	351
40	358
50	362

- Sketch a graph of the data, including a correct scale and labels.
- Describe the trends and patterns in the graph.
- What conclusions would you make from this investigation?

24.11 Exercise 3: Exam practice questions

Question 1 (8 marks)

Vicki decided to investigate the following experiment she found on YouTube.

An investigator constructed a Newton's Cradle. They connected five balls on separate strings, pulled the last ball back and released, and investigated how long it took to stop. Vicki wanted to take this investigation further and determine how the size of the balls affected the time for movement to stop.

- Identify the dependent variable in this investigation. **1 mark**
- List two variables that need to be controlled in this investigation. **1 mark**
- Describe what measuring equipment should be used in this investigation and identify one factor that could affect the accuracy of this piece of equipment. **2 marks**
- Write a clear experimental method for Vicki to investigate how the size of the balls affects the time for the Newton's Cradle to stop. **4 marks**



Question 2 (6 marks)

An investigation was being conducted to examine how the current in a circuit is affected by the length of a resistor. The devices explored were resistors, light bulbs and diodes.

- Write a suitable aim for this investigation. **1 mark**
- Identify the hypothesis for this investigation. **1 mark**
- Describe one piece of qualitative data and one piece of quantitative data that may be collected in this investigation. **2 marks**
- Explain two factors that may lead to differences in results between different students. **2 marks**

Question 3 (8 marks)

A student conducted an experiment, examining the relationship between current and voltage in a circuit containing a light globe.

The results from this investigation are as follows.

Current (A)	Voltage (V)
0.3	1.5
0.4	3.0
0.5	4.5
0.6	6.5
0.7	8.5

The student also calculated the uncertainty and found that their voltages all had an uncertainty of ± 1.2 V.

- Using graph paper:
 - plot the graph showing the data provided, ensuring that voltage is shown on the vertical axis
 - label the graph and axes as appropriate
 - draw a line of best fit
 - show error bars for voltage.**4 marks**
- Describe any trends in the data. **2 marks**
- Determine the gradient of the line of best fit. Show all working. **2 marks**

Question 4 (8 marks)

Two students, Joe and Paul, conducted an investigation to confirm that momentum is conserved in a system in which two cars collided. They explored the velocity and momentum of two model cars before and after a collision.

Their results are shown in the following table.

	Joe		Paul	
	Before collision	After collision	Before collision	After collision
Mass of car 1 (g)	251.0		270.0	
Mass of car 2 (g)	265.0		271.0	
Velocity of car 1 (cm s^{-1})	0.60	0.14	0.26	0.13
Velocity of car 2 (cm s^{-1})	0	0.14	0	0.13
Momentum of car 1 (g cm s^{-1})	150.6	35.14	70.2	35.1
Momentum of car 2 (g cm s^{-1})	0	37.10	0	35.23

- a. Describe one error that may have occurred which reduced the accuracy of the data for both Paul and Joe, and identify how this error may be avoided? **2 marks**
- b. Calculate the total momentum for 'after the collision' for Paul, using appropriate significant figures based on the data provided. **2 marks**
- c. Describe, with reference to the Law of Conservation of Momentum, why the results obtained by Paul are more accurate than those obtained by Joe. **2 marks**
- d. Momentum is often calculated in kg m s^{-1} . Convert the momentum of car 1 after the collision into kg m s^{-1} . **2 marks**

Question 5 (12 marks)

A student conducted an investigation to determine the rate in which the temperature of water decreases when in different types of insulating material.

The student's report is as follows.

Introduction: In this experiment, three materials are being examined: aluminium foil, paper and wool. This experiment was conducted over three days, with aluminium foil explored on the first day, paper on the second day and wool on the third day. All materials were wrapped around a polystyrene cup in which boiling water was placed.

Aim: To determine how different materials affect the temperature decrease of water

Hypothesis: If aluminium foil, paper and wool are used as insulation material, then aluminium foil will work best.

Method:

1. Collect a polystyrene cup and wrap a piece of aluminium foil around it.
2. Place 100 mL of boiling water in the cup and record the temperature.
3. Record the temperature every five minutes.

Results:

	Aluminium	Paper	Wool
Initial	100 °C	98 °C	95 °C
5 minutes	95 °C	85 °C	80 °C
10 minutes	92 °C	78 °C	71 °C
15 minutes	85 °C	62 °C	60 °C
20 minutes	80 °C	50 °C	48 °C
25 minutes	75 °C	40 °C	39 °C

- a. Describe an issue with the hypothesis written by the student. How would you adjust this to make it testable? **2 marks**
- b. The experiment was conducted over three days. Explain why this may lead to errors in the data obtained. **2 marks**
- c. Students were only able to use a thermometer in which temperature could be measured to the nearest 0.5 °C only. Identify the tolerance of this device and describe the uncertainty expected in the data. **2 marks**
- d. Outline two limitations in the experimental method or data collection process that would affect the conclusions drawn? **2 marks**
- e. Describe the most appropriate graph that the student should use to represent their data. Justify your choice. **2 marks**
- f. Based on the student's results, write a conclusion for this investigation, linking back to the hypothesis. **2 marks**

GLOSSARY

An **α particle** is a relatively slow-moving decay product consisting of two protons and two neutrons. It is equivalent to a helium nucleus and so can be written as ${}^4_2\text{He}$. α particles carry a positive charge.

A **γ ray** is the packet of electromagnetic energy released when a nucleus remains unstable after α or β decay. γ rays travel at the speed of light and carry no charge.

Absolute temperature is the temperature of an object taken in the scale using absolute zero.

Absolute zero is the lowest temperature that is physically possible. At this temperature, particles cease to vibrate. It is equal to 0 K or approximately $-273\text{ }^{\circ}\text{C}$.

Absorption bands are the range of wavelengths in the electromagnetic spectrum that are absorbed by atmospheric gases.

Acceleration is the rate at which an object changes its velocity. Acceleration is a vector quantity.

Accuracy relates to how close an experimental measurement is to a known value.

The **active wire** in a circuit is connected to the 240 V_{RMS} supply at the switchboard.

The **aim** is a statement outlining the purpose of an investigation, linking the dependent and independent variables.

Air resistance is the force applied to an object, opposite to its direction of motion, by the air through which it is moving.

Albedo is the proportion of solar radiation reflected by a surface.

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

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

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

The **atomic number** of an atom is the number of protons in its nucleus.

In a **bar graph** data is represented by a series of bars. They are usually used to when one variable is quantitative and the other is qualitative.

Baryons are hadrons with three quarks.

The **Big Bang** is the name for the dramatic beginning of the universe from an infinitely dense, small point.

The **binding energy** of a nucleus is the energy that is required to split a nucleus into individual nucleons.

A **black body** is an object that absorbs all radiation that falls on it.

Blackbody radiation is the characteristic radiation emitted by a black body when heated.

Categorical data, also known as qualitative data, has labels or names rather than a range of numerical quantities.

The **centre of mass** of an object is the point at which all of its mass can be considered to be.

A **Cepheid variable** is a type of star that has a relationship between its period of variation in luminosity and its maximum luminosity. They are useful for measuring distances to galaxies.

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

A **circuit breaker** carries out the same function as a fuse by breaking the circuit when the current through it exceeds a certain value.

Components are parts. Any vector can be resolved into a number of components. When all the components are added together, the result is the original vector.

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

A **conductor** is a material that contains charge carriers; that is, charged particles can move and travel freely through the material.

A **control group** is not affected by the independent variables and is used as a baseline for comparison.

Controlled variables those that are kept constant across different experimental groups.

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

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

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

The **cosmic microwave background** is radiation that can be found in all regions of empty space. It is left overenergy from the Big Bang.

Cosmic rays are very energetic charged particles that enter our atmosphere. They are mainly protons and originate from beyond the solar system.

Cosmology is the study of how the universe began, has evolved and will end.

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

A **daughter nucleus** is the nucleus remaining after an atom undergoes radioactive decay. It is more stable than the original nucleus.

A **decay chain** also known as a decay series, is the sequence of stages a radioisotope passes through to become more stable. At each stage, a more stable isotope forms. The chain ends when a stable isotope forms.

A **decay curve** is a graph of the number of nuclei remaining in a substance versus the time elapsed. The half-life of a substance can be determined by looking at the time that corresponds to half of the substance remaining.

A **decay equation** is a representation of a decay reaction. It shows the changes occurring in nuclei and lists the products of the decay reaction.

The **dependent variable** is the variable that is influenced by the independent variable. It is the variable that is measured.

A **diode** is a device that allows current to pass through it in one direction only.

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

The **discussion** is a detailed area of a report in which results are discussed, analysed and evaluated, relationships to concepts are made, errors, limitations and uncertainties are assessed and suggestions for future improvements are made.

Displacement is a measure of the change in position of an object. It is a vector quantity.

Distance is a measure of the length of the path taken by an object. It is a scalar quantity.

The **earth wire** is used in power circuits as a safety device; it connects the case of the appliance being used to the earth.

Eccentricity is a measure of how elliptical an object's orbit is.

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

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

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

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

An **electric shock** is a violent disturbance of the nervous system caused by an electrical discharge or current through the body.

Electrocution is death brought about by an electrical shock.

An **electromagnetic radiation** is an electromagnetic wave or radiation that includes visible light, radio waves, gamma rays and X-rays.

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

An **electron** is a negatively charged particle found around the nucleus of an atom.

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

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

An **element** is a substance that consists only of atoms of the same name.

Enhanced greenhouse effect is the greenhouse effect due to human civilization which is greater than that caused by natural forces alone.

An **error** is the difference between a measurement taken and the true value that is expected. Errors lead to a reduction in the accuracy of the investigation.

Ethics are related to acceptable and moral conduct determining what is 'right' and what is 'wrong'.

An **excited nucleus** is one that does not have an ideal arrangement of protons and neutrons in its nucleus. An excited nucleus emits γ radiation to become more stable.

The **experimental group** is the group exposed to the independent variable.

Falsifiable means that there has to be a way to prove the hypothesis wrong.

Feedback is when a system's input is fed by its previous output.

Fibrillation is the disorganised, rapid contraction of separate parts of the heart so that it pumps no blood; death may follow.

First Law of Thermodynamics:

$$\Delta U = Q - W \text{ or } Q = \Delta U + W$$

Where:

Q is the heat energy in joules

W is the work done in joules

ΔU is the change in internal energy in joules.

Fission fragments are the products from a nucleus that undergoes fission. The fission fragments are smaller than the original nucleus.

A **force** is a push or a pull. Forces model interactions between objects. Force is a vector quantity.

The **force due to gravity** is the force applied to an object, due to gravitational attraction.

Frequency is a measure of how many times per second an event happens.

Friction is the force applied to the surface of an object when it is pushed or pulled against the surface of another object.

A **fuse** is a short length of conducting wire or strip of metal that melts when the current through it reaches a certain value, breaking the circuit.

A **galaxy** is a collection of hundreds of billions of stars. Stars are organised into galaxies, with very few stars existing between galaxies.

A **globular cluster** is a very old, densely packed cluster of stars in the shape of a sphere.

Gravitational field strength (g) is the force of gravity on a unit of mass.

Gravitational potential energy is the energy stored in an object as a result of its position relative to another object to which it is attracted by the force of gravity.

Hadrons are composite particles made up of either two or three quarks.

A **half-life** is the time taken for half of a group of unstable nuclei to decay.

Heat is defined as the transfer of energy from one body to another due to a temperature difference.

In a **histogram** data is sorted in intervals and frequency is examined. This is used when both pieces of data are quantitative. All columns are attached in a histogram.

Hubble's constant is the constant of proportionality relating the speed that galaxies are receding from Earth and their distance from Earth.

Hubble's Law states that the speed of recession of galaxies is proportional to their distance from Earth.

A **hypothesis** is a tentative, testable and falsifiable statement for an observed phenomenon and acts as a prediction for the investigation.

An **idealisation** makes modelling a phenomenon or event easier by assuming ideal conditions that don't exactly match the real situation.

The **impulse** of a force is the product of the force and the time interval over which it acts. Impulse is a vector quantity.

The **independent variable** is the variable that is changed or manipulated by an investigator.

Instantaneous speed is the speed at a particular instant of time.

Instantaneous velocity is the velocity at a particular instant of time.

The **internal energy** of an object is the sum of all kinetic energy of the particles that make up that object.

An **ion** is a charged particle.

Isotopes are atoms containing the same number of protons but different numbers of neutrons.

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

A **kilowatt-hour** (kW-h) is the amount of energy transformed by a 1000 W appliance when used for one hour.

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

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

Leptons are the simplest and lightest of the subatomic particles. They are fundamental particles with no internal structure.

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

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

Limitations are factors that have affected the interpretation and/or collection of findings in a practical investigation.

In a **line graph** points of data are joined by a connecting line. These are used when both pieces of data are quantitative (numerical).

The **line of best fit** is a trend line that is added to a scatterplot to best express the data shown. These are straight lines and are not required to pass through all points.

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

The **mass defect** is the difference in the mass of the products and reactants in a nuclear reaction.

Mass number describes the total number of nucleons in an atom.

A **mechanical interaction** is one in which energy is transferred from one object to another by the action of a force.

Mesons are hadrons with two quarks.

A **model** is a representation of ideas, phenomena or scientific processes; can be a physical model, mathematical model or conceptual model.

Momentum is the product of the mass of an object and its velocity. It is a vector quantity.

Negative feedback occurs when the response to the feedback is in the opposite direction to the input.

A quantity that is **negligible** is so small that it can be ignored when modelling a phenomenon or an event.

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

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

The **neutral wire** in a circuit is connected to the neutral link at the switchboard, which is connected to the earth.

A **neutron** is a nucleon with no charge.

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

The **normal force** is a force that acts perpendicularly to a surface as a result of an object applying a force to the surface.

Nuclear fission is the process of splitting a large nucleus to form two smaller, more stable nuclei.

Nuclear fusion is the process of joining together two nuclei to form a larger, more stable nucleus.

The collective name for the particles found in the nucleus of an atom is **nucleon**.

The **nucleus** is the solid centre of an atom. Most of the mass of an atom is concentrated in the nucleus.

Numerical data, also known as quantitative data, involves numbers and can be measured or counted.

Obliquity is a measure of the angle tilt of a planet against its plane of orbit.

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

Outliers are results that are a long way from other results and seen as unusual. They should be accounted for and analysed, but are often not included when calculated averages.

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

Period is the amount of time one cycle or event takes, measured in seconds.

Photosynthesis is a chemical reaction that takes place in the chloroplasts of a plant cell consuming carbon dioxide and releasing oxygen.

Positive feedback occurs when the response to the feedback is in the same direction to the input.

A **positron** is a positively charged particle with the same mass as an electron.

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

A **potentiometer** is a variable voltage divider, with a fixed resistor that can slide up and down.

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

Precession is a change in direction of the rotational axis of a spinning object.

Precision is how close multiple measurements of the same investigation are to each other.

A **primary source** is direct or firsthand evidence about some phenomenon.

A **proton** is a positively charged particle in the nucleus of an atom.

Qualitative data is categorical data that examines the quality of something (e.g. colour, gender) rather than numerical values.

Quantitative data is numerical data that examines the quantity of something (length, time).

Quarks are the fundamental particles that combine to form hadrons.

Radiation is heat transfer without the presence of particles.

A **radioisotope** is an unstable isotope.

Random errors are chance variations in measurements.

Recombination is the event when electrons could remain bound to nuclei to form atoms. Prior to 380 000 years after the Big Bang, electrons had too much energy due to the temperature to remain bound to nuclei.

Red shift is the increase in wavelength that results from a light source moving away from the observer.

Reliability relates to whether another researcher could repeat the investigation by following the same method and obtain similar results.

A **residual current device** operates by making use of the magnetic effects of a current to break a circuit in the event of an electrical fault.

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

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

Results is a section in a report in which all data obtained is recorded. This is usually in the form of tables and graphs.

A **risk assessment** is a document that examines the different hazards in an investigation and suggested safety precautions.

Rotational kinetic energy is the energy due to the rotational motion of objects.

Scalar quantities specify magnitude (size) but not direction.

In a **scatterplot** two quantitative variables are plotted as a series of dots.

Sometimes referred to as scientific process, the **scientific method** is the procedure that must be followed in scientific investigations, which consists of questioning, researching, predicting, observing, experimenting and analysing.

The **scientific research methodology** is the principles of research based on the scientific method.

A **secondary source** comments on or summaries and interpretations of primary data.

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

A **short circuit** can occur when frayed electrical cords or faulty appliances allow the current to flow from one conductor to another with little or no resistance. The current increases rapidly, causing the wires to get hot and potentially cause a fire.

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

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

Speed is the rate at which distance changes over time. Speed is a scalar quantity.

Strain potential energy is the energy stored in an object as a result of a reversible change in shape. It is also known as elastic potential energy.

The **strong nuclear force** is the force that holds nucleons together in a nucleus of an atom. It acts over only very short distances.

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

Synchrotron radiation is the electromagnetic radiation produced when electric charges move in circular motion. It is radiated at a tangent to the curve.

Systematic errors are those that affect the accuracy of a measurement, that cannot be improved by repeating an experiment. They are usually due to equipment or system errors.

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

Testable means that a hypothesis can be easily tested by observations and/or investigations.

A **theory** is a well-supported explanation of a phenomena, based on facts that have been obtained through investigations, research and observations.

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

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

Transducers are devices that convert energy from one form to another form.

Translational kinetic energy is the energy due to the motion of an object from one location to another.

An **uncertainty** limits the precision of equipment, it is a range within which a measurement lies.

Validity relates to the credibility of the research results from experiments or from observations. Validity shows how much results measure what they intending to and how well they show the claims they make.

A **vector** quantity specifies direction as well as magnitude (size).

Velocity is the rate at which displacement changes over time, or the rate of change in position. Velocity is a vector quantity.

Vibrational kinetic energy is the energy due to the vibrational motion of objects.

The **voltage divider** is used to reduce, or divide, a voltage to a value needed for a part of the circuit.

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

The **weak nuclear force** is the force that explains the transformation of neutrons into protons, and vice versa.

Work is done when energy is transferred to or from an object by the action of a force. Work is a scalar quantity.

APPENDIX 1

Periodic table

	Group 1								
Period 1	1 Hydrogen H 1.0	Group 2							
Period 2	3 Lithium Li 6.9	4 Beryllium Be 9.0							
Period 3	11 Sodium Na 23.0	12 Magnesium Mg 24.3							
			Group 3	Group 4	Group 5	Group 6	Group 7	Group 8	Group 9
Period 4	19 Potassium K 39.1	20 Calcium Ca 40.1	21 Scandium Sc 45.0	22 Titanium Ti 47.9	23 Vanadium V 50.9	24 Chromium Cr 52.0	25 Manganese Mn 54.9	26 Iron Fe 55.8	27 Cobalt Co 58.9
Period 5	37 Rubidium Rb 85.5	38 Strontium Sr 87.6	39 Yttrium Y 88.9	40 Zirconium Zr 91.2	41 Niobium Nb 92.9	42 Molybdenum Mo 96.0	43 Technetium Tc (98)	44 Ruthenium Ru 101.1	45 Rhodium Rh 102.9
Period 6	55 Caesium Cs 132.9	56 Barium Ba 137.3	57–71 Lanthanoids	72 Hafnium Hf 178.5	73 Tantalum Ta 180.9	74 Tungsten W 183.8	75 Rhenium Re 186.2	76 Osmium Os 190.2	77 Iridium Ir 192.2
Period 7	87 Francium Fr (223)	88 Radium Ra (226)	89–103 Actinoids	104 Rutherfordium Rf (261)	105 Dubnium Db (262)	106 Seaborgium Sg (266)	107 Bohrium Bh (264)	108 Hassium Hs (267)	109 Meitnerium Mt (268)

1
Hydrogen
H
1.0

2
Helium
He
4.0

← Atomic number

← Name

← Symbol

← Relative atomic mass

1	2	Key
Hydrogen	Helium	← Atomic number
H	He	← Name
1.0	4.0	← Symbol
		← Relative atomic mass

- Alkali metal
- Alkaline earth metal
- Transition metal
- Lanthanoids
- Actinoids
- Unknown chemical properties
- Post-transition metal
- Metalloid
- Reactive non-metal
- Halide
- Noble gas

Lanthanoids

57 Lanthanum La 138.9	58 Cerium Ce 140.1	59 Praseodymium Pr 140.9	60 Neodymium Nd 144.2	61 Promethium Pm (145)	62 Samarium Sm 150.4	63 Europium Eu 152.0

Actinoids

89 Actinium Ac (227)	90 Thorium Th 232.0	91 Protactinium Pa 231.0	92 Uranium U 238.0	93 Neptunium Np (237)	94 Plutonium Pu (244)	95 Americium Am (243)

								Group 18
			Group 13	Group 14	Group 15	Group 16	Group 17	2 Helium He 4.0
			5 Boron B 10.8	6 Carbon C 12.0	7 Nitrogen N 14.0	8 Oxygen O 16.0	9 Fluorine F 19.0	10 Neon Ne 20.2
Group 10	Group 11	Group 12	13 Aluminium Al 27.0	14 Silicon Si 28.1	15 Phosphorus P 31.0	16 Sulfur S 32.1	17 Chlorine Cl 35.5	18 Argon Ar 39.9
28 Nickel Ni 58.7	29 Copper Cu 63.5	30 Zinc Zn 65.4	31 Gallium Ga 69.7	32 Germanium Ge 72.6	33 Arsenic As 74.9	34 Selenium Se 79.0	35 Bromine Br 79.9	36 Krypton Kr 83.8
46 Palladium Pd 106.4	47 Silver Ag 107.9	48 Cadmium Cd 112.4	49 Indium In 114.8	50 Tin Sn 118.7	51 Antimony Sb 121.8	52 Tellurium Te 127.6	53 Iodine I 126.9	54 Xenon Xe 131.3
78 Platinum Pt 195.1	79 Gold Au 197.0	80 Mercury Hg 200.6	81 Thallium Tl 204.4	82 Lead Pb 207.2	83 Bismuth Bi 209.0	84 Polonium Po (210)	85 Astatine At (210)	86 Radon Rn (222)
110 Darmstadtium Ds (271)	111 Roentgenium Rg (272)	112 Copernicium Cn (285)	113 Nihonium Nh (280)	114 Flerovium Fl (289)	115 Moscovium Mc (289)	116 Livermorium Lv (292)	117 Tennessine Ts (294)	118 Oganesson Og (294)

64 Gadolinium Gd 157.3	65 Terbium Tb 158.9	66 Dysprosium Dy 162.5	67 Holmium Ho 164.9	68 Erbium Er 167.3	69 Thulium Tm 168.9	70 Ytterbium Yb 173.1	71 Lutetium Lu 175.0

96 Curium Cm (247)	97 Berkelium Bk (247)	98 Californium Cf (251)	99 Einsteinium Es (252)	100 Fermium Fm (257)	101 Mendelevium Md (258)	102 Nobelium No (259)	103 Lawrencium Lr (262)

APPENDIX 2

Astronomical data

	Mean radius of orbit		Orbital period		Equatorial radius (m)	Mass (kg)
	(AU)	(m)	(years)	(seconds)		
Sun					6.96×10^8	1.99×10^{30}
Mercury	0.387	5.79×10^{10}	0.241	7.60×10^6	2.44×10^6	3.30×10^{23}
Venus	0.723	1.08×10^{11}	0.615	1.94×10^7	6.05×10^6	4.87×10^{24}
Earth	1.00	1.50×10^{11}	1.00	3.16×10^7	6.37×10^6	5.98×10^{24}
Moon	2.57×10^{-3}	3.84×10^8	27.3 days*	2.36×10^6 *	1.74×10^6	7.35×10^{22}
Mars	1.52	2.28×10^{11}	1.88	5.94×10^7	3.39×10^6	6.42×10^{23}
Jupiter	5.20	7.78×10^{11}	11.9	3.74×10^8	6.99×10^7	1.90×10^{27}
Saturn	9.58	1.43×10^{12}	29.5	9.30×10^8	5.82×10^7	5.68×10^{26}
Titan	8.20×10^{-3}	1.22×10^9	15.9 days*	1.37×10^6 *	2.57×10^6	1.35×10^{23}
Uranus	19.2	2.87×10^{12}	84.0	2.65×10^9	2.54×10^7	8.68×10^{25}
Neptune	30.1	4.50×10^{12}	165	5.21×10^9	2.46×10^7	1.02×10^{26}
Pluto	39.48	5.91×10^{12}	248	7.82×10^9	1.15×10^6	1.31×10^{22}

* The orbital period for the Moon and Titan is the time it takes to complete one orbit around Earth and Saturn respectively. All other listed measurements for the orbital period shows the time to orbit the Sun.

The Milky Way	1.50×10^5 light-years across
Alpha Centauri	4.37 light-years away
Andromeda	2.25×10^6 light-years away
Edge of observable universe	4.65×10^{10} light-years away

Source: Data derived from <https://solarsystem.nasa.gov>.

Answers

1 Thermodynamic principles

1.2 Explaining heat: the kinetic theory

1.2 Exercise

1. The particles of the air are in constant motion; this enables the molecules that make up the aroma of the food to travel from the kitchen to the front door.
2. Translational energy describes the displacement of particles from one position to another; other types of kinetic energy involve motion within the particles or potential energy from atomic and subatomic interactions.
3. The particles in the hot tea are moving rapidly and experiencing many collisions with each other and the sides of the cup. The collisions with the cup transfer the kinetic energy to the cup particles and they start to move faster. The temperature of the tea drops and temperature up the cup rises.
4. As the translational kinetic energy of the soup particles is transferred to its surroundings, the particles slow down thus exerting much less pressure on the cling film. The cling film is pushed into the bowl from the external air pressure.
5. Examples may include a meteorite crashing into Earth, a car hitting a wall, rubbing your hands together, or a spoon stirring a cup of tea.
6. A red-hot pin has less internal energy, less kinetic energy and fewer molecules to vibrate than a nail of the same material at the same temperature. There is just less matter to vibrate. So there is less energy to transfer to the water.
7. While you are swimming in the sea, your body maintains an even core temperature of 37.6°C . The sea around Melbourne is a lower temperature than this. The water particles do not vibrate as quickly as your molecules. Your molecules transfer their greater kinetic energy to the water.

1.3 Measuring and converting temperature

Sample problem 1

273 K

Practice problem 1

-270°C

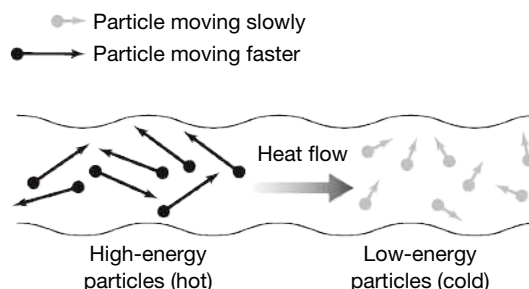
1.3 Exercise

1. The Celsius scale is commonly used because it is based on the properties of water and is easy to reproduce anywhere in the world, unlike Kelvin, where 0 K is hard to reproduce in a school or ordinary laboratory. The freezing of ice and the boiling of water with 100 divisions between is convenient.
2. The Kelvin scale is an absolute by which everything in the universe can be referenced.
3. a. 310 K b. 275 K c. 298 K
d. 288 K e. 373 K
4. The large thermometer is also surrounded by the air in the school laboratory. The liquid in the test tube might be cold, but the thermometer is also measuring the surrounding air, giving a falsely high reading.
5. 194.5 K
6. -17°C and -107°C

1.4 Transferring heat

1.4 Exercise

1. Some of the kinetic energy of the particles in the hot region is transferred to the particles in the cooler region. Thus, the temperature in the cooler region increases.



2. Liquids and gases have particles that are much further apart than those in solids. The particles have to travel further to transfer kinetic energy, so the process of conduction is generally slower in gases and liquids than in solids.
3. Warmer water moves upwards as it is displaced by the more dense, cooler water. Warm water does not generally move down the test tube because it is less dense than cooler water.
4. In solids, the particles are tightly bound together and unable to move to regions of different temperatures.
5. $3.0 \times 10^8\text{ m s}^{-1}$. This is the same value as the speed of light.
6. a. The water on the surface of a still body of water becomes warmer than the water deeper down due to absorbing radiated energy from the Sun and heat transfer from the warm air near the surface. There will be no convection currents as the cooler water is under the warm water.
b. If a wind is blowing, chopping up the surface, the cold water underneath mixes with the warm water on the top. The heat transfer from the surface water reduces its temperature. The wind also evaporates some of the surface water.
7. a. The feeling of warmth is caused by the concrete wall radiating infra-red energy due to its temperature being higher than its surroundings.
b. The walls of the building would have become warm due to heat transfer by radiation from the Sun warming them and by conduction from the warm air surrounding the walls.
8. Aluminium is a good conductor. It will conduct energy from the coffee to the surrounding air. The coffee will cool quickly. The aluminium will also transfer energy to the hand holding the cup, making this an unpleasant, painful experience before it cools below 50°C .
9. Floor ducts used for heating rely on the warm air leaving the duct and rising up through the room. Ceiling ducts need more powerful blower fans to counteract the tendency of the warm air to stay at ceiling level. It needs to be forced down to mix with the cold air to warm it by conduction and convection.

1.5 Thermal equilibrium and the laws of thermodynamics

Sample problem 2

- a. 150 J b. 100 J

Practice problem 2

−5500 J

1.5 Exercise

- When a cool thermometer is placed in a warm liquid, thermal energy transfers from the liquid to the thermometer until the two substances are at the same temperature. In that sense, the thermometer is measuring its own temperature.
- $Q = 500 \text{ J}$, $W = 0$, $\Delta U = 500 \text{ J}$; increase
 - $Q = -250 \text{ J}$, $W = -250 \text{ J}$, $\Delta U = 0$; no change
 - $Q = 0 \text{ J}$, $W = -150 \text{ J}$, $\Delta U = 150 \text{ J}$; increase
 - $Q = 0 \text{ J}$, $W = 5 \text{ J}$, $\Delta U = -5 \text{ J}$; increase
- Temperature decreases.
- The gas in the bottle is under pressure. As the valve is opened, the exiting gas expands as the pressure is now much lower. This expansion in volume lowers the temperature.

	(a)	(b)	(c)
Heat (+ is in)	0	+	+
Work (+ is out)	−	0	+
ΔU	+	+	+

1.6 Specific heat capacity

Sample problem 3

- $2.4 \times 10^3 \text{ kJ}$
- 37°C

Practice problem 3

227.5 kJ

Sample problem 4

- $5.5 \times 10^3 \text{ J}$
- 660.3°C

Practice problem 4

$3.45 \times 10^4 \text{ J}$

1.6 Exercise

- Cooking oil
 - Ethylene glycol
- 400 kJ
 - 1200 kJ
- The human body is mostly water, so you would expect the specific heat capacity to be similar to that of water.
 - Desert sand is dry, containing no moisture. Fertile soil is usually damp, so its specific heat capacity will be higher than that of desert sand because the specific heat capacity of water is large.
 - Steel pan
 - Metals have low heat capacities; water and things containing water have high specific heat capacities.
- $1.2 \times 10^6 \text{ J}$
 - 230 $^\circ\text{C}$
 - The energy is used to increase the potential energy of the particles as they change state from solid to liquid.
 - Liquid
 - 160 kJ kg^{-1}
 - Solid candle wax
 - Over the interval DE, the temperature remains the same. The energy put into the wax does not result in an increase in the kinetic energy of the particles; it just breaks the

attractive bonds between the particles as the substance changes state from liquid to gas.

- 8.2 kg
- A simmering saucepan loses heat by convection and evaporation. By keeping the lid on, the water is prevented from evaporating.
- A reduction in the kinetic energy of the water particles and the temperature of the body of the liquid.

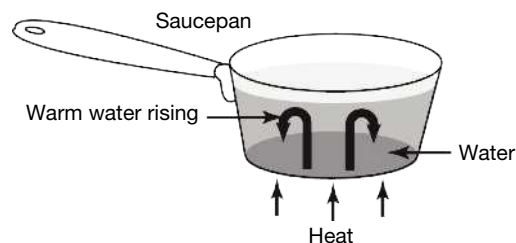
1.7 Review

1.7 Exercise 1: Multiple choice questions

- D
- A
- D
- C
- B
- B
- D
- C
- B
- D

1.7 Exercise 2: Short answer questions

- Testing your own temperature is a subjective exercise.
- Absolute temperature is measured using the Kelvin scale. On the Kelvin scale 28°C is not twice as hot as 14°C (301 K and 287 K , respectively).
- The warm, less dense liquid rises, while the cooler, more dense liquid sinks.



- After a major bushfire, the air is full of small particles of smoke. These particles restrict the transmission of radiant heat energy from the Sun. As a result, the daytime temperatures are reduced.
- Pies cooked in a microwave oven are cooked by the transfer of energy by vibrating particles. When the microwave magnetron is turned off, the water molecules continue to vibrate until their energy is transferred.
- Conventional ovens have heating elements at the bottom to allow air to become warmed, and then rise. This sets up convection currents, which move around the food. Food is then warmed by conduction and convection as well as by radiation from the element. The advantage of having an oven with a fan is that the inside of the oven is kept at an even temperature.
- Work is done by the gas in pushing up the plunger against the force of gravity.
 - Gas B cools, but is insulated and so stays cool. Gas A cools initially but eventually thermal energy from outside comes in to bring the gas back to its original temperature. Therefore, gas A has a greater transfer of heat from its surroundings than gas B.

- c. The work done by the gas lowers the internal energy, then the energy, Q , from the outside increases the internal energy. Overall, $\Delta U = 0$ and $W = -Q$.
- d. The work by the gas lowers the internal energy; there is no transfer of thermal energy: $\Delta U = -W$ and $Q = 0$.
- 8. There is no energy in or out: $Q = 0$, $W = 0$, $\Delta U = 0$.
- 9. Vegetables cook faster if steamed than if boiled because more energy is being transferred to them in the same amount of time.
- 10. a. The water evaporates by gaining energy from the skin to change state. Taking energy from the surface of the skin results in a reduction in the temperature of the skin.
- b. You feel cooler when the wind is blowing because the rate of evaporation of moisture from your skin is increased, lowering your skin temperature.
- c. Sweating in humid weather does not cool the body because the sweat does not evaporate.

1.7 Exercise 3: Exam practice questions

- 1. Adam is wrong, a thermometer measures its own temperature, not the average between itself and the object it is measuring.
Katie is wrong as the thermometer only indirectly measures the temperature of the object.
- 2. a. The heat sink has fins that enable the air to flow around the metal enabling a greater surface area and thus more conduction to the air. The convection of the air will move the hot air away to be replaced with cooler air. The device is painted black, which enables it to act as a black body and effectively radiate heat energy away from the sink.
- b. The heat sink is made of aluminium, which is a conductor of heat. This means it will retain the heat from the device, but will easily conduct the heat to the surface where it can transfer to the air.
- 3. 68.46°C
- 4. 6.1 MJ
- 5. In an oven at 300°C , your hand is bombarded by only a limited number of fast-moving air particles.
Touching the metal tray at the same temperature brings your hand into contact with more fast-moving particles thus causing injury.

2 Thermodynamics and climate science

2.2 Earth's energy systems

Sample problem 1

- a. 44 times
- b. 248°C

Practice problem 1

$1.413 \times 10^{27}\text{ W}$

Sample problem 2

- a. $2.64 \times 10^{-7}\text{ m}$
- b. Ultraviolet

Practice problem 2

6440 K

2.2 Exercise

- 1. a. 0.01 W
- b. 73 W
- c. 3300 K

- 2. a. 12.8 times
- b. 1066°C
- 3. 953 nm
- 4. 5690 K
- 5. $1.00 \times 10^{-5}\text{ m}$
- 6. a. $9.4 \times 10^{-6}\text{ m}$
- b. Infra-red
- 7. a. 16 times
- b. Maximum wavelength is halved.

2.3 The enhanced greenhouse effect

Sample problem 3

$$107\text{ W m}^{-2} + 235\text{ W m}^{-2} = 342\text{ W m}^{-2}$$

$$\text{Energy in} = 342\text{ W m}^{-2} = \text{energy out}$$

So conservation of energy holds for the Earth system.

Practice problem 3

Reflected by surface = 30 W

Absorbed by the atmosphere = 67 W

2.3 Exercise

- 1. Absorbed by ozone, carbon dioxide and other gases of the air before it reaches Earth
- 2. Many species can survive only within specific conditions (such as temperatures and gas concentrations). The greenhouse effect may change these conditions so they are not compatible to life on Earth.
- 3. Transfer of energy from the Earth's surface
- 4. High specific heat capacity, and evaporative and convective properties
- 5. a. i. CO_2 : $1.8\text{--}2.0\text{ }\mu\text{m}$, $2.5\text{--}2.7\text{ }\mu\text{m}$, $4.0\text{--}4.8\text{ }\mu\text{m}$, $9\text{--}19\text{ }\mu\text{m}$
ii. H_2O : $0.8\text{--}0.85\text{ }\mu\text{m}$, $1.0\text{--}1.1\text{ }\mu\text{m}$, $1.2\text{--}1.6\text{ }\mu\text{m}$, $1.75\text{--}2.0\text{ }\mu\text{m}$, $2.2\text{--}3.5\text{ }\mu\text{m}$, $4.5\text{--}9.0\text{ }\mu\text{m}$, $13\text{--}100\text{ }\mu\text{m}$
b. $4.0\text{--}4.5\text{ }\mu\text{m}$ and $9\text{--}13\text{ }\mu\text{m}$
- 6. a. The lighter one
b. Because the lighter one is travelling faster, it may penetrate the water surface further.
- 7. a. In: $67 + 350 + 24 + 78 = 519\text{ W m}^2$
Out: $324 + 165 + 30 = 519\text{ W m}^2$
- 8. a. i. ≈ 0.01
- ii. $0.2\text{--}0.3$
- iii. $0.1\text{--}0.2$
b. i. Positive feedback. Methane is an effective greenhouse gas. This increases the surface temperature.
ii. Negative feedback. The more clouds there are in the sky, the greater the amount of visible light that is reflected back into space.

2.4 Climate models

2.4 Exercise

- 1. a. The volcanic eruptions caused the Earth's surface temperature to drop.
- b. The volcanic dust in the atmosphere prevented some of the Sun's energy reaching the Earth's surface, so the surface cooled.
- 2. a. 1907–15, 1939–47
b. Military conflict may have limited the capacity to collect reliable data from across the globe.
- 3. 1960–70
- 4. a. Atmosphere
b. Air temperature is used because of the large variance in the composition of rocks and bodies of water.
- 5. The temperature increase is erratic due to factors such as sunspot activity, ocean currents and volcanic eruptions.

2.5 Investigating issues related to thermodynamics

2.5 Exercise

Student responses will vary as they are being asked to apply thermodynamic principles to investigate at least one issue related to the environmental impacts of human activity, with reference to the enhanced greenhouse effect.

For this task, students should:

- explain the issue they are exploring
- link the issue to various thermodynamic principles examined in topics 1 and 2 (for example, linking to Wien's law or the Stefan-Boltzmann law)
- describe the environmental impact of the issue
- explain how the issue leads to enhanced greenhouse effect
- use data to show either the issue or the impact of the issue
- analyse the reliability, validity and uncertainty of the data they have obtained.

2.6 Review

2.6 Exercise 1: Multiple choice questions

1. D
2. B
3. A
4. C
5. B
6. D
7. C
8. D
9. A
10. A

2.6 Exercise 2: Short answer questions

1. a. 6.7×10^{25} W
b. As temperature increases the peak wavelength gets shorter. As Antares is colder than the Sun, it will have a longer peak wavelength than the Sun, appearing redder in colour.
2. 285 K
3. a. 7.25×10^3 K b. 4.14×10^3 K
4. The star at 5800 K will appear yellow be in the infra-red region. The hotter star will be brighter by 16 times.
5. The specific heat capacity of water is greater than that of soil. It is, therefore, more resistant to change in temperature.
6. $E_{\text{in}} = 67 + 24 + 78 + 350 = 519 \text{ J}$
 $E_{\text{out}} = 324 + 165 + 30 = 519 \text{ J}$
 $\therefore E_{\text{in}} = E_{\text{out}}$
7. Some wavelengths of the infra-red radiation emitted by the Earth's surface are not absorbed by water molecules but are absorbed by carbon dioxide molecules.
8. The similarity is the amounts; they are the same. The difference is the spread of wavelengths.
9. 1.6 MJ
A major assumption is that the sky is clear. The value seems high but one must remember that:
 - some of the incident energy is reflected by the body and not absorbed

- while radiant energy is being absorbed, the body is also cooling by conduction, convection and/or evaporation.

2.6 Exercise 3: Exam practice questions

1. a. For any point on the graph, the product of the x - and y -values are the same.
b. i. 7000 K ii. 11 000 K
c. i. 193 nm ii. 523 nm
2. a. Sand heats in one-quarter of the time it takes to heat the same mass of water. Sand cools four times faster than the same mass of water.
b. The temperature of dry sand increases rapidly during the day due to its low specific heat capacity. The temperature of the water increases very slowly due to its high specific heat capacity.
In addition, there is a much greater mass of water to heat than sand.
c. The cooling effect of evaporation from bodies of water, the modifying influence of the sea breezes and the coolness of the air above the oceans due to the high specific heat capacity of water all contribute to a lower air temperature above beach sand than desert sand.
3. 22 km^2
4. The temperature of the Earth and the atmosphere as a whole is in balance. The differential warming of the atmosphere and ocean causes heat transfer from the tropics to the poles by convection in the form of winds and ocean currents.
5. a. 0.052°C b. 1000°C

3 Concepts used to model electricity

3.2 Electric circuits

3.2 Exercise

1. Rubbing the plastic pen with wool left the pen with a net negative charge and the wool a net positive charge. Therefore, the negatively charged paper is attracted to the positively charged pen.
2. Your hair has transferred electrons to the balloon, giving it a net negative charge. Your hair now has a net positive charge.
3. Each balloon will have a net negative charge, which means they will repel each other.
4. Your socks rub electrons off the carpet, leaving you with a net negative charge. You get an electric shock when electrons jump from you to the metal doorknob.
5. Rubbing the balloon on her hair caused it to become negatively charged. The electrons in the can moved away from the balloon and caused the can to roll.
6. After leaving the negative terminal, the electron can move freely through the conductor, as other electrons further along the conducting wire move. Like the electrons ahead of it, when the electron reaches the globe, it makes repeated collisions with atoms in the filament of the globe, converting electrical energy into internal energy, increasing the temperature of the filament and causing the globe to glow. After leaving the globe, the electron travels towards the cell's positive terminal.
7. Pushing the button creates a closed circuit, which is needed for electric current to flow and operate the bell.

3.3 Current

Sample problem 1

2.0 A

Practice problem 1

5.0 A

Sample problem 2

9.6×10^2 C

Practice problem 2

3.0 seconds

Sample problem 3

0.450 A

Practice problem 3

0.280 A

Sample problem 4

25 000 seconds

Practice problem 4

16 000 seconds

3.3 Exercise

1. Conventional current is the direction that positive charges would flow if they were free to do so. Electron current is the direction that electrons flow.
2. Direct current: the charge carriers move in only one direction.
Alternating current: the charge carriers periodically change direction.
3. 37.5 C
4. 0.045 A
5. 0.23 mA
6. 4.5×10^{-4} A
7. No. Electrons cannot be destroyed. Current is *not* used up in a light globe.
8. 4.2×10^3 C
9. 0.30 A
10. 8.0×10^{-5} m s⁻¹

3.4 Voltage

Sample problem 5

a. 0.75 J

b. 2.4×10^{-19} J

Practice problem 5

14 800 J

3.4 Exercise

1. 1.5 V
2. 3.3 V
6.0 V
31.5 J
1.02 J

2.7 C

31 C

3. 3.4×10^{-5} J

4. 60 μ C

3.5 Energy and power in an electric circuit

Sample problem 6

240 V

Practice problem 6

12 V

Sample problem 7

1.2 kW

Practice problem 7

0.60 W

Sample problem 8

16 kJ

Practice problem 8

175 mA

Sample problem 9

30 W

Practice problem 9

12 W

3.5 Exercise

1. a. 0.25 A b. 3.3 A c. 1.1 A d. 5.00 A
2. a. Each coulomb of charge passing through the heater will transform 240 J of energy.
b. 6.0×10^3 J
3. a. 4.3×10^4 J b. 24 W
4. 90 s
5. 2.4 kW
6. 40 s
7. 1.5 V

3.6 Resistance

Sample problem 10

a. $27 \times 10^3 \Omega \pm 1350 \Omega$

b. $1.0 \times 10^3 \Omega \pm 100 \Omega$

Practice problem 10

- a. $39 \Omega \pm 2 \Omega$
- b. $56\,000 \Omega \pm 5600 \Omega$
- c. $750 \text{ k}\Omega \pm 37.5 \text{ k}\Omega$

Sample problem 11

20 Ω

Practice problem 11

40 Ω

Sample problem 12

2.0 W

Practice problem 12

1.2 kW

Sample problem 13

a. 3.3 A

b. $72\ \Omega$

Practice problem 13

a. 2.5 A

b. $96\ \Omega$

3.6 Exercise

1. 1.08 kJ

2. 32 V

48 V

2.0 A

3.0 mA

1.5 Ω

33 Ω

3. a. $61 \times 10^3\ \Omega \pm 3050\ \Omega$

b. $49 \times 10^5\ \Omega \pm 490\ \text{k}\Omega$

c. $1200\ \Omega \pm 60\ \Omega$

4. a. Non-ohmic. The graph of current versus voltage is non-linear.

b. 0

c. ∞

d. 32.5 Ω

5. 0.45 W

6. a. 960 Ω

b. 5.7 Ω

c. 3.6 Ω

7. 1.2 kW

8. a. i. 5 k Ω

ii. 1 k Ω

b. i. 24 $^{\circ}\text{C}$

ii. 52 $^{\circ}\text{C}$

9. a. 5000 Ω

b. 200 $^{\circ}\text{C}$

3.7 Review

3.7 Exercise 1: Multiple choice questions

1. A

2. C

3. D

4. B

5. B

6. C

7. D

8. D

9. C

10. D

3.7 Exercise 2: Short answer questions

1. $2 \times 10^8\ \text{V}$

2. a. i. $4.8 \times 10^{-19}\ \text{J}$

ii. 3.0 J

b. $2.0 \times 10^{-3}\ \text{W}$

3. a. 11 A

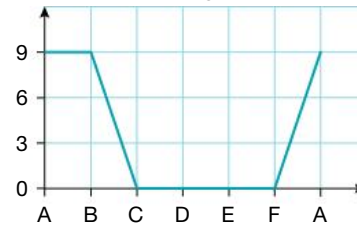
b. 405 kJ

4. a. 110 V

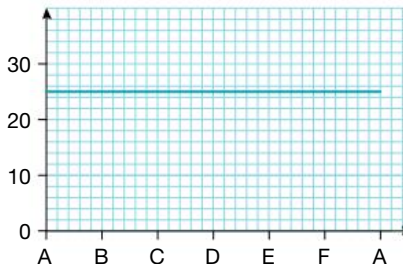
b. The current would also increase.

5. a. 0.2 W

b. Voltage (V)



c. Current (mA)



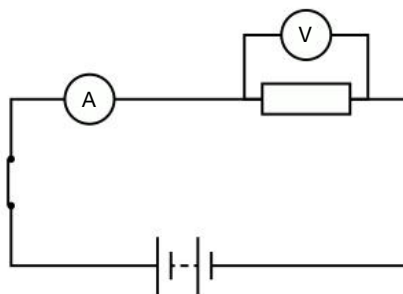
d. 360 Ω

6. a. 0.25 A

b. 12 Ω

c. 0.75 W

7. a.



b. 5.0 A

8. a. 15 Ω

b. For voltages up to 4.5 V, there is a constant relationship between the voltage across the globe and the current flowing through it. In this range, the globe exhibits ohmic characteristics. However, for higher voltages the relationship is not constant and therefore non-ohmic.

9. a. A device that has a varying resistance.

b. 20 mA

c. 2.5 Ω

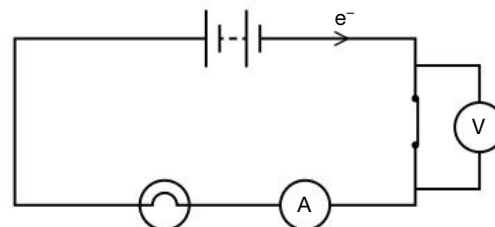
10. a. 73 Ω

b. 32 kJ

3.7 Exercise 3: Exam practice questions

1. Disagree. When a light switch is turned on the light comes on almost instantaneously. Similarly, Luke should feel the pull on the rope almost immediately. Electrons carry the electric charge in a circuit, they move more slowly than the energy that is transferred to the loads in the circuit.

2. a, b and e. See the following figure.



a. From the negative terminal to the positive terminal

b. Ammeter could be placed anywhere in the circuit.

c. 3.0 A

d. 0

7. a. $I_a = 1.5 \text{ A}$
 $V_1 = 6 \text{ V}$
 $V_2 = 6 \text{ V}$
 $I_1 = 1.0 \text{ A}$
 $I_2 = 0.5 \text{ A}$
 $R_2 = 12 \Omega$
8. a. $R_1 = 6.0 \text{ A}$
 $R_2 = 2.0 \text{ A}$
 $R_3 = 4.0 \text{ A}$
b. 12 A
c. 3.0Ω
9. a. G_1, G_2, G_3
b. G_1, G_3
c. G_1
10. a. 3.0 V
b. 6.0 V

4.4 Non-ohmic devices in series and parallel

Sample problem 11

- a. 10 V b. 3 A

Practice problem 11

- a. 6 V b. 5 mA

Sample problem 12

750Ω

Practice problem 12

$2.5 \text{ k}\Omega$

Sample problem 13

The resistance must be increased.

Practice problem 13

The voltage sensitive switch should be connected to the fixed resistor so that it turns on the cooling system as the temperature increases.

A $2.5 \text{ k}\Omega$ fixed resistor

4.4 Exercise

1. a. 6 mA b. 140 V c. $8.8 \text{ k}\Omega$
2. a. 30 V b. 6.0 mA c. 100 V d. 130 V
3. a. 100 V b. 100 V c. 6 mA d. 26 mA

4.5 Power in circuits

Sample problem 14

8.91 A

Practice problem 14

5.04 A

4.5 Exercise

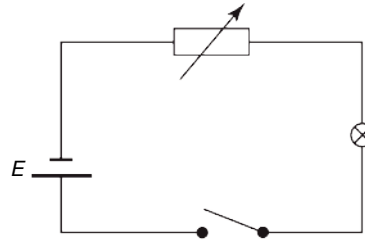
1. a. 0.20 A
b. $25 \Omega = 5.0 \text{ V}$
 $15 \Omega = 3.0 \text{ V}$
 $10 \Omega = 2.0 \text{ V}$

- c. $25 \Omega = 1.0 \text{ W}$
 $15 \Omega = 0.6 \text{ W}$
 $10 \Omega = 0.4 \text{ W}$

d. 2.0 W

2. a. 2.1 A
b. 10 V
c. $25 \Omega = 4.0 \text{ W}$
 $15 \Omega = 6.7 \text{ W}$
 $10 \Omega = 10 \text{ W}$
d. 21.7 W

3.



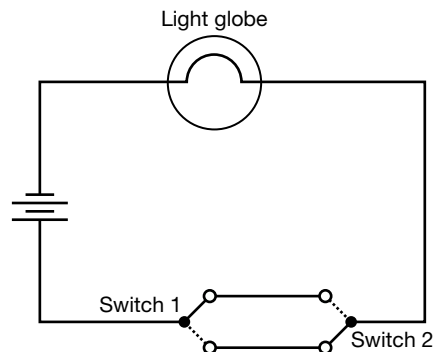
4.6 Review

4.6 Exercise 1: Multiple choice questions

1. C
2. A
3. C
4. B
5. A
6. D
7. A
8. C
9. C
10. C

4.6 Exercise 2: Short answer questions

1. a. 2 A b. 60 V c. 10Ω d. 40Ω e. 80 V
2. a. 12 V b. 12 V c. 12 V d. 0.30 A e. 40Ω
3. 3 A
4. a. 4.4Ω
b. No. The 24 W lamp will be brighter. The larger current flowing through the 24 W lamp means that more energy is being dissipated per second.
5. a. 0.30 A b. 7.2 W c. 1.2 A d. 29 W
6.



7. a. 4.0 V b. 3.0 V
8. a. $3.3 \text{ k}\Omega$ b. $2.5 \text{ k}\Omega$
9. a. The lamp will dim.

- b. The power provided to the circuit P is given by $P = \frac{V^2}{R}$.
 V_{source} is constant, so as the resistance of the series circuit increases the power in the circuit will decrease.

- c. No effect on the brightness of the lamp.
 - d. Power consumed in the circuit will increase.
10. a. $20\ \Omega$ b. $5\ \Omega$

4.6 Exercise 3: Exam practice questions

1. a. 10 mA
b. 15 V
c. 25 mA through the first person
17 mA through the second person
d. 25 V
2. Substituting in $V = IR$, where $V = 0$, R must be equal to 0.
3. a. $625\ \Omega$ b. 0.01 W c. Increase
4. a. $400\ \Omega$ b. $R_1 = 5000\ \Omega$
5. a. $1.5\ \text{k}\Omega$ b. 0.7 V

5 Using electricity and electrical safety

5.2 Household electricity and usage

Sample problem 1

- a. 6.09 A b. 37.8 Ω

Practice problem 1

- a. 65 mA b. 3.5 $\text{k}\Omega$

Sample problem 2

3.6 MJ

Practice problem 2

28.8 MJ

Sample problem 3

- a. 85 W b. 12 kW-h c. \$1.97

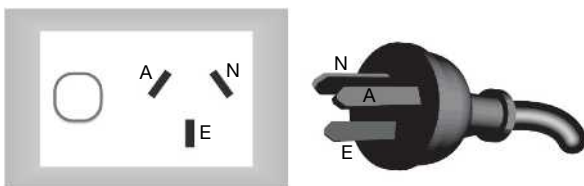
Practice problem 3

- a. 10 mA b. 1.45 MJ c. \$48.38

5.2 Exercise

1.
 - It is an alternating current.
 - The voltage varies between +325 V and -325 V.
 - The voltage oscillates 50 times per second.
 - The voltage provides heating effects equivalent to a DC voltage of 230 V.
2. Excessive current can cause wires to melt or materials surrounding the wires to catch fire.
3. Active: brown
Neutral: blue
Earth: green-and-yellow striped

4.



5. The neutral wire is used to provide an insulated path for the electricity to return to the generator. The earth wire connects the metal case of the appliance to earth so that, if a live active

wire accidentally contacts the outer case, a low resistance path is provided for the electricity to return to earth.

6. The earth wire is used in household lighting circuits when the light fittings have a metal case.
7. \$ 411.02

8. a.

Product	Energy kW-h
Laptop computer	127.0
Modem	29.8
Cordless phone equipment	32.4
DVD player	21.0
Television	54.3

- b. 381.9 kg CO_2

5.3 Electrical safety

Sample problem 4

- a. Total current in the circuit:
 $4.35 + 1.36 + 5.22 + 2.61 + 0.26 = 13.8\ \text{A}$
The fuse will not melt.
- b. The 2400 W heater will draw an additional 10.4 A, so the total current in the circuit will be 24.2 A. This is much greater than 15 A and the fuse will blow.

Practice problem 4

- a. 760 mA b. 1.7 A c. 3.4 A

5.3 Exercise

1. An electric shock is a violent disturbance of the nervous system caused by an electrical discharge or current through the body. Electrocution is death resulting from an electric shock.
2. Breaks or cuts in the skin; water, oil and other fluids reduce the resistance of human skin.
3. The size of the current will influence the size and type of muscle contraction.
4. Fibrillation is the disorganised rapid contraction of separate parts of the heart so that it pumps no blood.
5. Your muscles would contract and you could grip onto the victim and not be able to let go.
6. The longer the time of exposure, the more severe the shock.
7. Double insulation is a way to protect the user of hand-held appliances. There are two separate layers of insulation between the functional parts of the appliance and the user.
8. Voltage doesn't flow; current does. The paper should have reported that there was a voltage drop across his body of 50 000 V. The human body is not resistant to current flow at large voltage. However, it is the size of the current that determines the amount of injury; it is not the voltage that kills.

5.4 Review

5.4 Exercise 1: Multiple choice questions

1. C
2. B
3. A

4. B
5. C
6. B
7. D
8. C
9. B
10. B

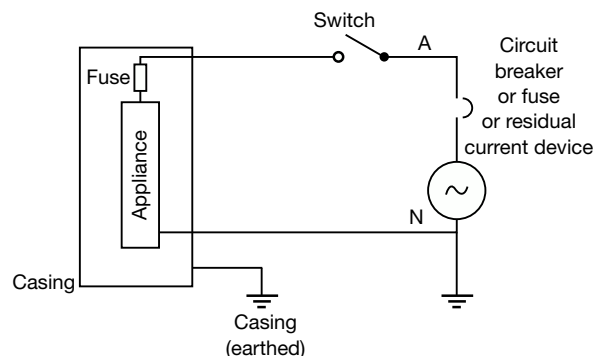
5.4 Exercise 2: Short answer questions

1. a. 3942 kW-h b. \$1104.00
2. a. Connect the speakers in parallel because each speaker can be independently controlled and the failure of one does not result in a total loss of sound – the second speaker can still function.
b. $P = 4.6 \text{ kW}$
c. \$8.83
d. Just larger than 10 A
3. a. 4.35 A b. 52.9Ω c. \$0.85
4. a. The metal casing on the appliance is connected to the earth wire and not the live wiring that provides energy to the appliance. This keeps the voltage of the casing at zero.
b. A shock could occur if the insulation between the casing and the functional parts of the appliance broke down.
5. a. The difference between electrocution and an electric shock is that electrocution is fatal.
b. An electric shock is more likely to be fatal if there is a large amount of current flowing through the body, the pathway of the current is through the trunk of the body or there is an extended time of exposure to the current.
6. Both fuses and circuit breakers provide overload protection in circuits. A fuse comprises a metal wire that melts when its current limit is exceeded. Fuses can be used in a variety of places including plugs, appliances and household circuits. They are also readily used in DC circuits. After the source of an electrical problem is resolved a melted fuse must be replaced.
Circuit breakers comprise resettable switches activated by either using the heat generated by an excessive current or by the electromagnetic effect in a circuit to activate a switch. They are initially more expensive to install but are readily reset. They also allow the isolation of circuits within a system of circuits as found in households.
7. a. 2.63 A b. 13.07 A
8. As the magnitude of the current passing through the body increases it takes less time to cause fibrillation. It is therefore important to safely remove a person in shock from the source.
9. Dry skin has a higher resistance than wet hands. Wet hands provide an easier pathway to earth and therefore attract a larger current that can cause damage when travelling through the body.
10. Whereas a circuit breaker provides overload protection in a circuit by detecting increasing current, a residual current device effectively detects a leakage of current as might happen when there is a short circuit. Residual current devices can be activated quickly and at low currents, providing good safety protection as long as the leakage of current is to earth. However, a residual current device is ineffective when a person acts as a conductor between the active and neutral wires of a circuit.

5.4 Exercise 3: Exam practice questions

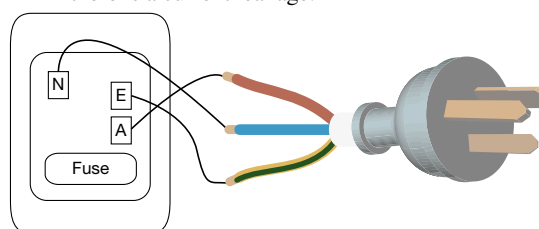
1. Factors that improve the safety of the person include not having wet hands or standing on a wet floor. It would be better if they were wearing shoes with an insulating sole and were not touching an easier path to earth such as a kitchen tap. Letting go of the appliance is also important because a longer contact causes more harm.

2. a.



- b. i. The earth wire in main circuit provides a low resistance conducting path for current should there be a short circuit.
ii. Insulation between the appliance and the case insulates the metal case from the live circuit.
iii. Separately earthing the metal case provides a low resistance conducting path for current to flow to earth if the insulation 'barrier' breaks down.
iv. A fuse, circuit breaker or residual current device on the active wire between the power supply and the appliance breaks the circuit if the current to the device is excessive, or in the case of a residual current device, there is a current leakage.

3.



4. a. $E = 8.76 \times P \text{ kW-h}$

Product	Power (W)	Power kW-h per year
Laptop computer	14.5	127.0
Microwave	4.2	36.8
Laser printer	8.5	74.5
Set top box	11.2	98.1
Television	6.2	54.3

- b. 564.2 kg CO₂
c. \$195.35
5. a. $I = 0.38 \text{ mA}$
The person will experience a shock, but provided the person does not continue to hold the appliance it should not be dangerous.

- b. Fibrillation could occur at 50 mA.
 $V = 30\text{ kV}$
- c. 76.7 mA
With this current, there is a risk that the person's muscles will contract and they will be unable to let go of the appliance. Fibrillation is likely and the person must be safely removed from the source of electricity.

6 Origins of atoms

6.2 Early developments of the Big Bang Theory

Sample problem 1

Leavitt discovered that a type of star called a Cepheid variable varied in luminosity in such a way that the more luminous the star, the longer its period of variation. This provided a method to determine the luminosity of the star and therefore its distance could be determined by the difference between its luminosity and its brightness when viewed from Earth.

Hubble used this discovery to show that clouds of stars were well beyond the limits of the Milky Way galaxy and therefore separate galaxies in their own right. He also found that the more distant the galaxies, the faster they were receding from us.

Practice problem 1

It is not possible to determine the luminosity from only its brightness because the brightness of the star diminishes with distance.

Sample problem 2

When Hubble measured the red shift of distant galaxies he noticed that it increased the further the galaxy was from us. This was interpreted by physicists as meaning that the universe must be expanding. Prior to this discovery they thought it was static.

Practice problem 2

As the light from distant galaxies travels through space to reach us, the space it travels through expands, expanding the wavelength of the light.

Sample problem 3

Gravity is a force that weakens with distance. Gravity can cause galaxies near to each other to move toward each other but for galaxies separated across a greater distance, the gravity becomes too weak and the expansion of space overwhelms its effect.

Practice problem 3

Hubble noticed that all of the galaxies apart from those local to the Milky Way were moving away from it.

6.2 Exercise

1. A galaxy is a gathering of many billions of stars held together by gravity.
2. a. The longer the period of variation in luminosity, the greater the maximum luminosity of the star.
 - b. Luminosity and distance
 - c. Stars, like all lights, get dimmer as they get further away. By using stars of relatively uniform distance from Earth

she knew that the difference in brightness of the stars was due to their different luminosities, not just their distances.

3. The light coming from all distant galaxies was red shifted.
4. The first spectrum is from the most distant galaxy as it is the most red shifted.
5. The General Theory of Relativity
6. Consider any dot on the rubber band. It does not matter which you choose; as the rubber band is extended, all of the other dots move away from it. The view of the expanding universe occurs from all points of observation.
7. Scientists had long believed that the universe had existed as it was forever.
8. Einstein thought the universe was static, neither expanding nor contracting. He had no explanation for why it did not collapse on itself due to gravity so added an unexplained cosmological constant to make the mathematics work for a static universe.
9. Although the space between the Milky Way and Andromeda galaxies is expanding, the gravitational attraction is strong enough that the galaxies are being pulled closer together. This causes the light to be blue shifted instead of red shifted.

6.3 Further developments of the Big Bang Theory

Sample problem 4

The universe is 1.8×10^9 years old. This is 2 billion years to one significant figure, so consistent with Hubble's estimate.

Practice problem 4

The gradient of the line is too steep.

6.3 Exercise

1. The Big Bang Theory describes the universe as beginning very small and hot. As it expanded that heat energy would have spread throughout the universe, cooling as the universe expanded. That is consistent with what we can observe today as the cosmic microwave background.
2. The observation of an expanding universe led astronomers and physicists to imagine what that meant for the history of the universe. They could imagine that space must have been much smaller and if traced back far enough, took up no space at all.
3. Time and space began with the universe, there was no time and space before.
4. According to the Big Bang Theory, space has expanded throughout the universe's existence.
5. The expansion of the universe has resulted in the light waves travelling through it from the early intense heat to be stretched as the space they passed through stretched. These waves have travelled for billions of years so the wavelengths are much longer, corresponding to much lower temperatures. They correspond to a temperature of only 2.7 K.
6. The longer the light from distant galaxies has travelled through the expanding universe, the more it is stretched and therefore red shifted. Light from closer galaxies has travelled shorter distances so has been stretched less.
7. In the past, the universe had a smaller volume. The galaxies were therefore packed into a smaller universe resulting in a higher density of galaxies.

6.4 Measurements of the universe

Sample problem 5

At aphelion: 250 500 000 000 m
At perihelion: 207 000 000 000 m

Practice problem 5

- a. 108 000 000 000 m
- b. 0.00257 AU

Sample problem 6

198 times further away

Practice problem 6

16 times further away

Sample problem 7

The light has travelled for 2.5 million years to reach us.

Practice problem 7

It has taken the light 643 years to reach Earth.

Sample problem 8

1.45×10^9

Practice problem 8

2.73×10^7

Sample problem 9

1 989 000 000 000 000 000 000 000 000 kg

Practice problem 9

4 540 000 000 years

Sample problem 10

1.5×10^7 K

Practice problem 10

5.683×10^{26} kg

6.4 Exercise

1. 4 515 000 000 000 m
2. 513 AU
3. The solar system is about half way between the centre and edge of the Milky Way.
4. 8.6 years
5. 4.495×10^{12} m
6. 13 390 000 000 years
7. 10^{10} K
8. 6.05×10^{24} kg
9. 3.2×10^2

6.5 The formation of the first atoms

Sample problem 11

Photons of energy were able to propagate through space after this point and it is the greatly red shifted photons that are observed as the cosmic microwave background.

Practice problem 11

Prior to recombination, the universe was filled with charged particles that scattered the light, making the universe opaque.

Sample problem 12

The quark era was when particles such as quarks, electrons and neutrinos began to appear in large numbers and matter began to dominate over antimatter.

Prior to the quark era particles were annihilated by their antiparticles as soon as they formed. Quarks existed as individual particles.

Practice problem 12

In the electroweak era, the strong nuclear force first separated from the other forces so that there were three separate forces in the universe: gravity, the strong nuclear force and the electroweak force (which is the combination of the electromagnetic force and weak nuclear force).

Sample problem 13

10

Practice problem 13

2.4×10^{31}

6.5 Exercise

1. Quarks, electrons and neutrinos started to dominate in the quark era but would have been rare in the Electroweak era. Matter began to be dominant over antimatter in the quark era, in the electroweak era matter tended to annihilate with antimatter as soon as it was created.
2. Quarks formed three quark particles (hadrons) such as protons and neutrons.
3. In the transition from the Planck era to the grand unified era. This was about 10^{-43} seconds after the beginning of the universe.
4. Protons and neutrons began to appear 10^{-6} seconds after the beginning of the universe.
5. Particles of matter were created with their own antiparticles. They tended to annihilate each other when they came in contact.
6. The flatness of the universe and the uniformity of the cosmic microwave background.
7. The universe was too hot for protons and neutrons to exist.
8. Once protons and neutrons were available for fusion, protons outnumbered neutrons 7 to 1. Two protons fused with two neutrons to make helium-4 nuclei and this occurred until the neutron supply was exhausted. To make one helium-4 nucleus would require 2 protons and 2 neutrons but given the ratio of 7:1, there would be 12 excess protons. In other words, the ratio of H to He was 12:1 in terms of number of nuclei. Each helium-4 has four times the mass of hydrogen-1 so by mass the ratio was 4:12 or 1:3. This is equivalent to 25% helium-4 and 75% hydrogen.
9. Above 3000 K, electrons have too much energy to remain bound to the nucleus. The universe needed to expand and cool to around 3000 K before the electrons would bond to the nuclei forming the first atoms, which happened 380 000 years after the beginning of the universe.

6.6 Review

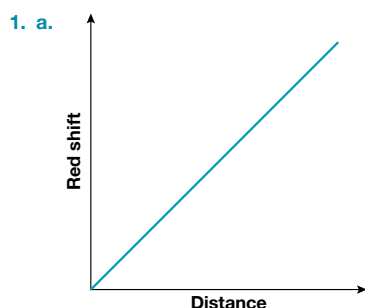
6.6 Exercise 1: Multiple choice questions

1. A
2. C
3. B
4. A
5. D
6. D
7. A
8. D
9. B
10. D

6.6 Exercise 2: Short answer questions

1. Hubble discovered that the more distant galaxies had a greater red shift, suggesting they were receding from us at a greater rate than the galaxies closer to us.
2. Andromeda and the Milky Way are close enough that the force of gravity between them has a greater impact than the expansion of the universe.
3. Normal explosions involve matter being thrown outwards so that in a very short time it moves through space. The Big Bang created matter as space expanded and time was created. The matter is not moving through space but is being carried away from other matter by an expanding universe. The Big Bang did not happen at a point in time but was the beginning of time.
4. The red shift of the galaxies, the ratio of hydrogen and helium in the universe, the density of galaxies and the cosmic microwave background
5. Prior to the discovery of the CMB, the theory was challenged by other theories. However, the theory predicted the existence of the CMB and when it was discovered no one had any other explanation for it.
6. It is easier to read, compare and perform calculations with.
7. $10^{-36} = 0.000\,000\,000\,000\,000\,000\,000\,000\,000\,001\,\text{s}$
 $10^{-32} = 0.000\,000\,000\,000\,000\,000\,000\,000\,000\,01\,\text{s}$
8. Heavier elements required fusion of helium nuclei, which required more time than was available as the universe was rapidly expanding.
9. Particle–antiparticle annihilation, inflation, nuclear fusion, the formation of atoms, ignition of the first stars
10. Stephen Hawking likened trying to understand time before the Big Bang to trying to go south of the South Pole. It is not possible to go past 90° latitude South. The geometry of the Earth results in us heading north again. A similar geometry could explain the beginning of the universe.

6.6 Exercise 3: Exam practice questions



- b. Hubble measured the red shift of the spectral lines of light coming from each galaxy in order to determine the speed of recession of galaxies.
- c. Cepheid variables
2. a. The source of the cosmic microwave background radiation is the Big Bang itself.
The event involved vast amounts of energy, some that should remain. This energy was able to travel freely through the universe after recombination when electrons bonded with nuclei to form the first atoms.
- b. $5.7 \times 10^{-4}\,\text{K}$
3. Particle accelerators
4. Energy needs to be increased.
5. Gravity separated first, then the strong nuclear force, then electromagnetism separated from the weak nuclear force.
6. a. The vast majority of protons and neutrons formed hydrogen-1 and helium-4.
Small amounts of lithium and beryllium were also formed.
- b. There is no stable nucleus with a mass number of 5.
This meant that simply adding more protons or neutrons was not enough to go beyond helium, larger nuclei needed to fuse. Fusing helium-4 nuclei takes more time than was available as the universe rapidly expanded to the point where the energy and density were insufficient for this fusion to occur.

7 Particles in the nucleus

7.2 The discovery of subatomic particles

Sample problem 1

Six:

- electron
- muon
- tau
- electron neutrino
- muon neutrino
- tau neutrino.

Practice problem 1

Electrons and the neutrinos are stable — they never decay. Muons and taus usually decay within tiny fractions of a second.

Sample problem 2

Mesons

Practice problem 2

Protons and neutrons

Sample problem 3

In a similar way to atoms and nuclei, a spectrum of allowable energies has been detected for protons and neutrons. Atoms produce electromagnetic spectra containing particular allowable energies that are interpreted as energy released by electrons as they change state in the atom. If the atom had no structure, but was a fundamental particle, this would be impossible as there would be no electrons or energy states. Similarly with protons and neutrons, the existence of possible energy states within these particles reveals that they have internal structure. They are not fundamental.

Practice problem 3

One

Sample problem 4

A proton has a charge of $+1$ so an antiproton has a charge of -1 .

An up quark has a charge of $+\frac{2}{3}$ and a down quark has a charge of $-\frac{1}{3}$. Therefore, an up antiquark has a charge of $-\frac{2}{3}$ and a down antiquark has a charge of $+\frac{1}{3}$.

An antiproton is made of two up antiquarks and one down antiquark. These have a total charge of $-\frac{2}{3} + -\frac{2}{3} + \frac{1}{3} = -1$. The sum of the antiquark charges is the same as the antiproton charge as expected.

Practice problem 4

The electron and the antiproton have the same charge: -1 . The electron is a lepton and the antiproton is a baryon (hadron) because it is made of three quarks. The electron is a fundamental particle but the antiproton is a composite particle. The proton has a mass of nearly 2000 times that of an electron so the antiproton is nearly 2000 times as heavy as an electron because antiparticles have the same mass as their particle.

Sample problem 5

The strong nuclear force acts on quarks and particles made from quarks — hadrons, including protons and neutrons. The weak nuclear force acts on leptons such as electrons and neutrinos, as well as quarks. While the strong force holds quarks to each other, the weak force changes properties of the particle. (It can change an up quark to a down and change the momentum of a neutrino.) The strong force acts over a distance of the order of a proton diameter. The weak force acts over a distance only about one-thousandth of this distance.

Practice problem 5

Weak nuclear force.

Sample problem 6

The neutron, neutrino, positron and Higgs boson were all predicted by scientific theory prior to their detection.

Practice problem 6

The Big Bang Theory predicted the existence of the cosmic microwave background, which was subsequently detected by Penzias and Wilson.

7.2 Exercise

1. The Large Hadron Collider was built to explore particle physics and test predictions of the Standard Model, including the existence of the Higgs boson.
2. A hadron is the name given to any particle made of quarks. There are two groups of particles made of quarks — mesons and baryons. Mesons are made of a quark–antiquark pair. Baryons are made of three quarks.

3. There are six quarks in the Standard Model. They are the up, down, strange, charm, top and bottom.
4. The Standard Model predicts six leptons: electron, muon, tau, electron neutrino, muon neutrino and tau neutrino.
5. The atomic nucleus is held together by the strong nuclear force, which is an attractive force between quarks. An electron is a lepton. Leptons are not acted on by the strong force so the only force holding electrons to a nucleus is the electromagnetic force.
6. Protons have charge, size and considerable mass. Most of the mass of Earth is made from protons and the similar sized neutrons. Protons cannot pass through the Earth because they interact both electromagnetically with other protons and strongly with other protons and neutrons if they become particularly close. Electrons have much less mass and size than protons but have the same sized charge. The electromagnetic force ensures that they cannot travel far without being scattered or absorbed into other atoms. Neutrinos, however, do not interact via either the strong or the electromagnetic forces. They are leptons without charge. Therefore, their interactions with other matter is very weak, through the weak force. These interactions are so weak and rare that most pass straight through the Earth unaffected.
7. A neutron has no charge. The antineutron must have the same mass as the neutron and also have no charge. The neutron is made from two down and one up quarks. The antineutron must therefore be made from two up antiquarks and one down antiquark.
8. They would annihilate each other, producing photons of energy.
9. The matter that appeared in the early universe was produced in pairs of particles and antiparticles. These quickly annihilate each other. After those first moments, for a reason that is not well understood, matter dominated over antimatter. Therefore, there was nothing to annihilate the protons, neutrons and electrons. The protons and electrons are stable particles. The neutrons have survived due to being bound in helium and later other nuclei.
10. The quark era was when energy conditions were such that quarks formed the bulk of the mass of the Universe. At this stage the universe was so hot and dense that the mass of quarks could not yet separate into individual hadrons. Later, when the universe had cooled a little further, the quarks separated into a new level of structure — hadrons (including protons and neutrons).
11. Zero

7.3 Nuclear radiation

Sample problem 7

Thorium-234

Practice problem 7

Iron-56

Sample problem 8

There is an attractive force called the strong nuclear force that acts between protons and neutrons. The strong nuclear force can only hold a nucleus together when it is stronger than the electromagnetic force pushing the protons apart.

The force holding protons and neutrons together to form nuclei must be an attractive force that works between neutrons and protons and is stronger than the electromagnetic force at close range.

Practice problem 8

The strong nuclear force acts between the two protons and each proton and the neutron. It is a small nucleus so the strong nuclear force extends to all nucleons from each of the other nucleons. The electromagnetic force also acts to repel the two protons but not as strongly as the strong nuclear force attracts them.

Sample problem 9

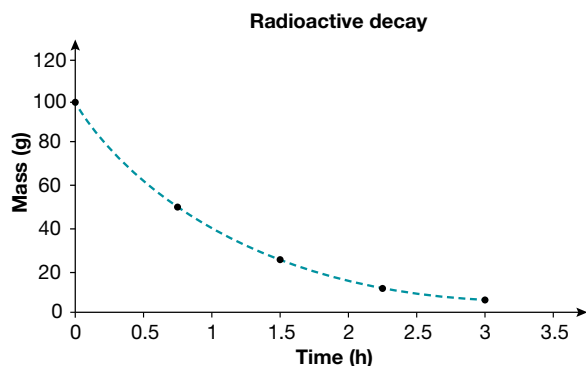
- a. $\frac{1}{4}$ b. $\frac{1}{256}$

Practice problem 9

21.08 years

7.3 Exercise

- Sodium-23.
- a. One proton and one neutron.
b. 95 protons and 146 neutrons
c. 63 protons and 101 neutrons
- The force between a proton and neutron is the strong nuclear force, but it only acts if the proton and neutron are very close together (within about 2×10^{-15} m).
- $\frac{1}{32}$ of the initial sample remains.
- A stable isotope is one that never decays.
- A nucleus can be unstable because the electromagnetic force becomes greater than the strong nuclear force at only a very small separation distance. Therefore, the sum of all of the repulsive electromagnetic forces can total more than the sum of the strong nuclear forces in large nuclei.
- 45 minutes.
-



- Nuclei decay at random. It is impossible to predict when any individual nucleus will decay but if a large sample of nuclei are decaying, it is possible to determine when a proportion (such as a half) of them will decay.
- After each half-life, half of the sample remaining decays. Only half of the nuclei are left to decay so the number of decays that will happen per second will halve.

11. $\frac{24}{3} = 8$ half-lives so $\left(\frac{1}{2}\right)^8 = \frac{1}{256}$ of the sample remains after 24 hours. You would need to order $20 \times 256 = 5120$ grams or 5.12 kilograms of the isotope to have enough left when you receive it.

7.4 Types of nuclear radiation

Sample problem 10

- a. ${}_{92}^{234}\text{U} \rightarrow {}_{90}^{230}\text{Th} + {}_2^4\text{He} + \text{energy}$
b. ${}_{82}^{210}\text{Pb} \rightarrow {}_{83}^{210}\text{Bi} + {}_{-1}^0\text{e} + \text{energy}$
c. ${}_{6}^{11}\text{C} \rightarrow {}_{5}^{11}\text{B} + {}_{+1}^0\text{e} + \text{energy}$

Practice problem 10

- a. ${}_{95}^{241}\text{Am} \rightarrow {}_{93}^{237}\text{Np} + {}_2^4\text{He} + \text{energy}$
b. ${}_{78}^{197}\text{Pt} \rightarrow {}_{79}^{197}\text{Au} + {}_{-1}^0\text{e} + \bar{\nu} + \text{energy}$
c. ${}_{12}^{23}\text{Mg} \rightarrow {}_{11}^{23}\text{Na} + {}_{+1}^0\text{e} + \nu + \text{energy}$

Sample problem 11

In a decay chain, a nucleus may decay to a less stable nucleus. This, however, is a step towards increased stability as the final nucleus is always stable.

Practice problem 11

- a. Uranium-238
b. If the decay chain started with an unstable nucleus with a shorter half-life, it would have all decayed by now.

7.4 Exercise

- ${}_{86}^{222}\text{Rn} \rightarrow {}_{84}^{218}\text{Po} + {}_2^4\text{He} + \text{energy}$
- ${}_{82}^{214}\text{Pb} \rightarrow {}_{83}^{214}\text{Bi} + {}_{-1}^0\text{e} + \bar{\nu} + \text{energy}$
- ${}_{27}^{60}\text{Co}^* \rightarrow {}_{27}^{60}\text{Co} + \gamma$
- a. 2
b. 4
c. An alpha particle.
- Both the neutrino and the gamma ray have a mass number and atomic number of zero.
- Kinetic energy of the emitted particles.
- Beta particles have atomic numbers of -1 or $+1$, however, they are only electrons or positrons. There are no protons. In these cases the atomic number refers to the charge of the particle.

7.5 Review

7.5 Exercise 1: Multiple choice questions

- A
- D
- C
- C
- A
- B
- C
- A
- C
- A

7.5 Exercise 2: Short answer questions

- uuu or ccc or ttt or any combination of these three flavours of quarks will have a charge of +2.
 - Any of the answers in part (a), as an antibaryon would have a charge of -2, for example, $\bar{u}\bar{u}\bar{u}$.
 - Any combination of three quarks whose charge adds to zero is an acceptable answer. An example is up down bottom.
- Mesons are particles containing one quark and one antiquark. If the quark and antiquark are of the same 'flavour' (for example, up and anti-up), then it will be its own antiparticle. For example, the antiparticle of $u\bar{u}$ is $\bar{u}u$, which is exactly the same.
- Charged particles interact strongly with other charged particles, and it is because of their effects on other particles that we know particles are there. In particular, charged particles tend to ionise atoms, leaving a trail showing where they have been. In the case of neutral particles, such as the neutron, neutrino and Higgs boson, they interact weakly with other matter making them difficult to detect.
- Number of protons = 30
Number of neutrons = 36
 - Number of protons = 90
Number of neutrons = 140
 - Number of protons = 20
Number of neutrons = 25
 - Number of protons = 14
Number of neutrons = 17
- ${}^4_2\text{He}$
 - β^- particle
 - β^- particle
 - α particle
- ${}^{226}_{88}\text{Ra} \rightarrow {}^{222}_{86}\text{Rn} + {}^4_2\alpha + \text{energy}$
 - ${}^{214}_{84}\text{Po} \rightarrow {}^{210}_{82}\text{Pb} + {}^4_2\alpha + \text{energy}$
 - ${}^{241}_{95}\text{Am} \rightarrow {}^{237}_{93}\text{Np} + {}^4_2\alpha + \text{energy}$
 - ${}^{60}_{27}\text{Co} \rightarrow {}^{60}_{28}\text{Ni} + {}^0_{-1}\beta + \bar{\nu} + \text{energy}$
 - ${}^{90}_{38}\text{Sr} \rightarrow {}^{90}_{39}\text{Y} + {}^0_{-1}\beta + \bar{\nu} + \text{energy}$
 - ${}^{32}_{15}\text{P} \rightarrow {}^{32}_{16}\text{S} + {}^0_{-1}\beta + \bar{\nu} + \text{energy}$
- Eight α decays and six β decays have occurred.
- Approximately 2 hours
- 17 190 years

7.5 Exercise 3: Exam practice questions

- Baryons
- The mass is equal.
The charge is opposite.
 - Gamma rays are produced when the positron that is emitted is annihilated with an electron.
- Neutrino, neutron, positron or Higgs
 - A scientific theory might require certain observations, for example, the conservation of mass. The proton had a charge equal to half the charge of the alpha particle. Therefore, they determined that the alpha particle would contain two protons, however, the mass of the alpha particle was about four times that of a proton, so assuming the mass of two protons should be around twice the mass of one proton, there must be another particle present with zero charge.
- Adding a neutron to a stable nucleus makes it more likely to undergo β^- decay.

- Nuclei stability follows a curve of neutron number versus proton number. Adding a neutron takes the nucleus away from that stability curve. Of the decay options α , β^+ and β^- , and γ , only β^- decay moves the nucleus back towards the line of stability.
 - Alpha emission relies on the bonding between a group of nucleons being stronger than the bonding of that group to the entire nucleus. As the strong nuclear force is stronger than the electromagnetic force for adjacent nucleons, this will only happen when the combined electromagnetic repulsion from a large nucleus affects protons that are less attached by the strong nuclear force.
- ${}^{225}_{89}\text{Ac} \rightarrow {}^{221}_{87}\text{Fr} + {}^4_2\text{He} + \text{energy}$
 - $\frac{1}{8}$
 - Four alpha particles cause a mass number change of $4 \times 4 = 16$. The beta decays do not change the mass number.
Four α decays reduce the atomic number by $4 \times 2 = 8$. Two β^- decays increase the atomic number by 2. The total change in atomic number is -6. The resulting mass number of the bismuth is $225 - 16 = 209$.
The atomic number is $89 - 6 = 83$.

8 Energy from the atom

8.2 Energy from mass

Sample problem 1

4.1 MeV

Practice problem 1

$7.487\,177 \times 10^{-30} \text{ kg}$

8.2 Exercise

- The equation $E = mc^2$ expresses the fact that energy and mass are equivalent. Mass and energy cannot be considered independently.
- $9 \times 10^{15} \text{ J}$
- $1.638 \times 10^{-13} \text{ J}$
- $2.8 \times 10^{25} \text{ eV}$
- $5.0 \times 10^{-11} \text{ kg}$

8.3 Energy from the nucleus

Sample problem 2

- 160.000 732 MeV
- $2.857\,62 \times 10^{-28} \text{ kg}$
- $2.568\,301 \times 10^{-11} \text{ J}$ or 160.300 789 MeV

Practice problem 2

- 166.744 812 MeV
- $2.972\,28 \times 10^{-28} \text{ kg}$
- $2.671\,352 \times 10^{-11} \text{ J} = 166.733 \text{ MeV}$

Sample problem 3

- 12.566 671 MeV
- $1.863 \times 10^{-29} \text{ kg}$
- $1.674 \times 10^{-12} \text{ J}$ or 10.45 MeV

Practice problem 3

- 5.639 928 MeV
- 1.0541×10^{-29} kg
- $9.473\,778 \times 10^{-13}$ J = 5.913 070 MeV

8.3 Exercise

- Fission is the name given to the process where a very large nucleus splits into two smaller nuclei. Fusion is the process of two small nuclei combining to form a single nucleus.
- Fusion
- Energy is released in a fission or fusion reaction if the binding energy per nucleon (the energy required to remove a nucleon from the nucleus) increases in the process. When uranium-235 nuclei are split into two roughly equal-sized nuclei, the binding energy per nucleon for each of these new nuclei is greater than that in uranium-235. When fusion of two hydrogen atoms occurs, the binding energy per nucleon also increases.
- According to the graph, each nucleon in uranium-235 has 7.6 MeV. This is a total of $235 \times 7.6 = 1786$ MeV. Each nucleon in barium-141 has 8.4 MeV according to the graph. This is a total of $141 \times 8.4 = 1184.4$ MeV. Each nucleon in krypton-92 has 8.7 MeV, according to the graph. This is a total of $92 \times 8.7 = 800.4$ MeV. The total energy of the fission products is $800.4 + 1184.4 = 1984.8$ MeV, which is 199 MeV greater than the uranium-235 nucleus. This agrees well with the measured value of 200 MeV.
- When two small nuclei are fused together to form a larger one, energy is released because the new nucleus exists in a lower energy state than the two nuclei that formed it. Energy is conserved so the difference in energy needs to be released in some form.
- For light elements (mass number less than 56) the binding energy per nucleon graph is much steeper than for heavy elements.
- Fusion occurs when combining two light nuclei results in an increase in binding energy per nucleon. This means that energy has been released to bind the nuclei more tightly together. The release of energy is equivalent to a release of mass so the nucleus after fusion is lighter than the two nuclei that it was fused from.
- The fission of uranium-236 results in two nuclei with higher binding energy per nucleon. This involves energy release so the sum of the masses of all of the particles after the fission is less than the mass of the nucleus that underwent fission.

8.4 Energy from accelerating charges

Sample problem 4

Include any three of the following:

- Electrons in atoms in a hot metal move between energy levels and emit electromagnetic radiation.
- Electrons moving in circles in a synchrotron produce intense electromagnetic radiation tangent to the path.
- Electrons passing through a gas at high voltage excite the electrons in the gas which then emit electromagnetic radiation as they return to ground state.
- Electrons accelerate in an antenna.

Practice problem 4

When electrons move in a circular or elliptical orbit they emit synchrotron radiation. If they were orbiting a nucleus in this way they would lose energy to this radiation and spiral into the nucleus. The electrons can be in stable atoms indefinitely, therefore, they cannot be orbiting the nucleus like planets.

8.4 Exercise

- Electrons or other charged particles moving around in circles at high speed leads to the production of synchrotron radiation. The motion involves changing direction, which involves acceleration. Whenever charged particles are accelerated, they emit electromagnetic radiation. When the acceleration results in them moving in circles or arcs, the radiation is called synchrotron radiation.
- Atoms emit or absorb electromagnetic radiation only at particular energies, producing emission and absorption spectra. This is explained if the electrons are only allowed to have particular energy levels in the atom. If they could take any energy in the atom, it would be difficult to explain the emission and absorption spectra observed.
- Acceleration of charged particles, particularly oscillating back and forth, produces electromagnetic radiation.
- The electrons in the antenna for frequency 621 kHz are oscillating back and forth with a lower frequency than for 774 kHz.
- The energy of gamma rays from the nucleus is usually much higher than the energy of electromagnetic radiation emitted by electrons.

8.5 Review

8.5 Exercise 1: Multiple choice questions

- A
- D
- A
- B
- C
- D
- A
- C
- B
- D

8.5 Exercise 2: Short answer questions

- Different elements produce different emission and absorption spectra because the energy levels available to electrons in each element are different — they depend on how many protons are in the nucleus.
- The re-emitted light does not necessarily go in the same direction as it was initially heading. In fact, it is emitted in random directions, so very little of it will be available to fill in the gap.
- The different lines in the hydrogen emission spectrum reveals that there are different energies that the electron in the atom can absorb or release.
- Neutrons have no charge so are not repelled by positively charged nuclei. They can easily come close enough to a nucleus to combine with the nucleus, making it unstable so that it decays to form a different, more stable isotope.

5. Kinetic energy of a neutron and a fused nucleus and some gamma radiation.
6. Extremely high temperatures and pressures—such as exist in the centre of the Sun. These conditions are required to bring the protons close enough together for the strong nuclear force to exceed the electromagnetic repulsion.
7. a. Einstein found that energy and mass are equivalent. Neither mass nor energy are conserved, but the total of mass and energy is conserved.
b. In radioactive decay and nuclear fission and fusion, it is observed that neither mass nor energy are conserved.
c. The amounts of energy normally encountered are such a small proportion of the object that is radiating them. In atoms the mass and energies of particles are known so precisely and the energies of interactions so significant that the effects can be detected.

8.5 Exercise 3: Exam practice questions

1. a. 173.334 717 MeV
b. $3.089\ 62 \times 10^{-28}$ kg
c. $2.776\ 812 \times 10^{-11}$ J = 173.315 040 MeV
2. a. 174.007 690 MeV
b. $3.107\ 62 \times 10^{-28}$ kg
c. $2.792\ 990 \times 10^{-11}$ J = 174.324 766 MeV
3. a. i. 17.589 279 MeV
ii. 3.1353×10^{-29} kg
iii. $2.817\ 867 \times 10^{-12}$ J = 17.587 750 MeV
b. i. 4.032 675 MeV
ii. 7.188×10^{-30} kg
iii. $6.460\ 252 \times 10^{-10}$ J = 4.032 174 MeV
c. i. 22.372 209 MeV
ii. 3.9879×10^{-29} kg
iii. $3.584\ 146 \times 10^{-12}$ J = 22.370 487 MeV
4. Fission is the process in which a large nucleus divides into two smaller nuclei. Fusion is the process where 2 light nuclei join to form a single larger nucleus. In both fission and fusion, the binding energy per nucleon is higher in the products than in the starting nuclei. Both fission and fusion release energy corresponding to the increase in binding energy per nucleon.
5. Responses will vary but should include any two of the following:
 - Fusion has an abundant fuel source — hydrogen — whereas the fuel for fission is rare — rare isotopes of uranium and a couple of other elements.
 - The waste from fission is radioactive. The waste from fusion is different harmless isotopes of hydrogen and helium.
 - Fusion generates more energy per mass of fuel than fission.

9 Analysing motion

9.2 Describing movement

Sample problem 1

- a. 100 metres north
c. 100 metres
- b. 220 metres
d. 60 metres south

Practice problem 1

- a. 16 km
b. 5.7 km
c. 0 metres

Sample problem 2

2700 kilometres

Practice problem 2

720 kilometres

Sample problem 3

- a. 11 m s^{-1}
b. 5 m s^{-1} north

Practice problem 3

- a. 3.5 m s^{-1}
b. 1.2 m s^{-1} east

Sample problem 4

- a. 2.5 m s^{-2} towards the letterbox
b. 5 m s^{-2} away from the letterbox
c. 4 m s^{-2} towards the letterbox
d. Braking at the letterbox and accelerating back towards home from the letterbox.
e. A decreasing speed in the negative direction is a positive change in velocity, and hence a positive acceleration.

Practice problem 4

- a. 15 m s^{-2}
b. i. $70\text{ km h}^{-1}\text{ s}^{-1}$
ii. 19.4 m s^{-2}

9.2 Exercise

1. a. Scalar
d. Vector
e. Vector
2. 27.8 m s^{-1}
3. 5.4 km h^{-1}
4. a. 88 km h^{-1}
b. 24 m s^{-1}
5. a.

Event (m)	Average speed (m s^{-1})
100	= 9.53 m s^{-1}
200	= 9.37 m s^{-1}
400	= 8.40 m s^{-1}
800	= 7.06 m s^{-1}
1500	= 6.52 m s^{-1}
3000	= 6.17 m s^{-1}
5000	= 5.87 m s^{-1}
10 000	= 5.69 m s^{-1}

- b. The acceleration from rest to the maximum speed takes place over a significant fraction of the time taken for the 100-metre event.
- c. 1 h 47 min 52 s
- d. Only Florence Griffith Joyner. Her event is the only one that involves straight-line motion.
6. a. 800 metres
b. 400 metres
c. 0 metres
7. a. i. 10 km h^{-1}
ii. 2.8 m s^{-1}
b. 12 s
8. a. 15.00 m s^{-1}
b. 2 h 48 mins
c. 1 h 53 mins
d. i. 75.5 km h^{-1}
ii. 0 km h^{-1}

9. Approximately 3 hours 37 minutes.
10. 3.3 m s^{-1}
11. 89 km h^{-1}
12. a. i. -40 km h^{-1}
 ii. 40 km h^{-1} south
 b. i. -20 m s^{-1}
 ii. -20 m s^{-1} in original direction
 c. i. $+5 \text{ m s}^{-1}$
 ii. -55 m s^{-1} in original direction
13. Yes, there is an acceleration. Even though the speed has not changed, the velocity has changed. The acceleration is therefore not 0.
14. For a car that accelerates from rest to 60 km h^{-1} (17 m s^{-1}) in 5 seconds: $a = 3.4 \text{ m s}^{-2}$
15. v_{av} for a 100-metre sprint in say $10.49 \text{ s} = 9.5 \text{ m s}^{-1}$.
 Estimate $v_{\text{max}} = 12 \text{ m s}^{-1}$ is reached after 2 seconds:

$$a = \frac{\Delta v}{\Delta t} = \frac{12 \text{ m s}^{-1}}{2 \text{ s}} = 6 \text{ m s}^{-2}$$

9.3 Analysing motion graphically

Sample problem 5

Approximately 4.7 seconds.

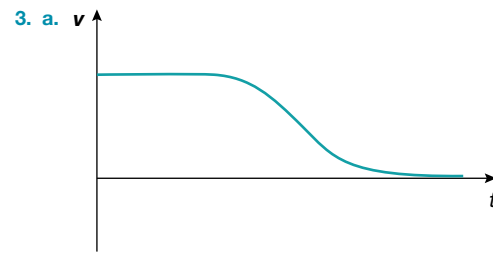
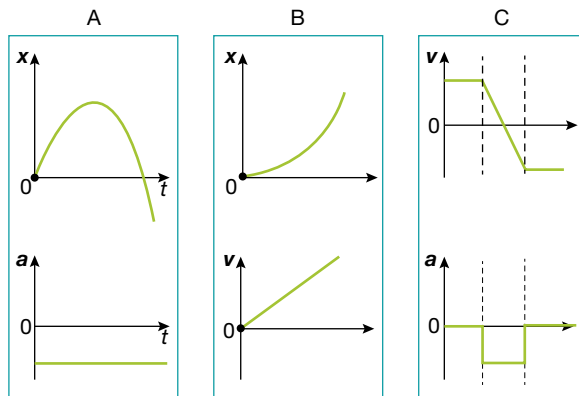
Practice problem 5

- a. 30 m b. 28 m

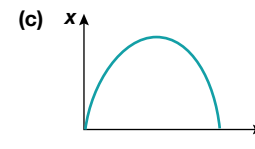
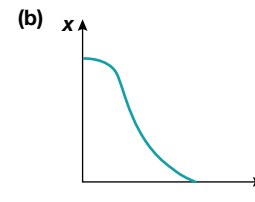
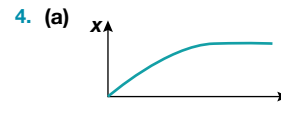
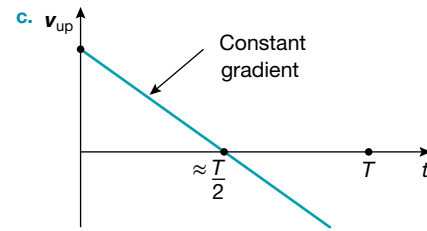
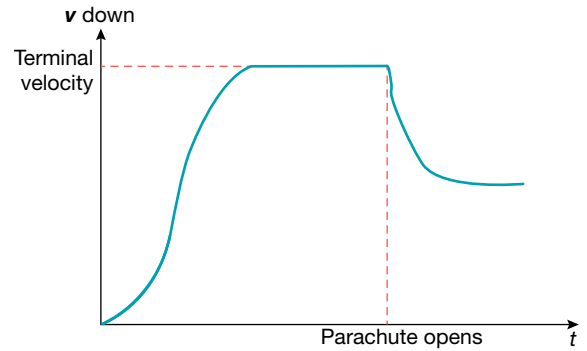
9.3 Exercise

1. a. B and C
 b. B and C
 c. A and E
 d. A and E
 e. C
2. a. A: Constant negative acceleration with an initial positive velocity
 B: Constant positive acceleration from rest
 C: Constant positive velocity, followed by an interval of constant negative acceleration until a negative velocity equal in magnitude to the initial velocity is reached. The velocity then remains constant.

b.



b.



5. a. B
 c. 40 seconds
 e. 260 metres
 g. E
 i. 6.0 m s^{-1} south
6. a. B, D, F
 b. $+20 \text{ m}$
 c. 0.25 m s^{-1}
 d. 30 seconds
 e. It didn't.
 f. C, G
 g. The first half of intervals C, E and G.
- b. A, D, E
 d. 20 metres north
 f. D
 h. 3.3 m s^{-1}
 j. 3 m s^{-1}

h. A negative acceleration doesn't always decrease the speed and a positive acceleration doesn't always increase the speed. A negative acceleration increases the speed if the velocity is negative and decreases the speed if the velocity is positive. Similarly, a positive acceleration decreases the speed if the velocity is negative and increases the speed if the velocity is positive.

i. 0.20 m s^{-2}

j. 0.050 m s^{-2}

k. First 10 seconds: The toy robot started from rest and increased its speed at a constant rate until reaching a speed of 1.0 m s^{-1} after 10 seconds.

10 s to 20 s: It maintained a constant speed of 1.0 m s^{-1} .

20 s to 30 s: It slowed down at a constant rate. It was at rest for an instant, 30 seconds after starting.

30 s to 40 s: It increased its speed at the same constant rate as the first interval, but in the opposite direction, to reach a maximum speed of 1.0 m s^{-1} .

40 s to 50 s: It maintained a constant speed of 1.0 m s^{-1} .

50 s to 55 s: It decelerated to rest at a constant rate.

55 s to 60 s: It increased its speed at a constant rate in the original direction. The acceleration was twice that of the first interval.

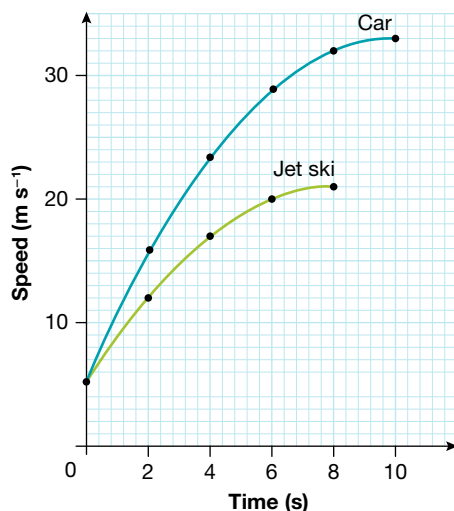
60 s to 70 s: It maintained a constant speed of 1.0 m s^{-1} .

70 s to 80 s: It decelerated to rest at a constant rate.

7. a. The acceleration of the jet ski becomes zero first, after 8 seconds.

b. i. 21 m s^{-1} ii. 33 m s^{-1}

c.



9.4 Equations for constant acceleration

Sample problem 6

a. 29 m s^{-1} b. 44 metres

Practice problem 6

a. 6.0 seconds b. 36 metres

Sample problem 7

a. 12 m s^{-1} b. -6 m s^{-2}

Practice problem 7

a. 18 metres b. -16 m s^{-2}

9.4 Exercise

1. a. 1.8 s

b. 5.0 s

2. a. 2.7 s

b. 27 m s^{-1}

3. a. 12 m s^{-1}

b. -6 m s^2

4. a. -8.0 m s^{-2}

b. 3.5 s

c. The reaction time of the driver needs to be known to determine the distance travelled between the instant that the branch is seen and the instant that the brakes are applied. An estimate of 0.2 seconds would be reasonable for the reaction time. At a constant speed of 100 km h^{-1} (27.8 m s^{-1}), the car would travel a distance of $27.8 \text{ m s}^{-1} \times 0.2 \text{ s} = 5.6 \text{ m}$. The total distance required to stop is, therefore, $5.6 \text{ m} + 48 \text{ m} = 53.6 \text{ m}$. The car would not stop in time.

5. The leap would take 0.8 seconds. The leap is not possible.

6. 793 metres

7. a. 32 m s^{-1}

b. The balls meet 50 metres from the ground.

9.5 Review

9.5 Exercise 1: Multiple choice questions

1. C

2. A

3. C

4. D

5. B

6. A

7. C

8. D

9. B

10. C

9.5 Exercise 2: Short answer questions

1. 3 m north

2. 185 m s^{-1}

3. 660 m s^{-2} away from the racket

4. 4 m s^{-1}

5. 117.5 m

6. 10 m s^{-2}

7. -3.375 m s^{-1}

8. 2.5 m s^{-1}

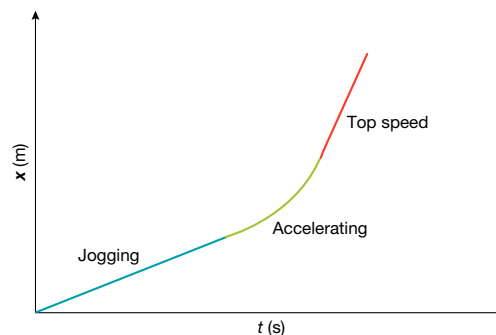
9. 458.3 m

10. $u = 43.2 \text{ km h}^{-1}$

Yes, the driver was travelling faster than the speed limit when they braked.

9.5 Exercise 3: Exam practice questions

1.



2. In this instance, the magnitude of the velocity (the speed) has not changed, but the direction has.
Therefore, there has been a change in velocity, and thus an acceleration.

3. a. 8.5 metres

- b. Assuming that the baton change starts at the 3-second mark and is just inside the interchange area at that point. From the calculations for the previous question, Bo starts 7 metres before the interchange, so therefore complies with the 10-metre maximum rule.

The exchange happens at a constant speed of 7 m s^{-1} and takes 2 seconds, so by inspection Alex and Bo will travel 14 metres together during the interchange.

Therefore, they also comply with the 20-metre interchange area rule.

4. 4.23 seconds

5. a. 3.2 seconds

b. 2.5 m s^{-2}

c. 10 seconds

d. 80 metres

10 Forces in action

10.2 Forces as vectors

Sample problem 1

a. 490 N downwards

b. 80 N downwards

Practice problem 1

a. Force at North Pole = 688 N

Force at equator = 685 N

b. Denver

Sample problem 2

a. Normal force, F_N

Force due to gravity, F_g

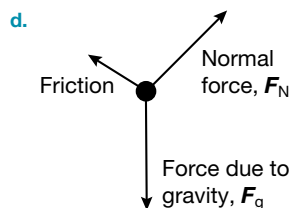
b. Tension, T

Force due to gravity, F_g

c. Normal force, F_N

Friction

Force due to gravity, F_g

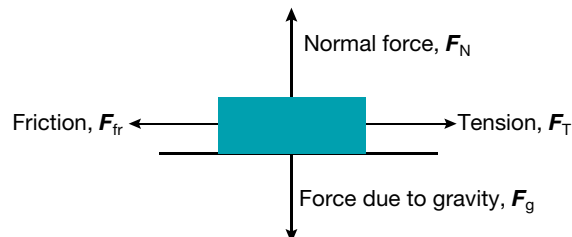


Practice problem 2

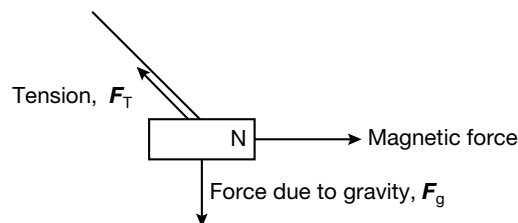
a. Air resistance

Force due to gravity, F_g

b.



c.



Sample problem 3

a. 20 N

b. 15 N

c. 21.2 N

Practice problem 3

89 N

10.2 Exercise

1. Vector quantities have magnitude and direction. Scalar quantities have magnitude only.

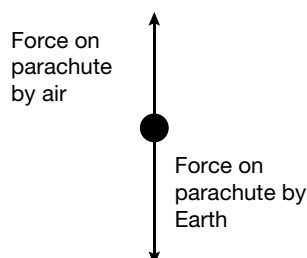
2. Force due to gravity and gravitational field strength

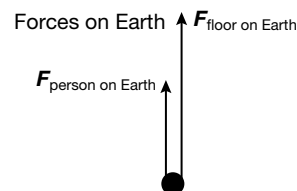
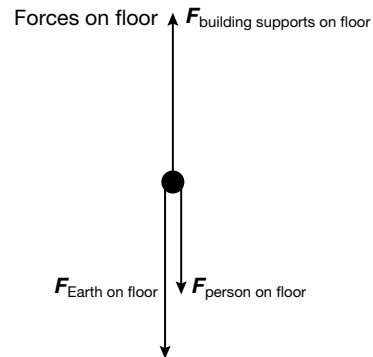
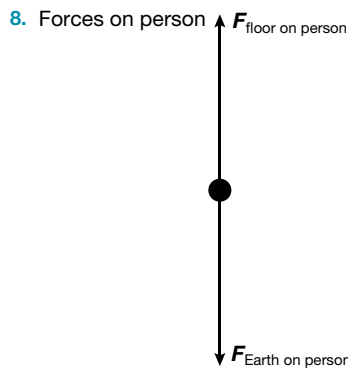
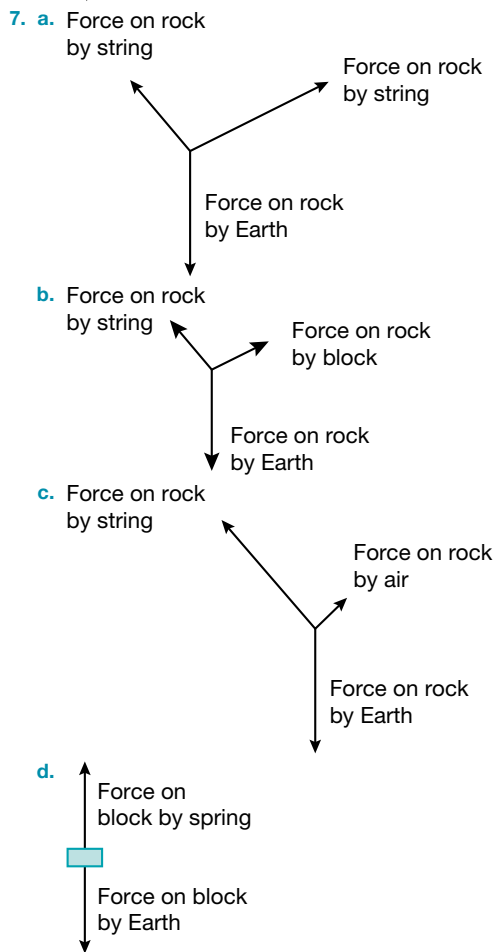
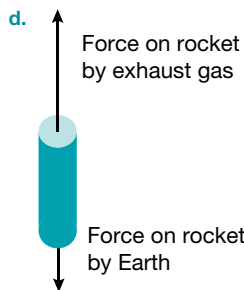
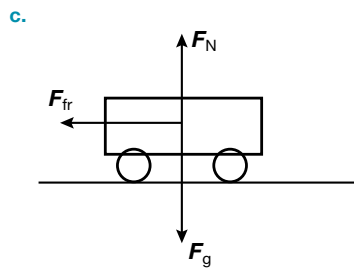
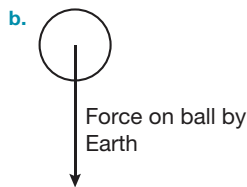
3. a. 13 720 N b. 5040 N c. 1400 kg

4. a. 0.98 N b. 9.8 N c. 784 N

5. a. 588 N b. 216 N c. 60 kg

6. a.





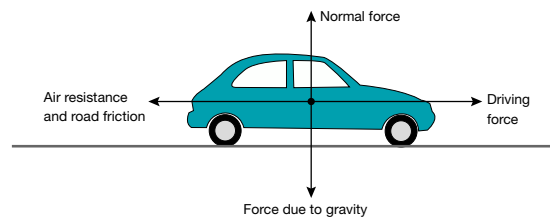
9. a. 3 N east

10. a. 346 N east

11.

b. 141.4 N east

b. 53.6 N east



12. a. 181 N

b. 100 N

c. 0 N

10.3 Newton's First Law of Motion

10.3 Exercise

- For a coin flicked across a table to maintain a constant speed there must be no unbalanced forces on the coin. Though the vertical forces cancel out, there will always be a horizontal friction force opposing the direction of motion. These horizontal forces act in the same direction, so there is a non-zero net force acting on the coin. According to Newton's first law, the net force will cause the motion of the coin to change, slowing until it comes to a stop.
- The vehicle experiences a non-zero net force that slows it down. No such force acts on you. The net force on you is zero. Therefore, you continue in your state of constant velocity.

3. There is an unbalanced force on the bike and so its velocity changes. Your inertia keeps you moving forward as there is no unbalanced force to change your motion (apart from gravity).

10.4 Newton's Second Law of Motion

Sample problem 4

9.3 m s⁻¹

Practice problem 4

- a. 696 N b. 0.8 kg

Sample problem 5

- a. 5.2 m s⁻² upwards
b. No

Practice problem 5

8259 N

Sample problem 6

- a. 160 N north b. 3 m s⁻² north
c. 80 N south

Practice problem 6

- a. 2 m s⁻² b. 320 N

Sample problem 7

- a. -15 N b. 4.5

Practice problem 7

- a. 400 N b. 1800 N

10.4 Exercise

- Idealisations can be made to allow the use of a simple mathematical model to solve a physical problem. For example, in order to use simple equations to analyse the motion of a falling ball, the idealisation can be made that the air resistance is insignificant and the ball does not spin.
- a. 6.6×10^6 N b. 2.8×10^7 N
- a. Both the bowling ball and gold bar have a very small air-resistance-to-mass ratio, so they will experience a very similar acceleration. Therefore, they will fall at the same rate, hitting the ground simultaneously.
b. The air resistance on the doormat is significant when compared with the force due to gravity acting on it. Therefore, the net force on the doormat is less than that of the bowling ball (which has the same mass as the doormat) and the acceleration of the doormat $\frac{F_{\text{net}}}{m}$ is smaller than that of the bowling ball (and the gold bar).
- a. 686 N downwards
b. i. The upwards force is greater when the jumper is accelerating upwards.
ii. The force due to gravity is greater than the upwards pull when the jumper is accelerating downwards.
c. The tension in the bungee cord must be equal in magnitude to the force due to gravity acting on the jumper in order for the speed to be constant.

- a. 7500 N b. 6.250 m s⁻² c. 31.25 m s⁻¹ d. 78.13 m
- 6.944×10^6 N
- 100 N
- a. 700 N b. 557 N c. 840 N
- 1.8 m s^{-2}
- a. 0 m s⁻¹ b. 9.8 m s⁻² c. 4.9 N down

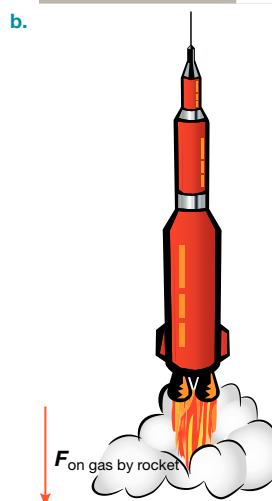
10.5 Newton's Third Law of Motion

Sample problem 8

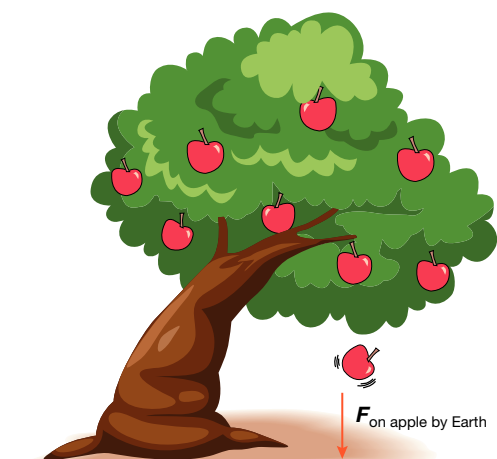
$$F_{\text{on A by B}} = -F_{\text{on B by A}}$$



Practice problem 8



c.



d.

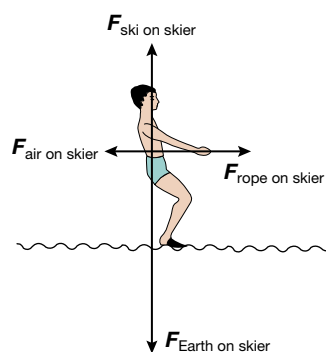


10.5 Exercise

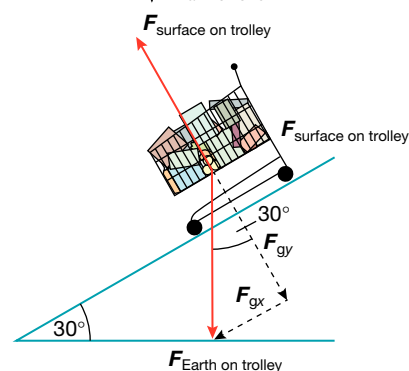
1.

Force 1	Pair of force 1
You push on a wall with the palm of your hand.	The wall pushes on your palm in the opposite direction.
Your foot pushes down on a bicycle pedal.	The bicycle pedal pushes up on your foot.
The ground pushes up on your feet while you are standing.	You push down on the ground when you are standing.
The Earth pulls down on your body.	Your body pulls up on the Earth.
You push on a broken-down car to try to get it moving.	The broken-down car pushes on you in the opposite direction.
A hammer pushes down on a nail.	The nail pushes up on the hammer.

2. a.



b.



3. The dinghy

Force	Action–reaction pair
Resistance forces	$F_{\text{dinghy on air and water}}$, $F_{\text{air and water on dinghy}}$
Gravity	$F_{\text{Earth on dinghy}}$, $F_{\text{dinghy on Earth}}$
Tension	$F_{\text{rope on dinghy}}$, $F_{\text{dinghy on rope}}$
Normal force	$F_{\text{dinghy on water}}$, $F_{\text{water on dinghy}}$

The boat

Force	Action–reaction pair
Resistance forces	$F_{\text{boat on air and water}}$, $F_{\text{air and water on boat}}$
Gravity	$F_{\text{Earth on boat}}$, $F_{\text{boat on Earth}}$
Tension	$F_{\text{boat on rope}}$, $F_{\text{rope on boat}}$
Normal force	$F_{\text{boat on water}}$, $F_{\text{water on boat}}$
Driving force	$F_{\text{boat on water}}$, $F_{\text{water on boat}}$

- All swimmers move forwards in the water because the water pushes them forwards. This is the unbalanced force that provides the acceleration during each stroke (Newton's first law). The size of the forward force is equal to, and opposite in direction to, the force that the swimmer applies to the water (Newton's third law). A freestyle stroke pushes water back with a greater force than a breaststroke stroke. Therefore, the forward force is greater for a freestyle swimmer.
- The student is correct but needs to make it clear that the two friction forces are not an action–reaction pair. The best way to do this is to identify the two action–reaction pairs involved. If the car is a front-wheel drive, the friction on each of the rear tyres is a reaction to the backward push of the front tyres on the road. The rear tyres are being pulled forward. So the friction on the rear tyres is a reaction to the forward push of the rear tyres on the road.

10.6 Forces in two dimensions

Sample problem 9

4058 N

Practice problem 9

- a. i. 16 759 N ii. 46 045 N
b. i. Zero ii. 15 146 N

Sample problem 10

- a. 3.6 m s^{-1} b. 16.2 m

Practice problem 10

- a. 35.2 N
b. 0.35 m s^{-2} down the slope
c. 4.2 m s^{-1}

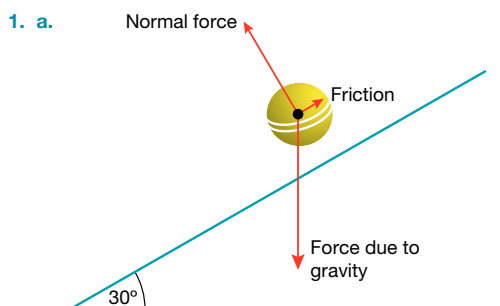
Sample problem 11

- a. 2 m s^{-2} right b. 1800 N

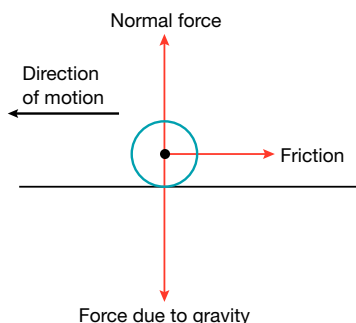
Practice problem 11

- a. 2 m s^{-2} b. 200 N c. 300 N

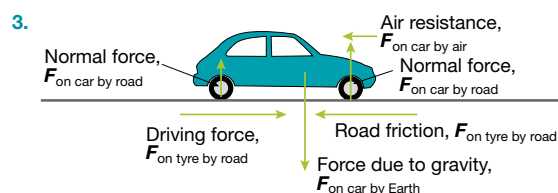
10.6 Exercise



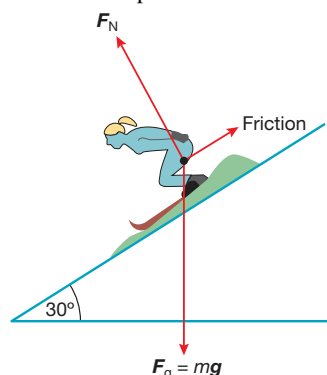
- b. The direction of the net force on the ball is down the hill (parallel to the hill) since the ball is speeding up as it rolls down the hill.
c. Force due to gravity.
d. The ball slows to a stop because of the effect of the friction acting on the ball. On a horizontal surface, the normal reaction is equal in magnitude to the force due to gravity, so the friction force is the net force, which causes the ball to decelerate.



2. When you attempt to push the car you are unable to provide enough force to overcome the friction between the stationary tyres (which cannot rotate due to the hand brake being on) and the road. This friction balances out your push, so the net force remains zero.

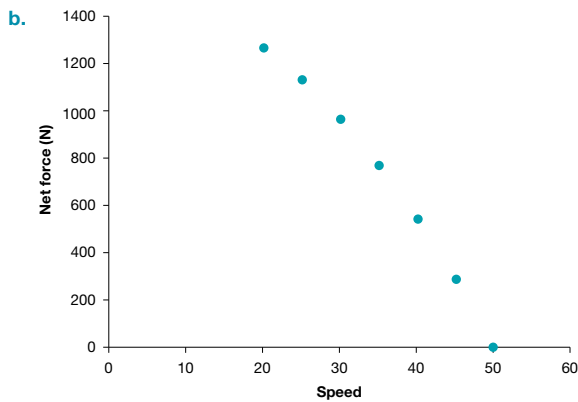


4. a. Zero b. 392 N c. 402 N d. 679 N
5. a. Down the slope.
b.



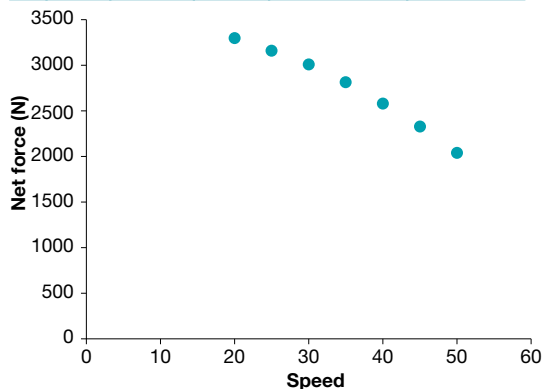
- c. 294 N
d. 286 N
6. 174 N
7. 5.85 m s^{-2}
8. a. 42 N
b. 19°
9. a. Traction (friction) on your blades
b. The component of gravity down the slope and the force of the ground on your poles if you use them
c. The tension in the rope attached to the handle that you are holding
d. The traction (friction) as you push back on the ground
e. The force exerted by the water on your hands, arms, legs and feet as you push back with your hands and kick
f. The force exerted by the water on the oar as the oar pushes back on the water
10. The driving force, the forward force applied to the tyres by the road, is a reaction to the force applied backwards to the road by the tyres. The size of the driving force is, therefore, controlled by the driver's use of the accelerator. The driving force acts on the front wheels of a front-wheel-drive vehicle, whereas it acts only on the rear wheels of a rear-wheel-drive car. The front wheels of a rear-wheel-drive car are pushed forward as a result of the driving force on the rear wheels. So the force applied to the front wheels cannot be controlled directly by the driver.
11. a. A sample spreadsheet is shown here.

	A	B	C	D	E
1	Speed (km h^{-1})	Driving force (N)	Friction (N)	Force due to air resistance (N)	Net force (N)
2	20	1800	-300	-240	1260
3	25	1800	-300	-375	1125
4	30	1800	-300	-540	960
5	35	1800	-300	-735	765
6	40	1800	-300	-960	540
7	45	1800	-300	-1215	285
8	50	1800	-300	-1500	0

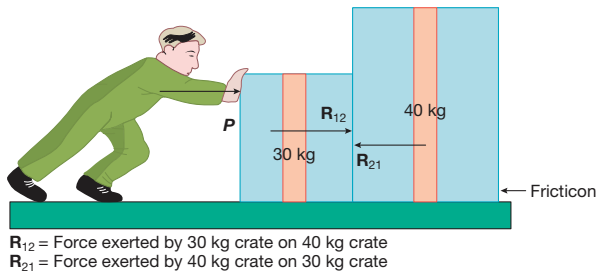


c.

	A	B	C	D	E
1	Speed (km h ⁻¹)	Driving force (N)	Friction (N)	Force due to air resistance (N)	Net force (N)
2	20	1800	-300	-240	3302.124
3	25	1800	-300	-375	3167.124
4	30	1800	-300	-540	3002.124
5	35	1800	-300	-735	2807.124
6	40	1800	-300	-960	2582.124
7	45	1800	-300	-1215	2327.124
8	50	1800	-300	-1500	2042.124



12. 0.9 m s^{-2}
 13. The friction on the rear wheels is the driving force, which pushes the bicycle forward. The friction on the front wheel opposes the motion of the bicycle. When the driving force is greater than the friction on the front wheel, the bicycle will accelerate.
 14. a. 2.0 m s^{-2} b. 6.0 N c. 8.0 N d. 3.5 m s^{-2}
 15.



- a. 4.0 m s^{-2} to the right
 b. 160 N to the right
 c. 240 N to the left
 d. 240 N to the right
 e. 4.0 m s^{-2} to the right. It is no easier.

10.7 Momentum and impulse

Sample problem 12

$1.2 \times 10^8 \text{ kg m s}^{-1}$ north

Practice problem 12

- a. $18\,000 \text{ kg m s}^{-1}$ east b. $25\,200 \text{ kg m s}^{-1}$ east

Sample problem 13

- a. 0.81 kg m s^{-1} b. 0.81 N s^{-1} c. 540 N

Practice problem 13

- a. $28\,000 \text{ kg m s}^{-1}$
 b. $28\,000 \text{ kg m s}^{-1}$
 c. $20\,000 \text{ N}$

Sample problem 14

490 N
 12.25 m s^{-1}

Practice problem 14

- a. 5.5 m s^{-1} b. 5.0 m s^{-2} c. 245 N

10.7 Exercise

- 23 kg m s^{-1} east
- $3.5 \times 10^3 \text{ N}$
 - 800 kg m s^{-1}
 - 560 kg m s^{-1}
 - 3 kg m s^{-1}
- 0.84 kg m s^{-1} up
 - 0.84 kg m s^{-1} down
 - No. The ground does not move a measurable amount. The impulse applied to the ground is 0.84 kg m s^{-1} but the mass of the Earth is so large that the change in velocity is negligible.
 - $4.2 \times 10^2 \text{ N}$ up
 - $4.2 \times 10^2 \text{ N}$ up
- 240 N s up
 - $3.1 \times 10^3 \text{ N}$ up
 - 0.52 metres
- $2.3 \times 10^4 \text{ N s}$
 - $2.9 \times 10^5 \text{ N}$ opposite to initial direction of motion
 - $2.1 \times 10^2 \text{ m s}^{-2}$
- The airbags allow the change in momentum (impulse) of the driver's head to take place over a longer time interval than would be the case if it collided directly with the steering wheel. The average net force on (and the magnitude of the acceleration of) the driver's head is therefore less.
- The change in momentum (impulse) on the legs takes place over a longer interval, reducing the force exerted by the ground on the knee joint and muscles, tendons and ligaments in the leg.
- 220 N s
 - 3.7 m s^{-1}
 - heavier

10.10 Exercise 3: Exam practice questions

- For two forces to be a Newton's third law pair, they must be equal and opposite in magnitude and act on different objects, such that $\mathbf{F}_{\text{on A by B}} = -\mathbf{F}_{\text{on B by A}}$.
In the given scenario, while the forces are equal and opposite, they are both acting on the book.
The normal force is the force of the table on the book. The pair of this is the force of the book on the table.
The force due to gravity is the force of the Earth on the book. The pair of this is the force of the book on the Earth.
- 38 N
- 0.64 m s^{-2}
- $-261\,250 \text{ N}$
- $335\,527.5 \text{ N}$

11 Energy and motion

11.2 Impulse and momentum in collisions

Sample problem 1

- 1 m s^{-1} to the right
- $\Delta p_A = 15 \text{ kg m s}^{-1}$ to the left
 $\Delta p_B = 15 \text{ kg m s}^{-1}$ to the right
- 15 kg m s^{-1} to the left
- 3.5 m s^{-1} to the right

Practice problem 1

- 15 kg m s^{-1} east
- 1.5 m s^{-1} east
- 2.5 kg m s^{-1} west
- 2.5 kg m s^{-1} east
- 2.5 kg m s^{-1}
- The impulses on the two cars are equal in magnitude, but opposite in direction.

11.2 Exercise

- By releasing a high-pressure propellant, the astronaut gains momentum in one direction while the propellant gains the same amount of momentum in the opposite direction. The total change in momentum of the astronaut and the contents of their backpack is zero.
- 0.3 m s^{-1}
 - 0.6 m s^{-1}
- 40 kg
 - 60 N s
 - 60 N s
 - Zero. As there is no external net force acting on the system of the two girls, momentum is conserved.
 - If they pushed each other harder they would have greater speeds but still in the same ratio as before. The total momentum would remain zero as there are no external horizontal forces acting on the girls.
- 1.7 m s^{-1}
 - -120 N s
 - 120 kg m s^{-1}
 - 120 kg m s^{-1}
 - They would have different speeds but the total momentum would be conserved as there are no external horizontal forces acting on the boys.
 - 0.92 m s^{-1}

- 15 m s^{-1}
 - $10\,500 \text{ N s}$ in the initial direction of motion
 - 420 N s opposite to the initial direction of motion
 - $105\,000 \text{ N}$ in the initial direction of motion
- The two forces act on different objects. Forces are what objects do, rather than something that objects have, so force cannot be conserved.

11.3 Work and energy

Sample problem 2

- 750 J
- 150 J
- 600 J

Practice problem 2

- 600 J
- 120 J

Sample problem 3

300 J

Practice problem 3

3.75 J

11.3 Exercise

- 4000 J
- 60 J
- None
- Zero
 - Zero

11.4 Energy transfers

Sample problem 4

62 times

Practice problem 4

- 64 000 J
- 1000 J
 - $2 \times 10^{-8} \text{ J}$

Sample problem 5

3.2 m s^{-1}

Practice problem 5

2 m s^{-1}

Sample problem 6

2.5 J

Practice problem 6

- 0.40 J
- 1.6 J

Sample problem 7

- 5.0 N
- 0.25 J
- 0.25 J

Practice problem 7

- 12 N
 - 7.5 J
 - 1.2 kg
- 80 N m

Sample problem 8

$$5.4 \text{ m s}^{-1}$$

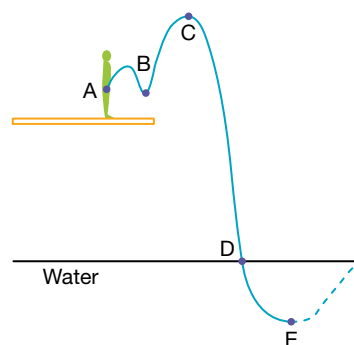
Practice problem 8

- a. 0.4 J b. 1 m s^{-1}

11.4 Exercise

- Work = Fs
Unit = N m
but $1 \text{ N} = 1 \text{ kg m s}^{-2}$
 $\Rightarrow \text{Unit} = \text{kg m s}^{-2} \times \text{m}$
 $= \text{kg m}^2 \text{ s}^{-2}$
Kinetic energy = $\frac{1}{2}mv^2$
Unit = $\text{kg (m s}^{-1})^2$
 $= \text{kg m}^2 \text{ s}^{-2}$
- a. 100 000 J b. 23 J
- 90 J
- a. 1715 J b. 588 J c. 510 J
- a. 196 J
b. 196 J
c. 196 J
- d. It is better to use the ramp. Although the amount of work needed to move the crate is the same, the force that needs to be applied to the crate is less if the ramp is used.
- So that as little of their kinetic energy as possible is transferred to gravitational potential energy. Subsequently, a greater proportion of their kinetic energy is available to cover the horizontal distance as fast as possible.
- a. Spring X: 40 N
Spring Y: 20 N
b. Spring X: 4.0 J
Spring Y: 2.0 J
- a. 235 J b. 20 m s^{-1}
- a. 32 400 J b. 20 m s^{-1} c. 27 metres
- a. 900 000 J b. 360 000 J c. 30 m s^{-1}
- 3.2 m s^{-1}
- a. The force applied by the spring is proportional to its compression.
b. $18\,750 \text{ N m}^{-1}$
c. 60 J
d. 60 J
e. 0.2 m
- As the child falls through the air from maximum height, gravitational potential energy is transformed into kinetic energy.
After the child touches the trampoline after falling through the air, kinetic energy and gravitational potential energy are transformed into strain potential energy until the trampoline is at maximum extension.
After maximum extension, strain potential energy is transformed into gravitational potential energy and kinetic energy until contact is lost with the trampoline.
After contact is lost, kinetic energy is transformed into gravitational potential energy until maximum height is achieved.

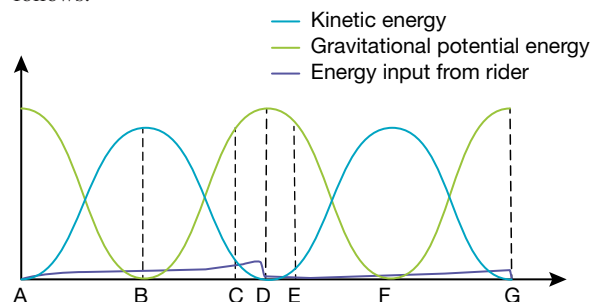
14.



The energy transformations include the following.

- A-B:** Chemical energy is transformed into strain potential energy of muscles, tendons and ligaments.
B-C: Kinetic energy and some gravitational potential energy are transformed into strain potential energy of the springboard until the springboard reaches its maximum deflection.
C-D: Gravitational potential energy of the diver is transformed into kinetic energy until the diver strikes the water.
D-E: Kinetic energy of the diver is transferred to the water (as kinetic energy) and eventually transformed into thermal energy of the water particles.

15. a. The energy transformations can be displayed with a graph of energy versus time or energy versus position, as follows.



As the rider moves down and up the slope, gravitational potential energy is transformed to kinetic energy and back again to gravitational kinetic energy. However, the total mechanical energy is not quite conserved and the rider needs to provide some additional energy 'input' to reach the top of the slope and point C. Further energy input is needed from the rider in order to gain the gravitational potential energy required at point D. Gravitational potential energy is then transformed into kinetic energy as the rider returns to point F and transformed into gravitational potential energy at point G. At points A, D and G, the rider's kinetic energy is zero.

- b. The rider therefore needs to make little effort to remain in contact with the skateboard. There is some skill involved in ensuring that the frictional forces made possible by the contact are used to turn the skateboard so that it lands on the ramp before the feet or any other part of the rider's body.

11.5 Efficiency and power

Sample problem 9

80%

Practice problem 9

0.82 m

Sample problem 10

a. 118 W b. 500 W

Practice problem 10

a. 1.5 m
b. 600 W

11.5 Exercise

- a. 3.1 J b. 1.0 J c. 0.64 m
- a. 241 000 N
b. 161 m s^{-2}
c. 965 m s^{-2}
d. The kinetic energy of the car is transformed into potential energy of the materials in the crumple zone, which undergo a permanent change in shape. This leaves a smaller amount of kinetic energy to be transferred to the passengers.
e. One could argue that a large car is safer. For a given force applied by an obstacle or another vehicle, the deceleration of a large car is less than that of a small car. Therefore, the deceleration of the occupants inside is less. For example, consider a car of mass 1500 kg coming to rest from 20 m s^{-1} when a concrete wall applies a force of 48 000 N to the car. The deceleration of an occupant with a correctly fitted seatbelt would be 40 m s^{-2} . Without seatbelts, an occupant would strike the interior of a larger car with a smaller relative speed.
- a. 1920 J
b. 5 N
c. 3600 J
d. 8500 J
e. Some of the gravitational potential energy is transformed into thermal energy and sound, due to the frictional force and air resistance.
- a. 2079 J b. 0.15 m
- Speed and momentum before impact, speed and momentum after impact, change in momentum on impact, average force during impact, loss of gravitational potential energy on falling, gain in kinetic energy on falling, gain of gravitational potential energy on rebounding, loss of kinetic energy on rebounding, percentage of energy lost.
- 50%
- As human muscle has an efficiency of 20% the total work done is: 392 W
- 400 610 N
- 22 375 W
- 49 W
- a. 3200 J
b. 1100 W
c. None
- 14 400 W
- 35 W
- a. 4.6 m s^{-1}
b. 1691 W

11.6 Review

11.6 Exercise 1: Multiple choice questions

- A
- C
- B
- B
- D
- B
- A
- D
- B
- C

11.6 Exercise 2: Short answer questions

- a. -2.7 kg m s^{-1} b. -54 N
- -22 m s^{-1}
- 32 J
- $1.35 \times 10^9 \text{ J}$
- a. 10.8 N b. 1.1 kg c. 0.65
- 130 000 J
- a. 720.3 J b. 58.6 m s^{-1}
- 32 m s^{-1}
- a. $E_{K \text{ before}} = 48 \text{ J}$ b. 19%
 $E_{K \text{ after}} = 9.0 \text{ J}$
- 34 500 W

11.6 Exercise 3: Exam practice questions

- Total energy is conserved, however, not all of the gravitational potential energy is converted into kinetic energy.
The most likely cause for the discrepancy is the work done on the object by friction acting to oppose its motion down the ramp. This will decrease the amount of gravitational potential energy that is transformed into kinetic energy.
- a. 6.4 m s^{-1}
b. -559 kN
- The student is not doing any work on the tray during the motion described.
For work to be done there must be a force applied and a displacement in the direction of that force. In this instance the student would be exerting an upwards force on the tray to balance the downwards force due to gravity on the tray. This is perpendicular to the horizontal motion of the tray.
- 21.2 kW
- 19 m s^{-1}

- 12 What are stars?
- 13 Is there life beyond Earth's solar system?
- 14 How do forces act on the human body?
- 15 How can AC electricity charge a DC device?
- 16 How do heavy things fly?
- 17 How do fusion and fission compare as viable nuclear energy power sources?
- 18 How is radiation used to maintain human health?
- 19 How do particle accelerators work?
- 20 How can human vision be enhanced?
- 21 How do instruments make music?
- 22 How can performance in ball sports be improved?
- 23 How does the human body use electricity?

24 Practical investigations

24.2 Key science skills in Physics

Sample problem 1

Research question: Does the type of salt added to water affect the time it takes for water to boil?

Aim: To determine if different types of salt affect the time it takes for water to boil

Hypothesis: If table salt, sea salt, Himalayan salt or chicken salt is added to water, then the time taken for the water to boil will decrease.

Practice problem 1

Research question (example): Does the type of material of clothing affect the speed in which a person will roll down a hill?

Aim (example): To determine if different clothing materials have an impact on the speed a person rolls down a hill

Hypothesis (example): If an individual wears a smooth fabric such as silk, they will have a faster speed when rolling down a hill compared to a rougher fabric (such as wool).

24.2 Exercise

- How much of a difference does placing water in an insulated thermos have on the drop in temperature?
 - What is the difference in brightness between globes in series and parallel circuits?
 - Does being placed in a vacuum affect the speed in which a ping pong ball falls to the ground?
- A logbook is important as it shows evidence of each step of an investigation, allowing work to be validated as your own. It shows the different components of scientific approach and contains all results obtained in your practical.
- B
- Decide on a topic.
 - Formulate a question.
 - Create an aim and hypothesis.
 - Select equipment.
 - Create a clear and reproducible method that will produce precise, accurate, valid and reliable results.
 - Complete a risk assessment.
 - Submit a practical proposal to your teacher.
- To investigate how the shape of a parachute affects the time it remains floating in the air
 - If circular, square and triangular parachutes are dropped from a similar height, the circular parachute will take the longest to hit the ground due to a larger surface area and increased air resistance.

24.3 Variables

24.3 Exercise

- The dependent variable is measured by the investigator and is influenced by the independent variable. The independent variable is manipulated and changed by the investigator.
- It is important to control variables to make sure that the dependent variables measured are only influenced by the independent variable and not influenced by other factors.
- Independent, as they are being manipulated and changed by Belinda and Paul.
 - Numerical
 - Categorical
 - Numerical
 - Categorical
 - Categorical
 - Numerical

- Some dependent variables include how many pins get knocked down, the final score of the game, how many strikes an individual gets or the speed in which a pin is hit.

4.

	Independent variables		Dependent variables
	NUMERICAL	CATEGORICAL	
(a) Performance of a parachute	- Size of the parachute - Angle of the parachute - Height from which the parachute is dropped - Speed of the wind	- Type of material used - Shape of parachute - Conditions in which the parachute is dropped (i.e. rainy, windy, indoors)	- Time to reach the ground - Speed - Force of impact on the ground
(b) Movement of a ball down a hill	- Angle of the slope - Size of the ball	- Type of ball - Surface of the hill	- Time to reach the bottom - Speed of ball
(c) Ice cube melting	- Temperature - Size of ice cube	- Shape of ice cube - Solution that ice cube is made of	- Time to melt - Volume of ice cube - Rate of melting

24.4 Concepts specific to investigations, key terms and representations

Sample problem 2

- 1.496×10^8 km
- 1.67×10^{-24} g

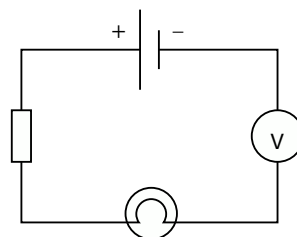
Practice problem 2

- 2.82×10^5 km
- 1.234×10^6 m
- 3×10^{-18} s

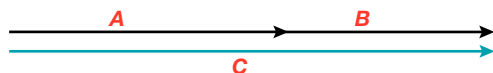
24.4 Exercise

- Within a report and included as part of a sentence or in a glossary at the end, with the key words bolded throughout and defined later.
- Representations are useful in scientific reporting as they allow us to show complex and abstract concepts in an easy to understand form, enhancing the clarity in scientific communication.

3.



4. a. 7.5×10^9
b. 9.46×10^{12}
c. 7.8×10^{-6}
5. $A + B \rightarrow C$



24.5 Scientific research methodologies and techniques

Sample problem 3

- a. Student 2
- b. Student 1
- c. Using the results from parts (a) and (b) it can be seen that Student 3 had the most accurate data and Student 2 had the most precise data.
The student who had the most precise data was not the same student who had the most accurate data. Students may have measurements very close together (precise), but they may not be accurate. Data may also be accurate without being precise; you can be close to the target but with inconsistent readings.

Practice problem 3

- a. Student 1
- b. Student 1
- c. The student with the most precise data was student 2 and the student with the most accurate data was also student 2.

24.5 Exercise

1. Reliability is linked with the repeatability and reproducibility of an investigation and whether or not someone could follow the same protocol and get similar results. It relies on results being accurate and precise and can be affected by errors. Validity, however, is more about if the credibility of data and if it shows what it was intended to. This is often more affected by bias and variables not being correctly controlled.
2. Yes. An experiment needs to be replicated in order to be seen as reliable.
3. Results would not be considered reliable if repetitions of an investigation lead to vastly different answers. An experiment would also not be considered reliable if the method is not clear enough that an individual cannot replicate the process and achieve similar results.
4. Examples of procedures that could affect the internal validity of an experiment include:
 - not correctly testing the variable outlined in the hypothesis
 - misinterpreting measurements
 - not controlling variables correctly.
5. Reliability can be affected by the validity of an experiment. An experiment might be invalid as the technique used did not control variables properly and not reliable as others would get very different results due to other factors influencing the dependent variable. Similarly, a valid experiment that accurately addresses the variables and controls factors will also be reliable, as others would get the same results. However, a method can be reliable (get the same results every time) but not address the hypothesis and the question, meaning it is not valid.
6. Precision is a measure of how close various measurements are to each other. For example, you record the room temperature three times with a thermometer and get 20.1 °C, 20.3 °C and 20.2 °C, therefore, these results are fairly precise. Accuracy on the other hand, is how close to the expected and known quantity a result is. For example, if the room temperature is known to be 23.5 °C, 23.4 °C would be accurate but 20.1 °C would not be.
7. A strength of quantitative data is it provides a clearer understanding of trends and patterns in results. A weakness is in that it can be harder and more time consuming to collect. A strength of qualitative data is that it is often easy and quick to collect. A weakness is that it can be subjective.
8. Primary data is going from the initial source, often through direct investigation, which allows for patterns to be observed more clearly without the impact of another source. Secondary data has often been interpreted, evaluating and analysed, so sometimes the message is misinterpreted and may not be specific to the investigation being conducted.

24.6 Health and safety guidelines

24.6 Exercise

1. a. The contents of batteries are corrosive so it's important to be careful in case of leakage. Battery can heat up easily, which can lead to rupture of case.
b. Light globes can reach high temperatures, which may lead to burns. Light globes are made of glass, so may break or chip leading to lacerations.
c. Bunsen burners are sources of ignition. The blue roaring flame is extremely hot and difficult to see and can lead to burns. Damage to the bases, jet and tubes can cause flames and increased temperatures, which may also lead to burns.
d. Beakers, being made of glass, can break or chip, leading to possible cuts or lacerations.
e. Thermometers are made of glass and can break leading to cuts. Some thermometers contain mercury, which is toxic.
2. Ethics may be important when confidentiality is involved. If an individual is conducting an opinion survey, it is important they have all relevant information and their personal information is kept private. It can also relate to personal beliefs, particularly if concepts go against the participant's own ideas and ethics.
3. Purposes of a risk assessment include:
 - identifying hazards with equipment or chemicals
 - suggesting standard handling procedures
 - outlining the correct disposal of chemicals
 - outlining any first aid that may be required
 - providing information for the practical, including the location, time and date.
4. Other things that could be added to a risk assessment may include information about devices used such as specific voltages, further information about allergies, contacts to emergency hotlines and clear information about how many students will be in each group and at each bench.
5. In any plan drawn, students should show the emergency gas and electricity shut-offs, the location of fire blankets and extinguishers, the exits, windows, location of safety glasses, lab coats and gloves, and the location of the fume cupboard, taps, eyewash and emergency shower. Other safety features may include the location of locked cupboards, the location of cleaning equipment (including spill kits) and the location where broken glass should be disposed.

24.7 Methods of organising, analysing and evaluating primary data

Sample problem 4

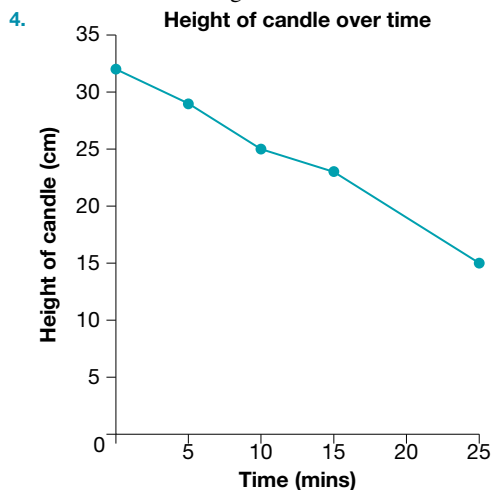
- a. 128.93 ± 0.005 g
b. 47 ± 0.25 °C

Practice problem 4

- a. 0.12 ± 0.005 g
b. 0.195 ± 0.0005 g

24.7 Exercise

1. A random error is chance variation in measurements and usually affects the precision of data and can be improved by repeating an experiment. A systematic error usually affects the accuracy of an experiment and is often due to equipment errors and therefore cannot be improved by repeating the experiment using the same equipment. Examples of random errors are not lining up a ruler correctly with the edge of an object being measured. Examples of systematic errors are a faulty scale that has been incorrectly calibrated.
2. You can minimise uncertainty by taking multiple results and averaging them out or by using more precise equipment.
3. a. A line graph would be most appropriate as a variable (height of rocket) is being observed over time.
b. A bar graph would be most appropriate, as one variable is qualitative (brand of car) and the other is quantitative (volume of airbag).
c. A line graph would be most appropriate as both variables (pH and temperature) are quantitative and a line graph would allow for trends to be seen. However, a scatterplot with a line of best fit may also be appropriate.
d. A histogram would be most appropriate as frequency and intervals are being used in the data.



It can be seen that as time passes, the height of the candle decreases, showing a negative correlation. On average, it decreases by around 4 centimetres per minute, except between 0 and 5 minutes and between 10 and 15 minutes, where the rate of size reduction is slower.

5. An outlier should be mentioned and discussed, with an outline of possible reasons. However, it usually is excluded when calculating averages or trying to add a line of best fit.
6. a. 9.6 ± 0.25 cm b. 8.5 ± 0.125 cm
c. 11.9 ± 0.005 cm

7. a. 60 W b. 40 W c. 180 W d. 20 W

24.8 Models and theories to understand observed phenomena

24.8 Exercise

1. Models can be useful as they:
 - allow us to visualise objects and concepts we can't see (i.e. atoms)
 - make abstract concepts tangible
 - provide explanatory frameworks for a variety of chemical concepts, allowing for more in-depth concepts to be explored.
2. Some limitations of models include:
 - an oversimplification of complex situations, as models cannot show every detail
 - a misrepresentation of the concept in the real world when conditions are not carefully controlled
 - the ever-changing nature of models and research means that models aren't definite.
3. A model is a representation of a phenomena, whereas a theory is a well-supported explanation of a phenomena.
4. Theories allow us to understand phenomena as they are based on investigations and observations, provide us with a structured idea that can be applied to different concepts. For example, theories around relativity and motion have allowed us to better gain an understanding of astronomy.

24.9 Nature of evidence and key findings of investigations

24.9 Exercise

1. Hypotheses are supported based on the evidence we have at the time and how this is interpreted. However, the nature of evidence is that new knowledge may become available, which may affect the outcome we obtain. Therefore, we cannot definitively prove a hypothesis, but rather support it with what we have at that point in time.
2. Three examples of strong evidence are quantitative data that was obtained when investigating a single variable, data that was not influenced by bias and data that has been obtained through a reliable method and repeated and obtained by other investigators.
3. Key findings communicated in your discussion should include information about trends and patterns in your data, the relationship to chemical concepts and theory and a clear answer to the question of your investigation.
4. It is important to link results to concepts to show the information is how theory can be used to show and support phenomena observed in a practical investigation.

24.10 Conventions of scientific report writing and scientific poster

Sample problem 5

- a. 12 412 μ L
b. 261.53 dg
c. 8 700 000 000 nm

Practice problem 5

- a. 0.7823 kg
b. 213 000 000 pL

Sample problem 6

0.87 g mL⁻¹

Practice problem 6

0.463 g L⁻¹

24.10 Exercise

- 2.487 A
 - 871 m
 - 0.000 684 s
- 6 520 000 mV
 - 487.234 ms
- The introduction is used to summarise key background concepts, explain any other research that has been done in this field, outline key terms, explain the purpose of your investigation (and why you choose the question) and to outline the hypothesis being explored.
 - The discussion is used to outline any trends and patterns in your data, describe any outliers and how they were treated, evaluate your results and link them to theory, discuss any errors, uncertainties and limitations, describe the precision, accuracy, reliability and validity of your investigation and suggest improvements and future investigations.
 - The conclusion acts to sum up your investigation, provide a clear answer to your question and link back to your aim and your hypothesis.
- In-text:* (O’Keeffe et al., 2020)
Reference list: O’Keeffe, D, Lofts, G, Pentland, P, Phillips, R, Coyle, J & Rosenbrock, M (2020). *Jacaranda Physics 1*. 4th edition. Milton: John Wiley & Sons

 - 5
 - 4
 - 4
 - 6
- 11.1 m
 - 130 m²

24.11 Review

24.11 Exercise 1: Multiple choice questions

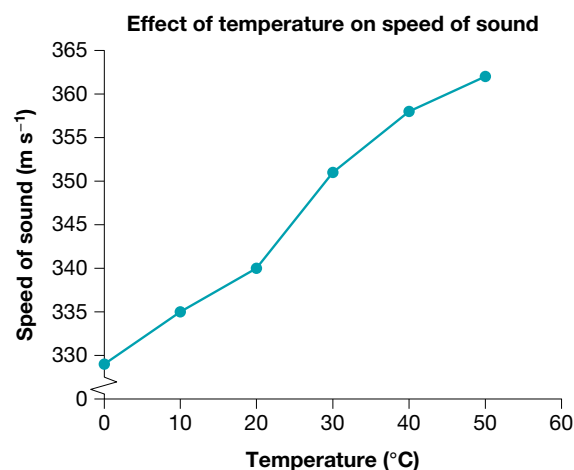
- A
- B
- C
- D
- A
- C
- D
- A
- D
- C

24.11 Exercise 2: Short answer questions

- You could record the voltage, the current or the resistance.
 - You would use a voltmeter, ammeter or multimeter.
 - You could observe the brightness of globes in a circuit or connect to a motor to see if it can be rotated by the voltage supplied.
 - Observations would be visual; you would use instruments such as globes or motors to observe.
- Independent variables are manipulated by the investigator. Dependent variables are measured and are the result of changes to the independent variable.
 - Qualitative data is categorical data (i.e. eye colour, type of metal), whereas quantitative data is numerical (i.e. distance, voltage).

- A control group does not have the independent variable applied to it and is a point of comparison, whereas, the experimental groups have been affected by the independent variable.
 - Primary sources of data are from the initial source of data collection, often through direct investigation. Secondary data is a summary of analysed primary data.
 - Uncertainty involves a limit to the precision of a piece of equipment (i.e. is a measurement on a ruler 0.011, 0.012 cm). It cannot be improved by repeating an investigation. An error relates to factors affecting the accuracy of the experiment and how close results are to their true value. These can be improved by repeating an investigation.
- 4
 - 1.43×10^{-2}
- To determine how the temperature of the hot plate and size of a water droplets affects how long the water stays on the hot plate.
 - The independent variables are size of droplet (numerical: discrete, as it was based on the number of drops) and temperature setting (numerical: discrete, as it was set to a specific setting). The dependent variable is the time the drop lasted (numerical: continuous, as it can be any value above 0 seconds).
 - It can be seen that the larger the size of the water droplets, the longer the drop will last. In regards to hot plate temperature, the higher the temperature setting, the shorter the time the droplet will last.
 - Chris tested too many variables and did not show how he controlled variables. He also chose a method of selecting water droplet size as number of droplets, which means things such as the shape and diameter of the droplet were not well controlled.
 - Another independent variable might be different types of water (tap water versus bottled), water with different initial temperatures and water with different surface areas.
 - Using a ruler to estimate the size would be appropriate in this case.

5. a.



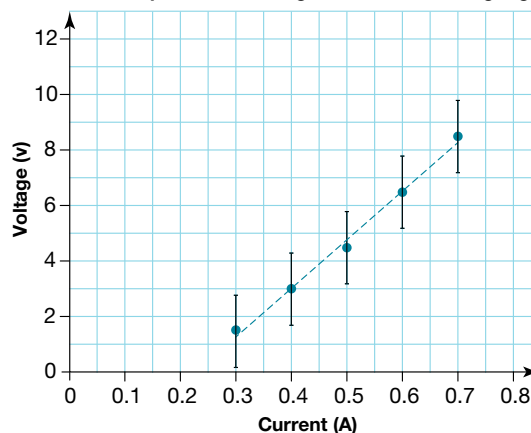
- As temperature increases, the speed of sound also increases. It appears that the rate of increase is most rapid between 20 °C and 30 °C.
- Increasing temperature causes an increase in the speed of sound.

24.11 Exercise 3: Exam practice questions

1. a. The dependent variable in this investigation is the time it took the movement of the balls in the Newton's Cradle to stop.
- b. Any two of the following:
 - the height the balls were pulled back and released from
 - the length of the string
 - the material the balls are made from
 - the force in which the ball is released
 - environmental conditions (for example, don't conduct one test outside in a windy location and the other inside).
- c. Measuring equipment that should be used in this experiment are the a ruler (to measure the balls) and a stopwatch.
Some factors that may affect the accuracy of the results, using this piece of equipment, include:
 - not using the ruler correctly on the curved surface
 - inaccuracy with reaction recorded time
 - different interpretation of when the balls have stopped
 - different precision on rulers.
- d. An example of a method is:
 - i. Collect five small metal balls with a diameter of 2 centimetres.
 - ii. Set up a frame to hang the balls from using two large sturdy metal loops attached to a base.
 - iii. Cut five pieces of string of 30 centimetres.
 - iv. Fold the string in half and attach the metal ball at the fold between the string. Attach each end of the string to each side of the frame, ensuring that there is equal spacing between each ball.
 - v. Pull the ball from the furthest end back 5 centimetres and release, beginning the timer.
 - vi. Record how long it takes for the movement to stop.
 - vii. Repeat this two times and take an average.
 - viii. Repeat steps (i) to (vii) using balls of 4 cm, 6 cm and 8 cm diameter.
2. a. To investigate how the current in a circuit is affected by the length of a resistor
- b. Student responses will vary; one example of a hypothesis is: If the length of a resistor in a circuit is increased, then the current will decrease, due to the increased resistance.
- c. Qualitative data could be if the current increases or decreases. It might also be that another device (e.g. a light globe) placed in the circuit provides qualitative data through the brightness of the globe. Quantitative data will be the current that is recorded on the ammeter.
- d. Factors that may lead to different results by students include:
 - differences in the use of the ammeter (one student may use the smaller scale and one may use the larger scale)
 - differences in the material of the resistor
 - differences in how the circuit is set up
 - differences in the power supply provided.

3. a.

The relationship between voltage and current in a light globe



- b. Some trends shown in the data include:
 - There was a positive correlation (upwards trend), in which the voltage increases as current increases.
 - Data was all very close to the line of best fit, but the voltage at 0.5 A was slightly lower than expected and at 0.7 A and 0.3 A was slightly higher than expected, however, they were well within the margins of the error bars.
- c. The gradient of the line of best fit is:

$$\begin{aligned} \text{Gradient} &= \frac{\text{rise}}{\text{run}} \\ &= \frac{y_2 - y_1}{x_2 - x_1} \\ &= \frac{6.5 - 4.8}{0.6 - 0.5} \\ &= \frac{1.7}{0.1} \\ &= 17 \end{aligned}$$
4. a. Errors that may have occurred includes:
 - systematic errors such as an incorrectly calibrated scale, stopwatch or a ruler that was inaccurate (markings not correct)
 - random errors such as the mass being incorrectly recorded (or the scales not being set to 0 before use), the speed relying on reaction times and different interpretations of the point just before and just after the collision.

A way to avoid the error may include:

 - *faulty scales.* Make sure all scales have been calibrated or record the mass using three different scales and get an average.
 - *faulty stopwatches.* Make sure all stopwatches have been calibrated and repeat the experiment multiple times.
- b. 70.3 g cm s^{-1}
- c. According to the Law of Conservation of Momentum, the momentum before the collision should equal the momentum after the collision, so to be accurate, the data should show this. Joe had a 'before' momentum of $150.6 \text{ g cm s}^{-1}$ and an 'after' momentum of $72.24 \text{ g cm s}^{-1}$, which has a significant difference, whereas Paul's 'before' momentum was 70.2 g cm s^{-1} and 'after' momentum of 70.3 g cm s^{-1} , showing much more accurate results.
- d. $0.000 3514 \text{ kg m s}^{-1}$

5. a. The student hasn't shown the dependent variable in their hypothesis, so it is not testable. An improved hypothesis might be:
If aluminium foil, paper and wool are used as an insulating material on water, then aluminium foil will cause the temperature of the water show the smallest decrease, as it is the best insulating material.
- b. The experiment conducted over three days leads to a loss of some controlled variables. This means that it is not a fair test, and other factors could have resulted in the change of temperature of the water.
- c. The tolerance of a device is half the smallest measurement (0.5°C), therefore, it is 0.25°C . This means that there is a level of uncertainty with the data.
- d. Limitations include:
- the inability to exactly interpret boiling point (as it is a subjective)
 - the inability to completely control room temperature
 - the lack of accuracy in the recorded results
 - the source of the boiling water not being consistent as it was done over multiple days
 - the lack of repetition in the method
 - the starting temperature of the water was not consistent.
- e. Line graph with the three types of variables superimposed on the same graph
- f. It was found that aluminium provides the greatest insulation for boiling water, leading to the slowest decrease in temperature (25°C drop over 25 minutes). This is followed by wool (55.5°C drop over 25 minutes) and finally by paper (58.5°C drop over 25 minutes). The hypothesis in this investigation was supported, as aluminium worked best in insulating water.

INDEX

Note: Figures and tables are indicated by *italic f* and *t*, respectively, following the page reference.

A

absolute temperature 39, 59
absolute zero 11, 30
absorption bands 45, 59
absorption patterns, spectra 213
acceleration
 average acceleration 283
 constant acceleration without
 graphs 299–305
 definition 283, 306
 from velocity-versus-time
 graph 293–5
acceleration-versus-time graphs, area
 under 295–6
accuracy 451, 486
acknowledgement of references
 481–3
active wire, in electric
 circuits 147, 162
aim, developing 435, 486
air resistance 318, 342, 369
air track 449
albedo 51, 59
alpha decay 228–30
alpha particles 228, 234, 236
Alpher, Ralph 200
alternating current (AC) 79, 104
ammeter 79, 104
amperes (A) 76, 104
Ampère, André-Marie 76
Anderson, Carl 217, 218
Andromeda galaxy 180, 181
Andromeda nebula 180
antimatter 215–16
apps, for practical investigations 450
Aristotle 325
astronomical unit (AU) 189
astrophysics, changing
 theories in 471*t*
atomic bomb, development 249
atomic number 222, 223, 236, 262
atomic structure, and nuclear radiation
 222
atoms
 definition 73
 formation 197, 200
 origins of 176, 196
 Rutherford's nuclear model 229
Australian Synchrotron 256

B

background radiation 187, 188
bar graphs 460, 486
baryons 212–13, 236
batteries 74
beam balance 448
Becker, Herbert 219
Becquerels (Bq) 226
beta decay
 beta+ decay 230
 types 230
beta particles 229, 231
Big Bang model of the universe 177,
 184, 186
Big Bang Theory 185, 203
binding energy 247–8, 262
black body 37, 59
blackbody radiation 37, 59
blue shift 182
Boltzmann, Ludwig 39
Bothe, Walter 219
burns, from steam or
 boiling water 28

C

cantilevers 365–7
carbon dioxide, in greenhouse
 blanket 45–8
carbon-12 48
carbon-13 48
categorical data 447, 486
cathode-ray oscilloscope (CRO) 450
Celsius temperature scale 10
Celsius, Anders 10
centre of mass 315, 369
Cepheid variables 179, 203
Chadwick, James 219
chain reactions 248*f*
changing theories,
 in astrophysics 471, 471*t*
charge carriers 76, 104
Charles, Jacques 11
circuit breakers 147, 156–8, 162
circuit diagrams, symbols used 114*t*
climate
 and albedo 51
 models 55–6
collisions
 impulse and momentum in 375–9
 modelling of 379–81

components, of vectors 344, 369
compression 319–20
computer crash modelling 357
conduction 14–15, 30
conductors 30, 70, 74, 104
 speed of electrons travelling
 through 81–3
continuous data 447
control group 439, 486
controlled variables 440, 486
convection 14, 30
 and energy transfer 14
convection currents 15, 31
conventional current 78, 104
conventions of report writing 474–5
cosmic microwave background
 radiation (CMB) 187, 195, 203
cosmic rays 217, 218, 218*f*, 236
cosmology 180, 203
coulombs (C) 76, 104
crash testing 358
Curie, Marie 219

D

Dark Ages (in history of
 universe) 195
data loggers, for
 practical
 investigations 450
daughter nucleus 228, 236
de Coulomb, Charles-
 Auguste 76
De Sitter, Willem 184
decay chain (or series) 233, 236
decay curve 225, 236
decay equation 228, 236
defibrillation 155
dependent variable 440, 486
derived SI units 478
derived units 478
diodes 97, 104
Dirac, Paul 215
direct current (DC) 79, 104
discrete data 447
discussion 442, 486
displacement
 definition 276, 306
 as vector quantity 276
 from velocity-versus-time graph
 291–3

- distance
 - definition 276, 306
 - as scalar quantity 276
 - double insulation 160–1
 - driving force 342
 - E**
 - Earth
 - age of 187
 - blackbody radiation 38–42
 - energy budget 49–51
 - energy from the Sun 37–42, 49
 - heat trapped by greenhouse blanket 45–8
 - surface air temperature 45
 - temperature observed from space 45
 - earth wire (earthing) 148, 158–9, 162
 - eccentricity 43, 59
 - efficiency 397–8
 - Einstein, Albert 184, 188
 - general relativity theory 184, 188, 196
 - mass-energy equivalence theory 249, 250
 - electric charge 72, 73, 104
 - electric circuits 104, 476, *see also*
 - household power circuits;
 - parallel circuits; series circuits
 - accounting for electrons 114–16
 - conductors and insulators 74
 - conservation of electrical energy 116–19
 - definition and operation 70, 112
 - diagrams 113–14
 - and electric charge 71–3
 - modelling 74–5
 - power delivered by 87–90
 - providing energy for 90–91
 - representations 444
 - rules 114–16
 - transformation of energy 86–7
- electric current 104
 - alternating current (AC) 79
 - conventional current 78
 - direct current (DC) 79
 - effect on human body 154–5
 - heating effects 98–9
 - hydraulic model 80–81
 - measuring 79–80
 - nature of 78
 - units of 76
- electric insulator 74, 104
- electric shock 153, 162
 - assisting victims of 155
- current-versus-time parameters 155*t*
- effect of current on human body 154–5
 - resistance of human body 154
- electrical devices, examination of 93
- electrical shock
 - definition and nature of 153–4
- electrical tools and appliances, double insulation 160
- electricity 147
 - household use 146–9
 - paying for 150–3
- electrocution 155, 162
- electromagnetic circuit breakers 156, 157
- electromagnetic force 197
- electromagnetic radiation 31
- electromagnetic spectrum 17*f*
- electromotive force 90, 104
- electron current 78, 104
- electronic timer 449
- electrons 222, 236
 - definition 222
 - positively and negatively charged 215
- electrostatic forces 72, 104, 223
- electroweak era of universe 198
- elements 222, 236
 - definition 222
 - discovery of 222
 - periodic table 222*f*
- energy
 - concept of 381–2
 - units of 6
- energy transfer
 - conduction 14
 - convection 14–16
 - processes 14
 - radiation 14
- enhanced greenhouse effect 47, 59
- equations and formulas 476–7
- equilibrium 362–7
- errors 446, 487
- ethics 456, 487
- evaporation 27–30
- excited nucleus 232, 237
- experimental groups 439, 487
- external validity 453
- F**
- Fahrenheit temperature scale 10
- Fahrenheit, Daniel 10
- falling down 333–7
- falsifiable statement 436, 487
- feedback 51, 59
- Fermi, Enrico 220, 248
- fermions 210
- fibrillation 154, 162
- First Law of Thermodynamics 20, 31
- fission fragments 248, 262
- fluid friction 318–19
- following through 355
- footnotes system 482
- force due to gravity 316, 369
- forces 314, 369
 - adding together 322
 - describing 314–15
 - investigation 314
 - in pairs 337–40
 - SI unit of 315
 - turning effect of 360–2
 - in two dimensions 342–51
 - as vector quantity 315
- forward motion 340
- Fosbury Flop high-jump technique 389
- fossil fuels 48–9
- Franklin, Benjamin 73
- frequency (f) 147, 162
- friction 318, 325, 342, 369
- Friedman, Aleksandr 184
- Frisch, Otto 248, 249
- fuses 156, 157, 162
- fusion, specific latent heat of 26
- G**
- galaxy 180, 204
 - discovery 178–81
 - Local Group 181
 - movement 181
- Galileo 325
- gamma decay 232–3
- gamma rays 17, 232, 236
- Gamow, George 200
- gases, movement of atoms in 7
- Gay-Lussac, Joseph 11
- Geiger, Hans 229
- Gell-Mann, Murray 214
- globular clusters (stars) 179, 180, 204
- grand unified era of universe 197
- graphs, primary data 458–62
- gravitational field strength 316, 369
- gravitational potential energy 5, 31, 388–90, 403
- gravity
 - Einstein's theory 184
 - force of 316–18
 - Newton's theory 184
- greenhouse effect 45–8

greenhouse gases 45
Guth, Alan 198

H

hadron era of universe 199
hadrons 212, 237
Hahn, Otto 248, 249
half-life 225, 237
 nuclei decay 225–7
Hawking, Stephen 188
heat 4, 31
 and kinetic theory of matter 6–9
helmets 356
Higgs boson particles 198,
 220–1, 244
histogram 461, 487
Hooke's Law 391–3
household lighting circuit 148*f*
household power circuits
 active wire 148
 circuit breaker 147
 earth wire (earthing) 148, 158
 faults and safety devices 156–8
 fuses and circuit breakers 156–8
 neutral wire 147
 short circuits 125–7, 156
Hoyle, Fred 188
Hubble, Edwin 180, 181,
 184, 186
Hubble's constant (H) 186, 204
Hubble's Law 186, 204
hydraulic model of electric
 current 80–1
hypothesis 435, 487

I

idealisations 329, 369
impulse
 definition 352, 369
 following through 355
 from a graph 354–5
 in collisions 375–9
 investigation 352
 as vector quantity 352
independent variable 440, 487
inflation era of universe 198
infra-red radiation 17, 45, 46
instantaneous speed 282, 306
instantaneous velocity 282, 306
insulation, double insulation of
 electrical devices 160
insulators 15, 74
internal energy 7, 31
internal validity 453
investigations *see* practical
 investigations

ions 74, 104
isotopes 48, 59, 222–3, 237, 262

J

Joliot, Frédéric 219, 249
Joule, James Prescott 5
joules (J) 6, 31

K

Kelvin temperature scale 11–13
key terms 442–3
kilowatt-hour (kW-h) 150, 162
kinetic energy 31
 changes in 385–8
 definition 5, 385, 403
 formula for 385
 and speed 387
 types 7
kinetic particle model of matter, and
 latent heat 25–7
kinetic theory of matter 6–9

L

Large Hadron Collider (CERN,
 Switzerland) 220, 256
Large Magellanic Cloud
 (stars) 179, 181
latent heat 31
 definition 25
 and kinetic particle model of matter
 25–7
 specific latent heat of common
 substances 26*t*
 specific latent heat of fusion 26
 specific latent heat of
 vaporisation 26
Law of Conservation of Energy 219
Law of Conservation of
 Momentum 379
Leavitt, Henrietta 179
Lemaître, Georges 185
length, measuring 449
leptons 210–11, 237
lie detectors 92
light
 from atoms 257–61
 as electromagnetic radiation 256
 and matter 256–7
 speed of 195
light-dependent resistors
 (LDR) 98, 104
light-emitting diodes (LED) 97, 104
light-year 192, 195
limitations 468, 487
line graph 459, 487
line of best fit 459, 487

liquids, movement of atoms in 7
load (electrical energy) 74, 104
Local Group of galaxies 181
logbook 433
Lucretius 6
luminosity 37

M

Magellanic Clouds (stars) 180, 181
Manhattan Project 249
Marsden, Ernest 229
mass, measuring 448
mass number 222, 237, 262
matter 476
 and light 256–7
Maxwell, James Clerk 18
measurements, of independent
 variables 467
measuring instruments 448–51
mechanical energy transformations,
 conservation and efficiency
 393–7
mechanical interaction 382, 403
Meitner, Lise 248, 249
mesons 212, 215, 237
meters 450
micrometer 449
Microsoft Excel, primary
 data 462
microwaves 17*f*
Milankovic, Milutin 43
Milky Way 178, 179, 181
models 104, 469–70, 487
momentum
 in collisions 375–9
 definition 351, 369
 following through 355
 investigation 351
 protecting human body from
 changes in 355–60
 as vector quantity 351
motion 476–7
 explaining 326
 forward motion 340
 Newtons laws 326
motion graphs
 acceleration-versus-time graphs
 295–6
 investigation 296–9
 position-versus-time graphs
 287–90, 296
 velocity-versus-time graphs
 290–6
motor vehicle safety, in
 collisions 357
movement, describing 276–87

multimeters 79, 450
muons 211

N

negative charge (electricity) 72
negative feedback 51, 59
negligible quantities 329, 369
net force 321–5, 369
neutral 104
neutral objects (electric charge) 72
neutral wire, in electric circuits
147, 162
neutrinos 211, 219–20
neutrons 222, 237, 262
definition 73, 222
prediction and discovery of
219, 220*f*
Newton, Isaac 184, 326
newtons (N) 315
Newton's First Law of Motion
325–7, 385
Newton's Second Law of Motion
327–37, 352
Newton's Third Law of Motion
337–41, 348
nichrome 99
Nishijima, Kzuhiko 214
nominal data 447
non-ohmic devices 104
definition 97
diodes 97
elements 97
LDRs 98
LEDs 97
in series and parallel circuits
130–5
thermistors 97
normal force 319, 342, 369
nuclear fission 248–52, 262
nuclear fusion 248, 252–6, 262
nuclear radiation
alpha decay 228–30
and atomic structure 221–5
beta decay 230–2
gamma decay 232–3
half-life 225–7
neutrinos 219
timeline of discoveries 207
nuclear transformations 234
nuclei (singular; nucleus) 222
binding energy 247–8
daughter nuclei 228
excited nuclei 232
nucleons 222, 237
nucleus 222, 237
numerical data 447, 487

O

obliquity 43, 59
Ohm, Georg Simon 92, 92*f*
ohmic devices 97, 104
ohms 92
Ohm's Law 96
Oliphant, Mark 252
ordinal data 447
outliers 462, 487

P

parallax 191
parallel circuits
connection of devices 119
hydraulic model 122–5
investigation 119–30
modelling resistors in 122–5
non-ohmic devices 130–5
resistors in 121–5
short circuits 125–7
uses 125
parsec 191
particle accelerators 234
Pauli, Wolfgang 219
Penzias, Arno 187
period (T) 147, 162
periodic table of elements 222*f*
photons 187, 210
photosynthesis 48, 59
physics representations 443–6
Planck era of universe 197
 π -mesons (pions) 212, 217
position-versus-time graphs,
instantaneous speed and velocity
287–90, 296
positive feedback 51, 59
positron 217–19, 230, 237
potential difference 104
measuring 84–6
potential energy
forms 388
gravitational potential energy
388–90
Hooke's Law 391–3
strain energy 388, 390–3
potentiometers 134–5
Powell, Cecil 217
power 104
definition 87, 398
delivered by electric circuits
87–90
in electric circuits 135–6
and resistance 99–103
transposing formulae 89
power ratings 149–50
practical investigation 430

acknowledgement of references
481–3
aims and questions 433–6
checklist 484
concepts specific to 442
conventions of report writing
474–5
equations and formulas 476–7
ethics 456
experiments 438–9
formulating hypotheses 436–8
identification of uncertainty
453–4
key findings 473
key terms 442–3
making predictions 436–8
measuring instruments 448–51
models and theories 469–72
nature of evidence 472–3
organising, analysing and
evaluating primary data 457–69
physics representations 443–6
planning 432*t*
precision, accuracy, reliability and
validity 451–3
presenting scientific poster 483–4
scientific method 431–3
scientific research methodologies
and techniques 446–54
significant figures 479–81
standard abbreviations 481
symbols 475
terminology and
representations 475
units of measurements 477–8
using logbook 433
variables 440–2
precession 43, 59
precision 451, 487
prefixes 477–8
primary data
analysing 462–4
evaluating 464–5
primary data, organising 457–62
scatterplots 459
using graphs 458–62
using Microsoft Excel 462
using tables 457–8
primary sources 447, 487
protons 73, 217, 222, 237

Q

qualitative data 447, 487
quantitative data 447, 487
quantum numbers 210
quark era of universe 198

quark model 213–14
quarks 210, 212, 237
names 244

R

radiation 14, 16–18, 31
radio waves 17*f*
radioactive decay 42, 232–3
radioisotopes 237
production of 234
random errors 465, 487
recombination 187, 204
red shift 182, 184, 204
reliability 453, 487
residual current device 159–60, 162
resistance 104
definition 91
and heating effects of current 98–9
of human body 154
ohmic and non-ohmic devices 97–8
Ohm's Law 96
and power 99–103
resistors 104
colour code 94*t*
modelling in parallel circuits 122–5
in parallel circuits 121–5
in series circuits 119–21
types 93
resources, evaluating 57–8
results 431, 487
risk assessments 454, 456, 487
road friction 342
rolling downhill 344–7
rotational kinetic energy 7, 31
Royal Institution (RI), London 5
Rutherford, Ernest 219, 234, 252
Röntgen, Wilhelm 207

S

safety rules 454–6
Sagittarius Dwarf Elliptical Galaxy 181
scalar quantities 276, 306, 315
scatterplots 459, 487
scientific method 431–3, 436, 487
scientific notation 444–6
scientific poster 483–4
scientific research methodologies 446–54, 487
characteristics of 446–7
sea ice in Arctic, melting of 51
seatbelts 357
secondary sources 447, 487

sensors 132–134
series circuits
connection of devices 119
non-ohmic devices 130–5
resistors in 119–21
voltage divider 127–30
Shapley, Harlow 179, 180
short circuits 125–7, 156, 162
SI units
derived units 478
of measurement 478
and negative indices 478
system of 382
significant figures 479–81
Small Magellanic Cloud (stars) 179, 181
solids, movement of atoms in 7–9
space
beginning of 195
expansion of 181–2, 184
specific heat capacity
of common substances 23*t*
definition 22–5
differences in 23
evaporation 27–30
and latent heat 25
specific latent heat
of common substances 26*t*
of fusion 26, 31
of vaporisation 26, 31
speed
average speed 278
converting units of 279–80
definition 278
instantaneous speed 282
and kinetic energy 387
as scalar quantity 278
units of 278
and velocity 282
spring balance 449
standard abbreviations 481
stars
fusion in 252
movement 181, 182
Stefan, Jozef 39
Stefan-Boltzmann Law 35, 39, 45
stopwatch 449
strain energy 388, 390–3
strain potential energy 388, 403
Strassmann, Fritz 248
strong nuclear force 197, 217, 223, 237, 262
subatomic particles, discovery 208–21
Sun
electromagnetic radiation 37, 43

energy falling on the Earth 43
fusion reactions 252–6
switches 74, 104
symbols 475
synchrotron radiation 257, 262
systematic errors 465, 487

T

tables, primary data 457–8
tau particles 211
temperature 31
conversion between degrees Kelvin and Celsius 9
definition 9
measuring 9–11
temperature scales 10
tension 319, 320
between connected bodies 347–51
terminology and representations 475
testable statement 436, 487
theories 470–2, 487
Theory of General Relativity 184, 196
thermal circuit breakers 156, 157*f*
thermal equilibrium 18, 31, 43
thermal radiation 43
thermistors 97, 104
thermodynamics 476
issues 56–7
laws of 19–22
thermometers 10
Thompson, Benjamin (later Count Rumford) 5
Thomson, William (later Lord Kelvin) 10
three-point power sockets 148–9
ticker timer 449
time
beginning of 195
measuring 449
top loading balance 449, 466–7
torque
description 360–2
net torque and rotation 360
problem-solving strategy 362–5
transducers 132–4
translational kinetic energy 7, 31

U

ultrasonic motion detector 450
ultraviolet radiation 17*f*, 45
uncertainty 446, 453, 487
uncertainty and errors
calculating 467–8
graphing 467
measuring 465–7

- repeated measurements 467
- sources of 465–8
- units of measurements 477–8
- universe
 - age of 186, 187
 - as infinite and timeless 184
 - big bang model 177, 184, 186
 - Dark Ages era 195
 - discovery of galaxies 178–81
 - electroweak era 198
 - expansion of space 181–2, 186
 - grand unified era 197
 - hadron era 199
 - inflation era 198
 - looking back in time 195
 - nucleogenesis 199
 - origins of 181, 198
 - Planck era 197
 - prior to formation of atoms 196
 - quark era 198
 - recombination 187
 - significant events 201*t*
 - size of 178–81
- universe, measurements of
 - light-year 192
 - metres 192
 - numbers 193
 - parsec 191
 - time 193

V

- validity 453, 487
- vaporisation, specific latent heat of 26
- variables 440–2
- vector quantities 276, 306, 315
- vectors 443–4
- velocity 443, *see also* acceleration
 - average velocity 281
 - constant velocity 282, 291
 - definition 280
 - instantaneous velocity 282, 296
 - position-versus-time graphs 287–90, 296
 - and speed 282
 - as vector quantity 280
- velocity-versus-time graphs
 - to determine acceleration 293–5
 - to determine changes in velocity 291–3
 - to determine displacement 291
 - features 296
- vernier calliper 449*f*
- vibrational kinetic energy 7, 31
- video with analysis software 450
- visible light 17*f*, 45
- visible spectrum of light 182
- voltage
 - batteries 83
 - as electric potential 84–6

- voltage divider 127–30, 137
- voltage drop 104
 - measuring 84–6
- voltmeters 84, 104, 450
- volts (V) 90

W

- water vapour, in greenhouse blanket 45–8
- weak nuclear force 197, 237
- weight
 - as force 315, 344
 - and gravity 315
- Wien, Wilhelm 40
- Wien's Law 37
- Wilson, Robert 187
- work
 - definition 381, 382, 403
 - as scalar quantity 382

X

- X-rays 17*f*, 207

Y

- Yukawa, Hideki 217

Z

- Zeroth Law of Thermodynamics 19–20
- Zweig, George 214