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PHYSICS

QUEENSLAND

STUDENT BOOK

11

UNITS 1 & 2

QCE 2019 SYLLABUS

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11

UNITS 1 & 2

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This syllabus forms part of a new senior assessment and tertiary entrance system in Queensland. Along with other senior syllabuses, it is still being refined in preparation for implementation in schools from 2019.

For the most current syllabus versions and curriculum information please refer to the QCAA website https://www.qcaa.qld.edu.au/

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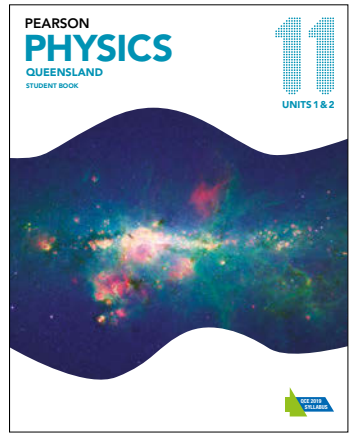

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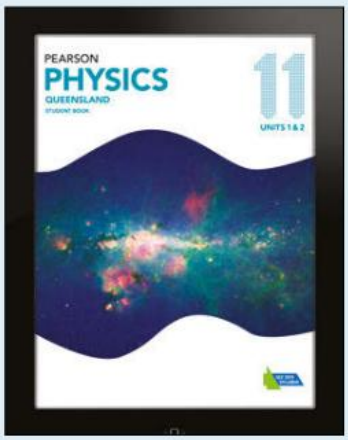

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How to use this book

PEARSON PHYSICS 11 UNITS 1 & 2 QUEENSLAND

Pearson Physics 11 Queensland has been written to the new QCE Physics Syllabus. The book is an easy-to-use resource that covers Units 1 & 2 as well as comprehensively addresses Skills and Assessment.

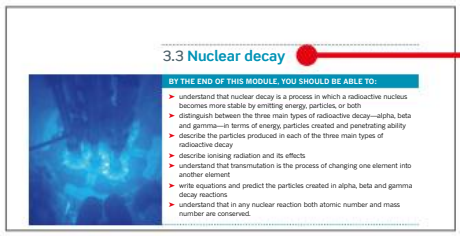
Explore how to use this book below.

Design

The best-practice literacy and instructional design supports all learners. A simple-to-navigate predictable design enables ease of use. The high-quality, relevant photos and illustrations assist student understanding of concepts.

Chapter opener

The Syllabus subject matter addressed in each chapter is clearly listed, along with any Science as a Human Endeavour features and Mandatory practicals.



Module

Module openers outline the key concepts and skills to be developed and link to the syllabus subject matter listed in the Chapter opener.

Science as a Human Endeavour

The feature provides an opportunity to appreciate the development of science and its use and influence on society. The SHE features provide a segue into the development of claims and research questions for the research investigation.

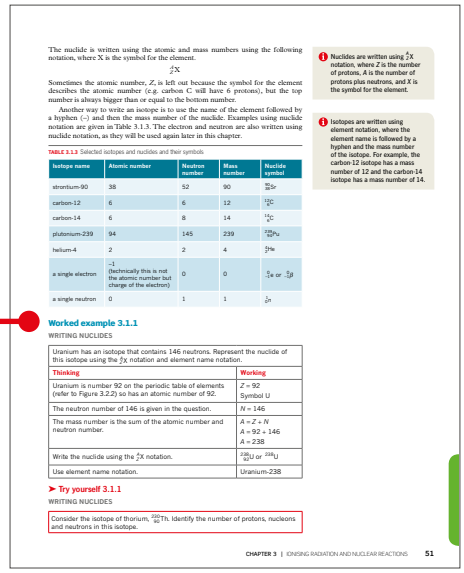
Nuclides are written using ${}^{A}_{Z}X$ notation, where Z is the number of protons, A is the number of protons plus neutrons, and X is the symbol for the element.

Highlight box

Highlight features focus students' attention on important information such as key definitions, formulas and salient points.

Worked Examples

Worked Examples use sequential steps of thinking and working to model calculations and problem-solving, step-by-step. Each Worked Example is followed by a Try Yourself task where students apply their learning to a mirrored problem, to practise the skill. Fully worked solutions to all Try Yourself problems are available online on *Pearson Physics 11 Queensland* Teacher Support.



The nuclide is written using the atomic and mass numbers using the following notation, where X is the symbol for the element.

$^{A}_{Z}X$

Sometimes the atomic number, Z, is left out because the symbol for the element describes the atomic number (e.g. carbon C will have 6 protons), but the top number is always bigger than or equal to the bottom number.

Another way to write an isotope is to use the name of the element followed by a hyphen (-) and then the mass number of the nuclide. Examples using nuclide notation are given in Table 3.1.3. The electron and neutron are also written using nuclide notation, as they will be used again later in this chapter.

Nuclides are written using $^{A}_{Z}X$ notation, where Z is the number of protons, A is the number of protons plus neutrons, and X is the symbol for the element.

Isotopes are written using element notation, where the element name is followed by a hyphen and the mass number of the isotope. For example, the carbon-12 isotope has a mass number of 12 and the carbon-14 isotope has a mass number of 14.

TABLE 3.1.3 Selected isotopes and nuclides and their symbols

Isotope name	Atomic number	Neutron number	Mass number	Nuclide symbol
strontium-90	38	52	90	$^{90}_{38}Sr$
carbon-12	6	6	12	$^{12}_{6}C$
carbon-14	6	8	14	$^{14}_{6}C$
plutonium-239	94	145	239	$^{239}_{94}Pu$
helium-4	2	2	4	$^{4}_{2}He$
a single electron	-1 (technically this is not the atomic number but charge of the electron)	0	0	$^{0}_{-1}e$ or $^{0}_{-1}\beta$
a single neutron	0	1	1	$^{1}_{0}n$

Worked example 3.1.1

WRITING NUCLIDES

Uranium has an isotope that contains 146 neutrons. Represent the nuclide of this isotope using the $^{A}_{Z}X$ notation and element name notation.

Thinking	Working
Uranium is number 92 on the periodic table of elements (refer to Figure 3.2.2) so has an atomic number of 92.	$Z = 92$ Symbol U
The neutron number of 146 is given in the question.	$N = 146$
The mass number is the sum of the atomic number and neutron number.	$A = Z + N$ $A = 92 + 146$ $A = 238$
Write the nuclide using the $^{A}_{Z}X$ notation.	$^{238}_{92}U$ or ^{238}U
Use element name notation.	Uranium-238

Try yourself 3.1.1

WRITING NUCLIDES

Consider the isotope of thorium, $^{232}_{90}Th$. Identify the number of protons, nucleons and neutrons in this isotope.

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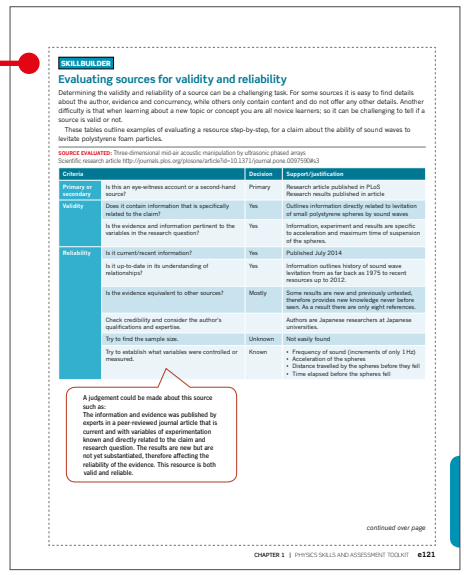
Skillbuilder

A Skillbuilder outlines a method or technique. Each is instructive and self-contained. Skillbuilders step students through the skill to support science application required when analysing or utilising knowledge.



SKILLBUILDER

Evaluating sources for validity and reliability

Determining the validity and reliability of a source can be a challenging task. For some sources it is easy to find details about the author, evidence and concurrency, while others only contain content and do not offer any other details. Another difficulty is that when learning about a new topic or concept you are all novice learners; so it can be challenging to tell if a source is valid or not.

These tables outline examples of evaluating a resource step-by-step, for a claim about the ability of sound waves to levitate polystyrene foam particles.

SOURCE EVALUATED: Three-dimensional mid-air acoustic manipulation by ultrasonic phased arrays.
Scientific research article http://journals.plos.org/plosone/article?id=10.1371/journal.pone.0075590#s3

Criteria		Decision	Support/justification
Primary or secondary	Is this an eye-witness account or a second-hand source?	Primary	Research article published in PLoS Research results published in article
Validity	Does it contain information that is specifically related to the claim?	Yes	Outlines information directly related to levitation of small polystyrene spheres by sound waves
	Is the evidence and information pertinent to the variables in the research question?	Yes	Information, experiment and results are specific to acceleration and maximum time of suspension of the spheres.
Reliability	Is it current/recent information?	Yes	Published July 2014
	Is it up-to-date in its understanding of relationships?	Yes	Information outlines history of sound wave levitation from as far back as 1975 to recent resources up to 2012.
	Is the evidence equivalent to other sources?	Mostly	Some results are new and previously untested, therefore provides new knowledge never before seen. As a result there are only eight references.
	Check credibility and consider the author's qualifications and expertise.		Authors are Japanese researchers at Japanese universities.
	Try to find the sample size.	Unknown	Not easily found
	Try to establish what variables were controlled or measured.	Known	• Frequency of sound (increments of only 1 Hz) • Acceleration of the spheres • Distance travelled by the spheres before they fell • Time elapsed before the spheres fell

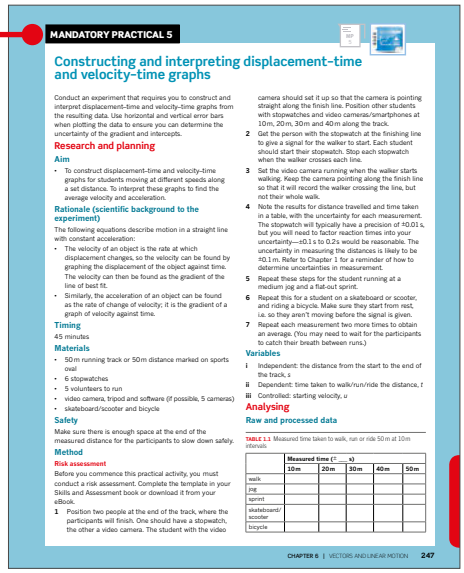
A judgement could be made about this source such as:
The information and evidence was published by experts in a peer-reviewed journal article that is current and with variables of experimentation known and directly related to the claim and research question. The results are new but are not yet substantiated, therefore affecting the reliability of the evidence. This resource is both valid and reliable.

continued over page

CHAPTER 1 | PHYSICS SKILLS AND ASSESSMENT TOOLKIT e121

Mandatory practicals

The Student Book includes all Mandatory practicals. Practicals fully address the syllabus requirements. Each practical has been trialled and tested to ensure it can be safely performed and yields effective, safe results.



MANDATORY PRACTICAL 5

Constructing and interpreting displacement–time and velocity–time graphs

Conduct an experiment that requires you to construct and interpret displacement–time and velocity–time graphs from the resulting data. Use horizontal and vertical error bars when plotting the data to ensure you can determine the uncertainty of the gradient and intercepts.

Research and planning

Aim

- To construct displacement–time and velocity–time graphs for students moving at different speeds along a set distance. To interpret these graphs to find the average velocity and acceleration.

Rationale (scientific background to the experiment)

The following equations describe motion in a straight line with constant acceleration:

- The velocity of an object is the rate at which displacement changes, so the velocity can be found by graphing the displacement of the object against time. The velocity can then be found as the gradient of the line of best fit.
- Similarly, the acceleration of an object can be found as the rate of change of velocity; it is the gradient of a graph of velocity against time.

Timing

45 minutes

Materials

- 50 m running track or 50 m distance marked on sports oval
- 6 stopwatches
- 5 volunteers to run
- video camera, tripod and software (if possible, 5 cameras)
- skateboard/scooter and bicycle

Safety

Make sure there is enough space at the end of the measured distance for the participants to slow down safely.

Method

Risk assessment

Before you commence this practical activity, you must conduct a risk assessment. Complete the template in your Skills and Assessment book or download it from your eBook.

1 Position two people at the end of the track, where the participants will finish. One should have a stopwatch, the other a video camera. The student with the video camera should set it up so that the camera is pointing straight along the finish line. Position other students with stopwatches and video cameras/smartphones at 10 m, 20 m, 30 m and 40 m along the track.
2 Get the person with the stopwatch at the finishing line to give a signal for the walker to start. Each student should start their stopwatch. Stop each stopwatch when the walker crosses each line.
3 Set the video camera running when the walker starts walking. Keep the camera pointing along the finish line so that it will record the walker crossing the line, but not their whole walk.
4 Note the results for distance travelled and time taken in a table, with the uncertainty for each measurement. The stopwatch will typically have a precision of ±0.01 s, but you will need to factor reaction times into your uncertainty—±0.1 s to 0.2 s would be reasonable. The uncertainty in measuring the distances is likely to be ±0.1 m. Refer to Chapter 1 for a reminder of how to determine uncertainties in measurement.
5 Repeat these steps for the student running at a medium jog and a flat-out sprint.
6 Repeat this for a student on a skateboard or scooter, and riding a bicycle. Make sure they start from rest, i.e. so they aren't moving before the signal is given.
7 Repeat each measurement two more times to obtain an average. (You may need to wait for the participants to catch their breath between runs.)

Variables

i Independent: the distance from the start to the end of the track, s
ii Dependent: time taken to walk/run/ride the distance, t
iii Controlled: starting velocity, u

Analysing

Raw and processed data

TABLE 1.1 Measured time taken to walk, run or ride 50 m at 10 m intervals

	Measured time (± ___ s)				
	10 m	20 m	30 m	40 m	50 m
walk					
jog					
sprint					
skateboard/scooter					
bicycle					

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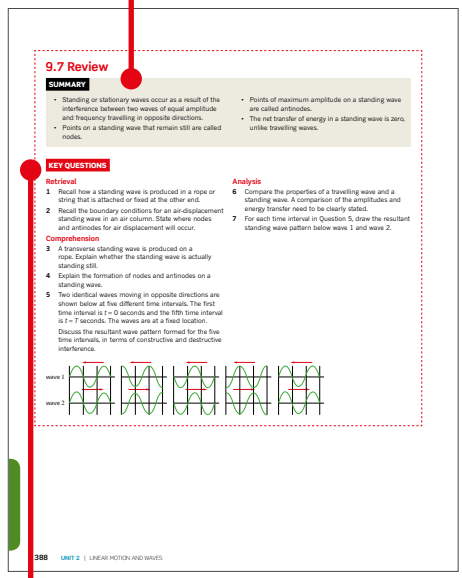
Module summary

Each module concludes with a summary to consolidate key points and concepts.



9.7 Review

SUMMARY

- Standing or stationary waves occur as a result of the interference between two waves of equal amplitude and frequency travelling in opposite directions.
- Points on a standing wave that remain still are called nodes.
- Points of maximum amplitude on a standing wave are called antinodes.
- The net transfer of energy in a standing wave is zero, unlike travelling waves.

KEY QUESTIONS

Retrieval

1 Recall how a standing wave is produced in a rope or string that is attached or fixed at the other end.
2 Recall the boundary conditions for an air-displacement standing wave in an air column. State where nodes and antinodes for air displacement will occur.

Comprehension

3 A transverse standing wave is produced on a rope. Explain whether the standing wave is actually standing still.
4 Explain the formation of nodes and antinodes on a standing wave.
5 Two identical waves moving in opposite directions are shown below at five different time intervals. The first time interval is $t = 0$ seconds and the fifth time interval is $t = 7$ seconds. The waves are at a fixed location.

Discuss the resultant wave pattern formed for the five time intervals, in terms of constructive and destructive interference.

wave 1
wave 2

Analysis

6 Compare the properties of a travelling wave and a standing wave. A comparison of the amplitudes and energy transfer need to be clearly stated.
7 For each time interval in Question 5, draw the resultant standing wave pattern below wave 1 and wave 2.

388 UNIT 2 | LINEAR MOTION AND WAVES

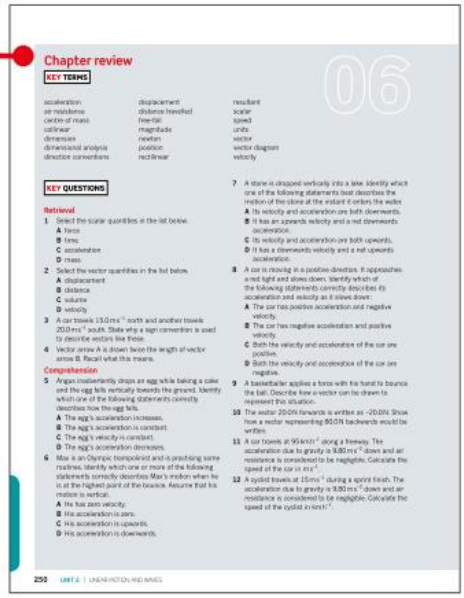
Module review

Key questions are provided to test students' understanding of concepts. Tasks are carefully categorised under the relevant cognitive level—Retrieval, Comprehension, Analysis—and are developed to assess the syllabus requirements.

How to use this book

Chapter review

Each chapter finishes with a list of key terms covered in the chapter and a set of tasks to test students' abilities to apply the knowledge gained from the chapter.


Chapter review

KEY TERMS

06

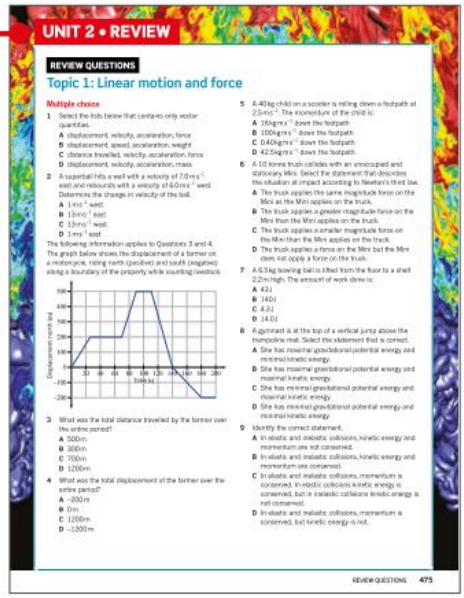
KEY QUESTIONS

Retrieval

Comprehension

Unit review

Each Unit finishes with a comprehensive set of exam-style instructions, including multiple choice, short answer and extended response. These review tasks assist students to draw together their knowledge and understanding of the whole unit.


UNIT 2 • REVIEW

REVIEW QUESTIONS

Topic 1: Linear motion and force

Multiple choice

Glossary

Key terms are shown in **bold** throughout the Student Book and are listed at the end of each chapter. A comprehensive glossary at the end of the book defines all the key terms. The glossary aligns with the syllabus context and includes the QCAA defined terminology.

Answers

Numerical answers and key short-response answers are included at the back of the book. The Teacher Reader+ eBook provides comprehensive answers to all tasks; and fully worked solutions for all module review tasks, Try Yourself, Science as a Human Endeavour, Chapter review questions and Unit review questions.

Icons

Go To icons make important links to relevant content within the student books in the course. The Go To icons indicate where to engage with Chapter 1 in your eBook.

GO TO ➤

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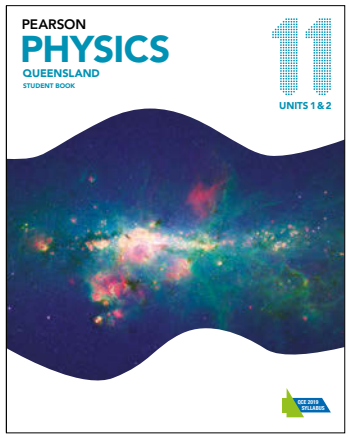

Student Book

Pearson Physics 11 Units 1 and 2 Queensland has been developed by experienced Queensland teachers to address all the requirements of the new QCE Physics 2019 Syllabus. The series features the very latest developments and applications of physics, literacy and instructional design to ensure the content and concepts are fully accessible to all students.

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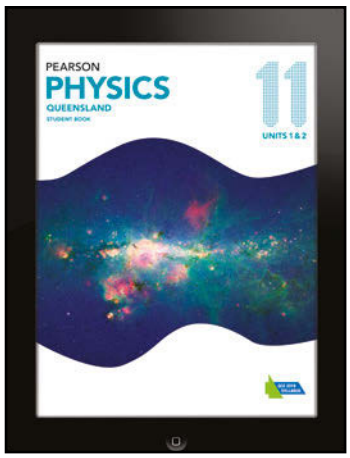

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Understanding assessment instructions

The Queensland Certificate of Education (QCE) 2019 Physics Syllabus uses an inquiry approach, guiding students in a systematic way to a better understanding of the world.

You will notice as you read through the Syllabus for Units 1 to 4 that many terms are underlined. Two examples are provided:

a the General Senior Syllabus objectives
b a sample of Topic 1 subject matter.

The General Senior Syllabus objectives showing the underlining of terms

Syllabus objective		Unit 1	Unit 2	Unit 3	Unit 4
1	describe and explain scientific concepts, theories, models and systems and their limitations	●	●	●	●
2	apply understanding of scientific concepts, theories, models and systems within their limitations	●	●	●	●
3	analyse evidence	●	●	●	●
4	interpret evidence	●	●	●	●
5	investigate phenomena	●	●	●	●
6	evaluate processes, claims and conclusions	●	●	●	●
7	communicate understandings, findings, arguments and conclusions.	●	●	●	●

The QCAA Syllabus states that students 'are required to use a range of cognitive processes to demonstrate they meet the syllabus'. Many of the underlined words in the Syllabus are action verbs. These verbs are often placed at the start of dot points, to identify the level of thinking (cognitive process) you are expected to demonstrate. Note the action verbs from the two Syllabus extracts.

Remember the cognitive verbs used in the Syllabus subject matter dot points indicate the highest level of thinking and subject engagement to be covered. You will not be assessed at a higher cognitive level.

A subject matter description from Physics Unit 1, Topic 1 showing the underlining of terms

Subject matter

Kinetic particle model and heat flow

- describe the kinetic particle model of matter
- define and distinguish between thermal energy, temperature, kinetic energy, heat and internal energy
- explain heat transfers in terms of conduction, convection and radiation.

Temperature and specific heat capacity

- use $T_K = T_C + 273$ to convert temperature measurements between Celsius and Kelvin
- use digital and other measuring devices to collect data, ensuring measurements are recorded using the correct symbol, SI unit, number of significant figures and associated measurement uncertainty (absolute and percentage); all experimental measurements should be recorded in this way
- explain that a change in temperature is due to the addition or removal of energy from a system (without phase change)
- define *specific heat capacity* and the concept of proportionality
- interpret tabulated and graphical data of heat added to a substance and its subsequent temperature change (without phase change)
- solve problems involving specific heat capacity.

UNDERSTANDING COGNITIVE PROCESSES AND VERBS

It is important to understand that the verbs that drive the syllabus objectives and topic subject matter are not randomly chosen. By gaining a better understanding of cognitive verbs, you will be able to respond more satisfactorily to questions and instructions in assessment tasks.

Cognitive verbs are signals to the learner of the type of thinking to be demonstrated. For example:

- the verb *evaluate* indicates that an assessment or judgment must be made
- the verb *describe* requires that an account or outline be provided.

There is a difference between the thinking needed by each of these verbs. To *evaluate* is of a higher level of thinking than to *describe*. Generally, the higher the thinking level required in a task, the more challenging it is.

Cognitive verbs can be arranged or classified into different levels of thinking (also known as cognitive processes) ranging from remembering to complex thinking. The QCAA Syllabus uses an arrangement (taxonomy) of cognitive processes devised by educational researchers Robert Marzano and John Kendall.

In this arrangement, four levels of cognitive process are identified: retrieval, comprehension, analysis and knowledge utilisation. An outline of these levels is provided in Chart A. A large number of different cognitive verbs are used in the Syllabus. These verbs can be aligned with different levels of thinking as shown in Chart B.

Pearson Physics Queensland Student Book provides a comprehensive number of questions and instructions. The review question sets are arranged by cognitive levels using the Marzano and Kendall taxonomy and provide students with the opportunity to demonstrate knowledge and application of the subject matter at the following levels:

Module review – Retrieval, Comprehension and Analysis

Chapter review – Retrieval, Comprehension, Analysis and Knowledge utilisation

Unit review – Retrieval, Comprehension, Analysis and Knowledge utilisation.

CHART A Cognitive processes, as arranged by Marzano and Kendall

Cognitive processes—levels of thinking
(Marzano and Kendall taxonomy)

Retrieval	Comprehension	Analysis	Knowledge utilisation
Level 1—basic level of thinking • Involves remembering, recalling, recognising and executing information.	**Level 2**—higher level of thinking than Retrieval • Involves understanding and identifying key information.	**Level 3**—more complex thinking than Comprehension • Involves examination of information and the identification and separation into its separate parts.	**Level 4**—most complex thinking level • Involves applying information to investigate, experiment, problem solve and make decisions.

Increasing complexity of thinking
Each level of thinking builds upon lower levels. For example, you must be able to retrieve information and comprehend it before you can analyse it.

CHART B Cognitive processes, associated verbs and sample instructions and questions

Cognitive processes, associated verbs and sample questions

Retrieval	Comprehension	Analysis	Knowledge utilisation
Processes: • recognising • recalling • symbolising	**Processes:** • integrating • symbolising	**Processes:** • matching • classifying • analysing errors • generalising • specifying	**Processes:** • investigating • experimenting • decision-making • problem-solving
Cognitive VERBS	**Cognitive VERBS**	**Cognitive VERBS**	**Cognitive VERBS**
define demonstrate describe indicate identify label list name paraphrase recall recognise (e.g. features) select show state use	calculate (e.g. numerical answer; mathematical processes) clarify comprehend (meaning) construct (e.g. a diagram) demonstrate describe determine develop discuss draw (visual depiction) explain illustrate implement (e.g. plan, proposal) recognise (e.g. features) represent select show summarise symbolise (e.g. through diagram, illustration, model) understand use	analyse apply assess calculate (e.g. numerical answer; mathematical processes) categorise classify compare conclude consider contrast critique deduce derive determine diagnose differentiate discriminate distinguish edit evaluate extrapolate explore identify errors/ problems infer interpret e.g. meaning judge organise /sequence/ structure predict reflect (on) sort scrutinise	adapt appraise appreciate argue assess comment (make a judgment) conduct (e.g. investigations) conclude construct (e.g. an argument) convince create design (e.g. a methodology, an artefact, a proposal) decide determine develop (e.g. a strategy, product or process) devise discuss/explore draw conclusions evaluate experiment/test (e.g. hypotheses) explore (e.g. information, ideas, components) into a whole, in order to create new meaning generate/test (e.g. hypotheses) hypothesise /propose (e.g. arguments, concept) investigate /examine (e.g. an argument, statement or conclusion) judge justify/prove (e.g. an argument, statement or conclusion make decisions manipulate (e.g. language texts; skills; technologies) modify persuade predict (e.g. a result) propose prove research realise/resolve (e.g. artistic works) solve (e.g. problems) synthesise test

Note that some cognitive verbs appear in more than one cognitive level.

Note that a question may not necessarily include a cognitive verb.

Sample instruction and question	Sample instruction and question	Sample instruction and question	Sample instruction and question
Define thermal energy. What is a definition for thermal energy?	**Explain** why protons in the nucleus repel each other. Why do protons in the nucleus repel each other?	**Compare and contrast** elastic and inelastic collisions. In what ways are elastic and inelastic collisions similar and different?	**Solve** problems involving wavelength, period and velocity of a wave. A mechanical wave vibrator attached to a string operates at a frequency of 50.0 Hz. If the wave crests formed on the string are 5.0 cm apart, what is the speed of the waves in the string (in $m\,s^{-1}$)?

UNDERSTANDING THE INSTRUCTION/QUESTION

The cognitive verb alone is not enough of a guide to understanding what the question or instruction requires as a response. As seen in the previous chart, questions may not include a cognitive verb. In addition, a cognitive verb may apply to more than one level of thinking.

Consider these examples:

Examples	Use of the cognitive verb 'explain'	Scope and context of the instruction or question
	What is the question asking?	**How much do I write?**
Example 1a: Explain diffusion. What is diffusion?	The key aspect/s of the question: **a** definition response—**retrieval** **b** paraphrase response—**comprehension**	A task that focuses on: **a** one key term—diffusion
Example 1b: Explain convection. What is convection?		A task that focuses on one concept: **a** convection
Example 2a: Explain the **difference** between simple and facilitated diffusion. What is **different** between simple and facilitated diffusion?	The key aspect/s of the question: **a** compare and contrast—**analysis**	A task that focuses on: **a** two terms: simple diffusion and facilitated diffusion **b** differences between the two terms
Example 2b: Explain the difference between convection and conduction. What is different between convection and conduction?		A task that focuses on: **a** two terms: convection and conduction **b** differences between the two terms
Example 3a: Determine how you would conduct an experiment using chromatography to **analyse** proteins. What experimental procedure would you use to **analyse** proteins using chromatography?	The key aspect/s of the question: **a** create, design, experiment—**knowledge utilisation**	A task that focuses on: **a** two terms: proteins and chromatography **b** their analysis **c** design of an experiment
Example 3b: Determine how you would conduct an experiment using convection to **analyse** the specific heat capacity of a metal. What experimental procedure would you use to analyse the specific heat capacity of a metal using convection?		A task that focuses on: **a** two terms: convection and specific heat capacity **b** their analysis **c** experimental ideas and methods

Strategies for understanding the question or instruction

As you can see, analysing a question or instruction can be quite challenging. This particularly applies when more complex cognitive processes are required.

The following steps provide a framework for understanding and analysing questions and instructions.

Strategies for understanding the question or instruction	**Example** A 65.0 kg patient suffering from a fever has a core temperature of 40.2°C and is placed in a cool bath to bring down her temperature. The specific heat capacity of a human is known to be 3.50 kJ kg^{-1} K^{-1}. If the goal is to have the temperature of the patient and the bath water reach 37.0°C, and the bath contains 40.0 L of water, **determine** the temperature of the 'cool' bath water. 1.00 L of water = 1.00 kg, and c_{water} = 4200 J kg^{-1} K^{-1}.
1 Underline the cognitive verb/s and identify a plausible thinking level for the verb.	'… determine the temperature of the "cool" bath water.' **Determine** is found in the cognitive verb list for **comprehension**, **analysis and knowledge utilisation** thinking levels.
2 Determine the scope, context of the question and its thinking level.	The scope of the question includes calculations from given data under specific conditions to determine the temperature of the 'cool' bath water to solve a problem. The context is analysing the problem, performing calculations to determine the answer.
3 Consider some cognitive actions from Chart B that are required to complete the question.	The question is complex. It asks for **analysis** of the data provided and complex problem solving. It requires a **determination** to be made based on the analysed data.
4 Make sure you know the meaning of every word in question or instruction.	**Determine** means to 'establish, conclude or ascertain after consideration, observation, investigation or calculation; decide or come to a resolution'. *QCAA definition*
5 Rephrase the question or instruction in your own words, elaborating on all the details required.	Rephrasing may involve writing as a question or instruction. For example: 'I know the person's mass, the volume of bath water, the target temperature of the person and of the bath water. I need to use all the data to calculate the temperature of the water in the bath before the person gets in the bath.'

ASSESSMENT TASKS AND COGNITIVE PROCESSES

Pearson Physics Queensland Student Book provides a solid foundation for undertaking all assessment tasks in the Syllabus. Comprehensive sets of key instructions, arranged by cognitive thinking levels, and mirroring the instructions of the examination, are provided at the end of each module and chapter.

Module reviews have tasks under Retrieval, Comprehension and Analysis.

Chapter review tasks cover these three levels as well as Knowledge utilisation.

In addition, **Unit reviews** provide the opportunity to consolidate and test you on a broader area of subject matter.

Mandatory practicals provide support in this skill area through practise in this cognitive level.

This approach will support you in developing the skills and level of application required to complete the assessment tasks.

You are required to complete the following assessment tasks:

a Data test
b Student experiment
c Research investigation
d Examination

The following charts provide an indication of the cognitive processes you should expect to encounter in each type of assessment task. Note that the student experiment and research investigation assessment tasks are designed for thinking at the highest cognitive levels. While retrieval, comprehension and analysis are required to complete these two assessment tasks, they are the underlying thinking levels necessary to complete the tasks; hence, the differences in the sizes of the ticks, with the largest tick indicating the focal cognitive thinking level.

Data test (IA1)				
Retrieval	**Comprehension**	**Analysis**	**Knowledge utilisation**	The task requires you to demonstrate thinking that is complex and at the high levels of analysis and knowledge utilisation. Retrieval and comprehension underlie the thinking so data can be analysed in the test.
✔	✔	✔	✔	

Student experiment (IA2)				
Retrieval	**Comprehension**	**Analysis**	**Knowledge utilisation**	The task requires you to demonstrate thinking that is complex and at a high level. Retrieval, comprehension and analysis underlie the experimenting and problem solving required for this task.
✔	✔	✔	✔	

Research investigation (IA3)				
Retrieval	**Comprehension**	**Analysis**	**Knowledge utilisation**	The task requires you to demonstrate thinking that is complex and at a high level. Retrieval, comprehension and analysis underlie the investigation and decision-making required for this task.
✔	✔	✔	✔	

The examination (EA) will include two papers. Each paper consists of a number of different types of items, including short and combination responses.

	Retrieval	**Comprehension**	**Analysis**	**Knowledge utilisation**	
Short response: • multiple choice • single-word • sentences • calculating using algorithms.	✔	✔	✔	✔	Short responses generally draw on factual subject matter in the retrieval and comprehension cognitive processes areas but may require analysis where calculations and data interpretation are involved.
Combination response: • short items requiring single-word, sentence or short paragraph responses • calculating using algorithms • interpreting graphs, tables or diagrams • responding to unseen data and/or stimulus.	✔	✔	✔	✔	The calculations and responses to unseen data move the cognitive processes required to the highest levels of thinking.

DEFINITIONS OF COGNITIVE VERBS

The list that follows provides definitions for cognitive verbs. Where available, the definitions are taken from the QCAA Syllabus. Those verbs whose definitions are not in the QCAA Syllabus appear in grey text. Refer to the list to clarify exactly what is required when any of these verbs appear in a question or instruction. Verbs are organised according to cognitive levels of thinking.

Increasing complexity of thinking levels

Level of thinking	Cognitive verb	Definition of cognitive verb
Retrieval: **processes of recognising, recalling, symbolising**	define	give the meaning of a word, phrase, concept or physical quantity; state meaning and identify or describe qualities
	demonstrate	prove or make clear by argument, reasoning or evidence, illustrating with practical example; show by example; give a practical exhibition
	describe	give an account (written or spoken) of a situation, event, pattern or process, or of the characteristics or features of something
	identify	distinguish; locate, recognise and name; establish or indicate who or what someone or something is; provide an answer from a number of possibilities; recognise and state a distinguishing factor or feature
	indicate	suggest, show or recommend a course of action
	label	Identify by applying a name to an object or person
	list	write the names of connected items, usually one below the other
	name	specify or give a label to an object or person
	paraphrase	use different words to convey the same meaning
	recall	remember; present remembered ideas, facts or experiences; bring something back into thought, attention or into one's mind
	recognise	identify or recall particular features of information from knowledge; identify that an item, characteristic or quality exists; perceive as existing or true; be aware of or acknowledge
	select	choose in preference to another or others; pick out
	show	provide the relevant reasoning to support a response
	state	express something definitely and clearly
	use	operate or put into effect; apply knowledge or rules to put theory into practice

Increasing complexity of thinking levels

Level of thinking	Cognitive verb	Definition of cognitive verb
Comprehension: **processes of integrating, symbolising**	calculate (e.g. numerical answer, mathematical processes)	work out using mathematical processes and determine by reasoning
	clarify	make clear or intelligible; explain: make a statement or situation less confused or more comprehensible
	comprehend (meaning)	understand the meaning or nature of; grasp mentally
	construct	create or put together (e.g. an argument) by arranging ideas or items; display information in a diagrammatic or logical form: make; build
	demonstrate	prove or make clear by argument, reasoning or evidence, illustrating with practical example; show by example; give a practical exhibition
	describe	give an account (written or spoken) of a situation, event, pattern or process, or of the characteristics or features of something
	determine	establish, conclude or ascertain after consideration, observation or calculation; decide or come to a resolution
	develop	elaborate, expand or enlarge in detail; add detail and fullness to; cause to become more complex or intricate
	discuss	examine by argument; sift the considerations for and against; debate; talk or write about a topic, including a range of arguments, factors or hypotheses; consider, taking into account different issues and ideas, points for and/or against, and supporting opinions or conclusions with evidence
	draw (visual depiction)	produce a picture, diagram or other visual representation
	explain	make an idea or situation plain or clear by describing it in more detail or revealing relevant facts; give an account; provide additional information
	illustrate	provide pictures, provide an example for a point being made
	implement	put something into effect, e.g. a plan or proposal
	recognise	identify or recall particular features from knowledge; identify that an item, characteristic or quality exists; perceive as existing or true; be aware of or acknowledge
	represent	scientific representations are a verbal, physical or mathematical demonstration of understanding of a science concept or concepts; a concept can be represented in a range of ways and using multiple models (ACARA 2015c)
	select	choose in preference to another or others; pick out
	show	provide the relevant reasoning to support a response
	summarise	give a brief statement of a general theme or major point/s; present ideas and information in fewer words and in sequence
	symbolise	represent or identify by a symbol or symbols
	understand	perceive what is meant by something; grasp; be familiar with (e.g. an idea); construct meaning from messages, including oral, written and graphic communication
	use (models)	operate or put into effect; apply knowledge or rules to put theory into practice

Increasing complexity of thinking levels

Level of thinking	Cognitive verb	Definition of cognitive verb
Analysis: **processes of matching, classifying, analysing errors, generalising, specifying**	analyse	dissect to ascertain and examine constituent parts and/or their relationships; break down or examine in order to identify the essential elements, features, components or structure; determine the logic and reasonableness of information; examine or consider something in order to explain and interpret it, for the purpose of finding meaning or relationships and identifying patterns, similarities and differences
	apply	use knowledge and understanding in response to a given situation or circumstance; carry out or use a procedure in a given or particular situation
	assess	measure, determine, evaluate, estimate or make a judgment about the value, quality, outcomes, results, size, significance, nature or extent of something
	calculate	work out using mathematical processes and determine by reasoning.
	categorise	place in or assign to a particular class or group; arrange or order by classes or categories; classify, sort out, sort, separate
	classify	arrange, distribute or order in classes or categories according to shared qualities or characteristics
	compare	display recognition of similarities and differences and recognise the significance of these similarities and differences
	conclude	make a judgment based on evidence (ACARA 2015c)
	consider	think deliberately and carefully about something, typically before making a decision; taking something into account when making a judgment; view attentively or scrutinise; reflect on
	contrast	display recognition of differences by deliberate juxtaposition of contrary elements; show how things are different or opposite; give an account of the differences between two or more items or situations, referring to both or all of them throughout
	critique	review (e.g. a theory, practice, performance) in a detailed, analytical and critical way
	deduce	reach a conclusion that is necessarily true, provided a given set of assumptions is true; arrive at, reach or draw a logical conclusion from reasoning and the information given
	derive	arrive at a reasoning: manipulate a mathematical relationship to give a new equation or relationship; in mathematics, obtain the derivative of a function
	determine	establish, conclude or ascertain after consideration, observation, investigation or calculation; decide or come to a resolution
	develop	elaborate, expand or enlarge in detail; add detail and fullness to; cause to become more complex or intricate
	devise	think out; plan; contrive; invent
	diagnose	identify the nature of a problem or illness
	differentiate	identify the difference/s in or between two or more things; distinguish, discriminate; recognise or ascertain what makes something distinct from similar things; in mathematics, obtain the derivative of a function
	discriminate	note, observe or recognise a difference; make or constitute a distinction in or between; differentiate; note or distinguish as different
	discuss	examine by argument; sift the considerations for and against; debate; talk or write about a topic, including a range of arguments, factors or hypotheses; consider, taking into account different issues and ideas, points for and/or against, and supporting opinions or conclusions with evidence
	distinguish	recognise as distinct or different; note points of difference between; discriminate; discern; make clear a difference/s between two or more concepts or items
	draw conclusions (conclusion)	a judgment based on evidence (ACARA 2015c)
	edit	correct written material by careful checking
	evaluate	make an appraisal by weighing up or assessing strengths, implications and limitations; make judgments about ideas, works, solutions or methods in relation to selected criteria; examine and determine the merit, value or significance of something, based on criteria
	experiment	try out or test new ideas or methods, especially in order to discover or prove something; undertake or perform a scientific procedure to test a hypothesis, make a discovery or demonstrate a known fact

Increasing complexity of thinking levels

Level of thinking	Cognitive verb	Definition of cognitive verb
Analysis: **processes of matching, classifying, analysing errors, generalising, specifying** *(continued)*	explore	look into both closely and broadly; scrutinise; inquire into or discuss something in detail
	extrapolate	infer or estimate by extending or projecting known information; conjecture; infer from what is known; extend the application of something (e.g. a method or conclusion) to an unknown situation by assuming that existing trends will continue or similar methods will be applicable
	hypothesise	formulate a supposition to account for known facts or observed occurrences; conjecture, theorise, speculate; especially on uncertain or tentative grounds
	identify (categories, errors, problems)	recognise and establish things such as groupings of similar items, mistakes or issues
	infer	derive or conclude something from evidence and reasoning, rather than from explicit statements; listen or read beyond what has been literally expressed; imply or hint at
	interpret	use knowledge and understanding to recognise trends and draw conclusions from given information; make clear or explicit; elucidate or understand in a particular way; bring out the meaning of, e.g. a dramatic or musical work, by performance or execution; bring out the meaning of an artwork by artistic representation or performance; give one's own interpretation of; identify or draw meaning from, or give meaning to, information presented in various forms, such as words, symbols, pictures or graphs
	judge	form an opinion or conclusion about; apply both procedural and deliberative operations to make a determination
	organise	arrange, order; form as or into a whole consisting of interdependent or coordinated parts, especially for harmonious or united action
	predict	give an expected result of an upcoming action or event; suggest what may happen based on available information
	reflect (on)	think about deeply and carefully
	scrutinise	to examine closely or critically (Macquarie 2015)
	sort	arrange in prescribed groupings or order

Increasing complexity of thinking levels

Level of thinking	Cognitive verb	Definition of cognitive verb
Knowledge utilisation: processes of investigating, experimenting, decision-making, problem-solving	adapt	modify or change something for a new purpose or use
	appraise	valuate the worth, significance or status of something; judge or consider a text or piece of work
	appreciate	recognise or make a judgment about the value or worth of something; understand fully; grasp the full implications of
	argue	give reasons for or against something; challenge or debate an issue or idea; persuade, prove or try to prove by giving reasons
	assess	measure, determine, evaluate, estimate or make a judgment about the value, quality, outcomes, results, size, significance, nature or extent of something
	comment	express an opinion, observation or reaction in speech or writing; give a judgment based on a given statement or result of a calculation
	conclude (conclusion)	make a judgment based on evidence (ACARA 2015c)
	conduct	direct an action or course; manage; organise; carry out
	construct	create or pull together (e.g. an argument) by arranging ideas or items; display information in a diagrammatic or logical form; make; build
	convince (convincing)	persuade by argument or proof; leaving no margin of doubt; clear; capable of causing someone to believe that something is true or real; persuading or assuring by argument or evidence; appearing worthy of belief; credible or plausible
	create	bring something into being or existence; produce or evolve from one's own thought or imagination; reorganise or put elements together into a new pattern or structure or to form a coherent or functional whole
	decide	reach a resolution as a result of consideration; make a choice from a number of alternatives
	design	produce a plan, simulation, model or similar; plan, form or conceive in the mind; in English, select, organise and use particular elements in the process of text construction for particular purposes; these elements may be linguistic (words), visual (images), audio (sounds), gestural (body language), spatial (arrangement on the page or screen) and multimodal (a combination of more than one)
	determine	establish, conclude or ascertain after consideration, observation, investigation or calculation; decide or come to a resolution
	develop	elaborate, expand or enlarge in detail; add detail and fullness to; cause to become more complex or intricate
	devise	think out; plan; contrive; invent
	discuss	examine by argument; sift the considerations for and against; debate; talk or write about a topic, including a range of arguments, factors or hypotheses; consider, taking into account different issues and ideas, points for and/or against, and supporting opinions or conclusions with evidence
	draw conclusions (conclusion)	make a judgment based on evidence (ACARA 2015c)
	evaluate	make an appraisal by weighing up or assessing strengths, implications and limitations; make judgments about ideas, works, solutions or methods in relation to selected criteria; examine and determine the merit, value or significance of something, based on criteria
	experiment	try out or test new ideas or methods, especially in order to discover or prove something; undertake or perform a scientific procedure to test a hypothesis, make a discovery or demonstrate a known fact
	explore	inquire into something or discuss in detail
	generate	produce; create; bring into existence
	hypothesise	formulate a supposition to account for known facts or observed occurrences; conjecture, theorise, speculate; especially on uncertain or tentative grounds
	investigate	carry out an examination or formal inquiry in order to establish or obtain facts and reach new conclusions; search, inquire into, interpret and draw conclusions about data and information

Increasing complexity of thinking levels

Level of thinking	Cognitive verb	Definition of cognitive verb
Knowledge utilisation: **processes of investigating, experimenting, decision-making, problem-solving** *(continued)*	judge	form an opinion or conclusion about; apply both procedural and deliberative operations to make a determination
	justify	give reasons or evidence to support an answer, response or conclusion; show or prove how an argument, statement or conclusion is right or reasonable
	make decisions	select from available options; weigh up positives and negatives of each option and consider all the alternatives to arrive at a position
	manipulate	adapt or change to suit one's purpose
	modify	change the form or qualities of; make partial or minor changes to something
	persuade (persuasive)	capable of changing someone's ideas, opinions or beliefs; appearing worthy of approval or acceptance; (of an argument or statement) communicating reasonably or credibly
	predict	give an expected result of an upcoming action or event; suggest what may happen based on available information
	propose	put forward (e.g. a point of view, idea, argument, suggestion) for consideration or action
	prove	use a sequence of steps to obtain the required result in a formal way
	research	to locate, gather, record, attribute and analyse information in order to develop understanding (ACARA 2015c)
	resolve	in the Arts, consolidate and communicate intent through a synthesis of ideas and application of media to express meaning
	solve	find an answer to, explanation for, or means of dealing with (e.g. a problem); work out the answer or solution to (e.g. a mathematical problem); obtain the answer/s using algebraic, numerical and/or graphical methods
	synthesise	combine different parts or elements
	test	take measures to check the quality, performance or reliability of something

CHAPTER

01 Physics skills and assessment toolkit

This chapter provides important information and support in the study of the QCAA Physics syllabus for Units 1 and 2.

The Physics Skills and Assessment Toolkit is designed to be used as a reference tool. It should be consulted on a need-to-know basis, where relevant, during this course of study. It is not intended that this chapter be worked through as a whole.

Focus

The chapter focuses on providing support and guidance in:

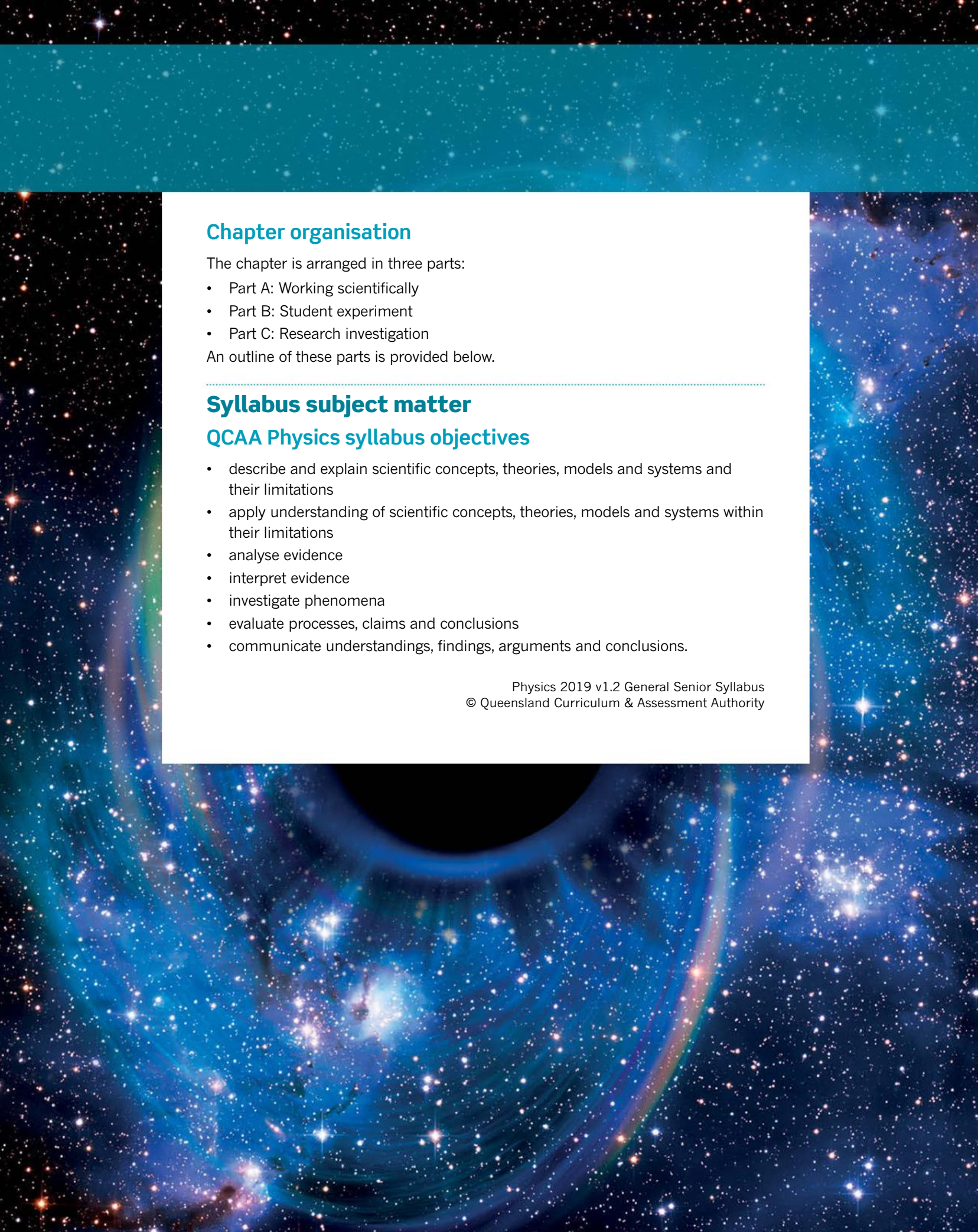
- Development and application of scientific skills
  - Mathematical and statistical processes used in physics
  - SI units
  - Visual representations
  - Graphical representations
  - Measurement—errors and uncertainty
- Completing the assessment tasks
  - Preparation in skill development
    - Understanding, analysing, interpreting data and statistics
  - Student experiment
    - Developing the experiment question or hypothesis
    - Considering variables, risks, types of data
    - Planning methodology
    - Presenting, analysing and interpreting data
    - Writing the scientific report
  - Research investigation
    - Understanding and analysing claims
    - Developing research questions
    - Strategies to evaluate resources
    - Note-taking
    - Writing a scientific report

Assessment

In Units 1 and 2, students are required to complete at least two and no more than four assessment tasks developed by the teacher. At least one assessment task must be completed per unit. In preparation for Physics Units 3 and 4, teachers may choose to mirror some of the assessment requirements of Units 3 and 4, in assessing Units 1 and 2.

The support material in this chapter is based on requirements in Units 3 and 4, and relates to the following assessments:

- Student experiment (Internal Assessment 2: IA2)
- Research investigation (Internal Assessment 3: IA3)



Chapter organisation

The chapter is arranged in three parts:

- Part A: Working scientifically
- Part B: Student experiment
- Part C: Research investigation

An outline of these parts is provided below.

Syllabus subject matter

QCAA Physics syllabus objectives

- describe and explain scientific concepts, theories, models and systems and their limitations
- apply understanding of scientific concepts, theories, models and systems within their limitations
- analyse evidence
- interpret evidence
- investigate phenomena
- evaluate processes, claims and conclusions
- communicate understandings, findings, arguments and conclusions.

Physics 2019 v1.2 General Senior Syllabus
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Part A: Working scientifically

The focus of Part A is on basic mathematical skills and their applications to physics. It features many worked examples and opportunities to apply these skills throughout the modules. These skills are assessed in a range of assessment tasks, directly and indirectly, and drawn upon to analyse data in experiments and investigations.

Engage with Part A in order to help prepare yourself with the skills you will need in the data test, and when undertaking a range of mandatory and suggested practicals. You will also find these skills useful when completing sections of the student experiment, research investigation and the examination.

Refer to the following outline of Part A: Working scientifically to learn, revise or practise skills in the areas in which you need help.

Module	Look here for	eBook page
1.2 Orders of magnitude and estimation	• writing numbers into and out of scientific notation • estimating the value of a quantity using its order of magnitude • estimating the value of a quantity of calculation • examples of calculations	e15
1.3 Mathematical basics for physics	• examples of maths used in physics • basic mathematical operations using percentages and fractions • rearranging and substituting formulas using algebraic rules and the index laws • use of trigonometric ratios to determine side lengths and angles of right-angled triangles • use of formulas for curved shapes to approximately calculate the areas, surface areas and volumes of more complex objects	e22
1.4 Units and prefixes	• the International System (SI) of units • the seven fundamental units, their symbols and definitions • differentiation between fundamental and derived units • the SI prefixes are multipliers of powers of ten of the base units • converting between various units of the same type using SI and some non-SI units	e28
1.5 Uncertainties in measurement	• explanations of the terms uncertainty, error, accuracy, precision • differentiating between accuracy and precision • calculations using significant figures • differences between mistakes, systematic uncertainties and random uncertainties • determining the limit of reading and absolute uncertainty of an analog and a digital instrument • converting between absolute, fractional and percentage uncertainties • performing propagation of uncertainties including addition, subtraction, multiplication, division and powers of measurements and their uncertainties	e34
1.6 Graphing	• predicting relationships between variables or finding outliers in data • displaying data, including error bars, line of best fit, minimum and maximum lines of primary or secondary data • the common types of graphs or relationships seen in physics and examples of each • linearising data that is not already producing a straight line graph • using the equation of a straight line of best fit to determine the gradient and *y*-intercept • using the gradient and *y*-intercept in further processing of data • using the minimum and maximum lines to calculate an uncertainty in the gradient and *y*-intercept	e50

GO TO ➤ your R+ eBook to access Chapter 1 Physics Skills and Assessment Toolkit.

Part B: Student experiment

The focus of Part B is on the student experiment. This internal assessment task requires you to follow the full scientific method over an extended and defined period of time. You will develop your own research question or hypothesis to investigate, based on an initial practical already completed in class.

Part B supports you through all aspects of the student experiment. The QCAA syllabus objectives and instrument-specific marking guide (ISMG) for the assessment are explained.

Engage with Part B for examples of how to modify, extend, refine or redirect the initial practical and write a research question or hypothesis. Be guided by the step-by-step instructions to evaluate the quality of your research question or hypothesis. Delve into particular sections of Part B as needed, to reinforce your knowledge and understanding of scientific methodology.

Refer to Part B for support on data types, data collection and analysis of data to draw valid conclusions. This includes how to identify errors in data, validity and relationships between data. Be guided in the write-up of your scientific report with support material on scientific writing style, and the structure of the report. Refer to the following outline of Part B: Student experiment to learn, revise or practise skills in the areas you need.

Module	Look here for	eBook page
1.7 Research and planning	• identifying and explaining the difference between controlled, measured, independent and dependent variables • developing a research question or hypothesis • evaluating research questions and hypotheses • using a scientific journal to record experiments and experimental data • planning, evaluating and refining scientific experiments • explaining what validity and reliability mean in relation to experimentation • explanations of qualitative and quantitative data • characterising qualitative data as either nominal or ordinal • characterising quantitative data as either discrete or continuous • explanations of replication and repeat trials • conducting risk assessments for planned experiments • recognising common chemical Globally Harmonised System of classification (GHS) codes and symbols • understanding the criteria against which research and planning will be assessed	e70
1.8 Conducting and experimenting	• determining relevant data that is needed to test a research question or hypothesis • determining what is considered to be sufficient data to test a research question or hypothesis • selecting appropriate equipment to collect relevant and sufficient data	e90
1.9 Results	• analysing raw data to produce processed data • interpreting data to draw valid conclusions • identifying errors • analysing precision	e96
1.10 Communicating and writing a scientific report	• sections of a report • scientific writing style • writing a scientific report • acknowledging sources • addressing the ISMG	e101

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Part C: Research investigation

The focus of Part C is on the research investigation. This internal assessment task requires you to gather secondary evidence on a research question over an extended and defined period of time. You will develop your own research question to investigate, based on a claim (provided by your teacher) related to the course.

Part C supports you through all aspects of the research investigation. The QCAA syllabus objectives and instrument-specific marking guide (ISMG) for the assessment are explained.

Engage with Part C for assistance with writing your research question. Delve into the examples of claims and their analysis for context and elements to guide you in developing your own research question. Be guided by the information about locating and evaluating suitable secondary sources for the research. This includes how to identify errors in data, validity and relationships between data. Part C will assist you in the writing of your scientific report, with support material on the scientific writing style and the structure of the report. Part C provides a brief overview of different ways to present your report and provides details on the literature review format.

Refer to the following outline of Part C: Research investigation to learn, revise or practise skills in the areas in which you need help.

Module	Look here for	eBook page
1.11 Developing the research question from a claim	• analysing a claim • identifying variables and measureable terms in the claim • examples of claims and questions developed from them • guidelines for developing a question • developing a research question • refining a research question	e111
1.12 Finding and choosing suitable resources	• difference between primary and secondary sources • locating resources • determining reliability and validity of resources	e116
1.13 Research: taking and organising notes	• recording notes in a scientific journal • paraphrasing information • different ways to record information • recording data and results • recording information about sources	e124
1.14 Writing a report for the research investigation	• different ways to present the report • presenting the report as a literature review • features of a literature review • structure of the literature review	e130

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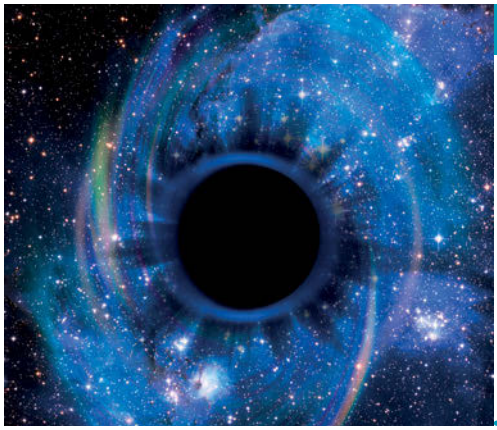
1.1 Physics



BY THE END OF THIS MODULE, YOU SHOULD BE ABLE TO:

- understand and appreciate that physics is a fundamental science, and its capacity to ask the 'big' questions makes it incredibly interesting
- appreciate that physics uses mathematics as its language
- understand that physics uses natural laws, theories, models and principles to describe real phenomena
- recall the major branches of physics
- explain how a vast number of professions use some aspect of physics
- appreciate that physics is a dynamic and evolving branch of science, and that not every problem has been solved.

Physics is the study of motion, forces and energy. It is the most **fundamental** science. It deals with the laws, theories and principles governing force, energy and motion across all imaginable scales throughout the universe. These range from the interactions between particles that make up the individual protons and neutrons inside every atomic nucleus, to the motions of galaxies that comprise the universe itself. Physics is full of history and amazing discoveries and famous scientists, such as the person in Figure 1.1.1, who developed many of the concepts contained in this book.

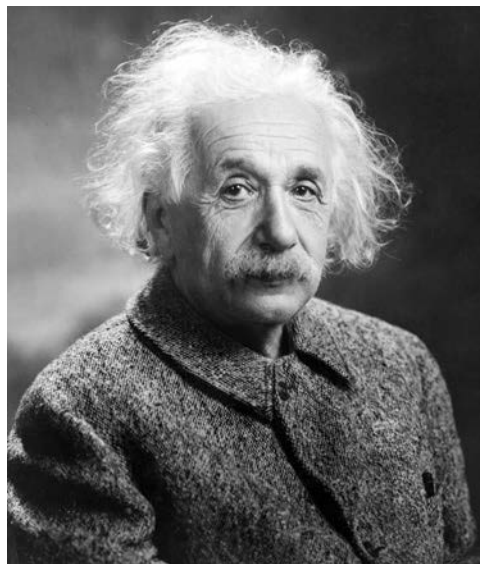


FIGURE 1.1.1 Perhaps the most famous physicist of all time, Albert Einstein, helped change our understanding of the laws of physics in the early 20th century.

WHAT IS PHYSICS?

The wonder of physics lies in its ability to ask the 'big' questions, such as:

- Where did the universe come from? To date, our best theory is the Big Bang theory (Figure 1.1.2).
- Does the universe have an end?
- Are we alone in the universe, or is the universe full of intelligent, alien civilisations (Figure 1.1.3)?
- What is matter made up of?
- Is there a single theory or equation that can describe everything?

Interestingly, the answers to these questions are still unknown, but perhaps you will be inspired to try to answer them.

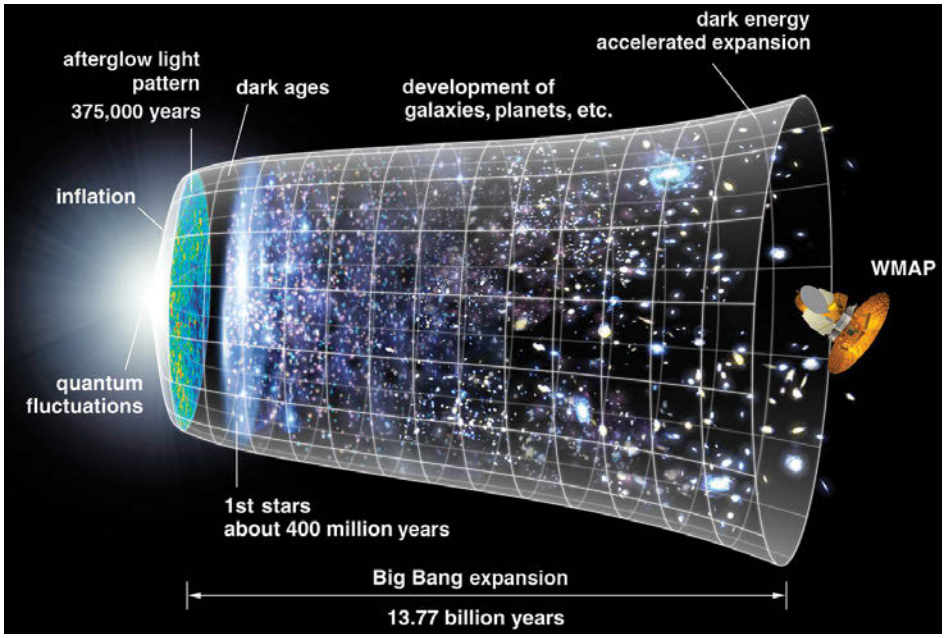


FIGURE 1.1.2 Fourteen billion years of history of the universe. The Big Bang theory for the creation of the universe is shown on the far left. The present-day universe is on the far right, along with a satellite called the Wilkinson Microwave Anisotropy Probe (WMAP), which collected data to help piece together the theory.

FIGURE 1.1.3 An artist's illustration of a planet being destroyed as it orbits a very strange star in our galaxy called 'Tabby's Star'. The light from this star appears to randomly fluctuate and currently defies all known explanations. The latest theory is that it is likely due to an uneven dust cloud moving around the planet.

THE LANGUAGE OF PHYSICS

Physics uses the language of mathematics in order to make logical sense of the universe, using models and theories to explain natural **phenomena**. If it is not supported by observations and experiments, then the model or theory is rejected and a new theory takes its place.

If a ladder showing the level of fundamental explanations of the natural world is made, as in Figure 1.1.4, physics would be on the second-bottom rung, second only behind mathematics in the way it can describe the basic interactions in the natural world.

All other sciences have their basis in some aspect of physics. For example, an understanding of how chemical bonding works can be explained by the laws of electrostatic forces and the theory of quantum mechanics.

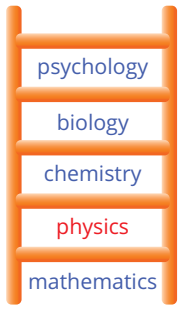


FIGURE 1.1.4 Physics uses mathematics to explain how the natural world works. Chemistry uses the laws of physics to explain matter and the interactions of matter, whereas biology and psychology use the products of chemical reactions to explain the living world.

Physics had its origins more than 5000 years ago when the ancient Babylonians recorded the positions of stars, planets and comets, so it is generally considered that astronomy (a major branch of physics) is the oldest science. In the 21st century, physics is used in almost every aspect of science. One of the newest branches of physics is gravitational wave astrophysics, which originated with Albert Einstein in 1916 and was only confirmed with data in 2016.

Since Einstein's time, physicists have refined their understanding of the universe. Most of the time, physicists have used that body of knowledge to improve the lives of humans and the other organisms that share this planet.

Physics can be roughly divided into four domains, depending on the size of the objects that are interacting and how fast they travel. Each domain has several branches stemming from historical advances in thinking or in experimental results, as shown in Figure 1.1.5.

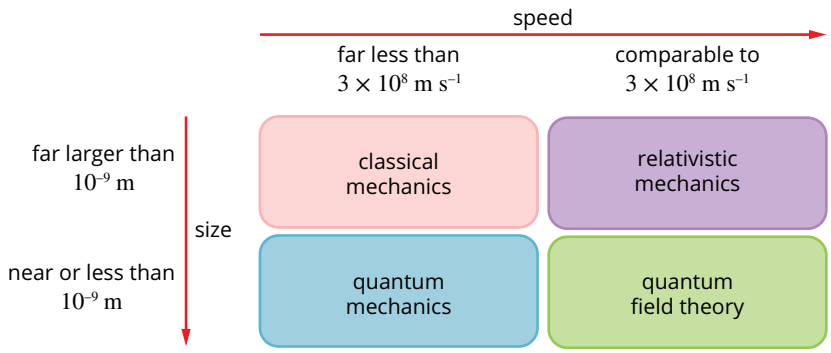


FIGURE 1.1.5 The four domains of physics describe matter and energy of various sizes moving at various speeds.

Classical mechanics is the first branch of physics. It deals with the forces, energy, gravity and motion of everyday objects, planets, stars and galaxies as long as they are not moving at close to the speed of light. Most of the physics you will study in Years 11 and 12 comes from classical mechanics, or the view of the universe given to us by Isaac Newton from the 17th century.

Quantum mechanics is the second branch of physics. In Units 3 and 4 you will touch on the 'modern' view of physics by exploring quantum mechanics, or the strange world of light and very small particles such as the atom and its constituents. Physicists formulated these theories in the early 20th century. Quantum mechanics has been described as the most accurate and precise scientific theory ever written, but it does not include gravity in its formulation.

Relativistic mechanics is the third branch of physics. In Units 3 and 4 you will explore part of the bizarre and counterintuitive world of relativistic mechanics brought to us by Albert Einstein also at the beginning of the 20th century. Relativistic mechanics deals with the motion, gravity and energies of all objects larger than an atom when they travel at speeds approaching the speed of light.

Physics deals with very light and very heavy objects that travel slowly, at, or near the speed of light.

Quantum field theory (QFT) is the fourth branch of physics. It is a combination of the theories of the very small (quantum mechanics) and very fast (relativistic mechanics). The mathematics of QFT is beyond high school level and you will not explore this in any detail.

To date, nobody has come up with a successful unification or grand unified theory (GUT) of these four aspects of physics. The GUT would have to describe the entire universe at every scale and speed, and make measurable predictions that can be tested with experiments. In other words, the physics of very small objects moving very fast under gravity is yet to be understood. For example, at the very centre of a black hole, known as the singularity, the laws of physics break down because we do not yet understand how small particles behave under the influence of strong gravity.

String theory describes everything in the universe as a tiny vibrating string of energy (Figure 1.1.6). It is a possible GUT, but so far has not been used to make measurable predictions.

FIGURE 1.1.6 String theory describes everything in the universe as a tiny, vibrating string whose frequency determines if the object is a particle of matter or a wave of energy.

BRANCHES OF PHYSICS

Using the four domains of physics, Figure 1.1.7 shows all of the branches of physics you will study in this course. These branches are briefly explained in Table 1.1.1, which also lists some of the famous people who worked in them.

The major branches of physics are mechanics, thermodynamics, atomic and nuclear physics, electromagnetism, waves and relativity.

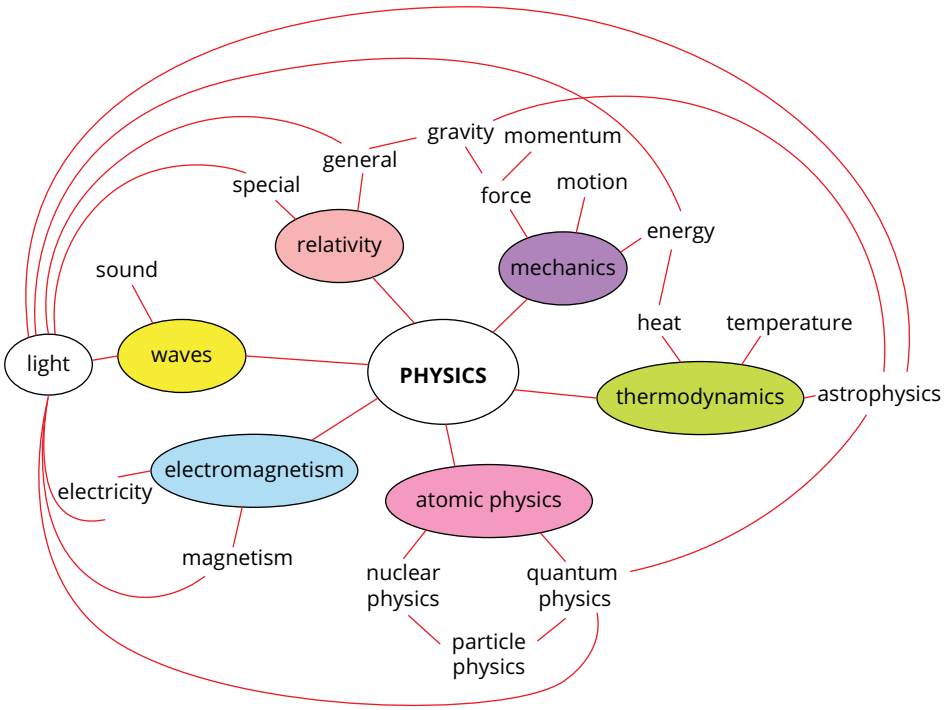


FIGURE 1.1.7 This non-exhaustive concept map shows the branches of physics and the links between their concepts.

TABLE 1.1.1 A brief description of the branches of physics

Branch of physics	What it explains	Famous people involved in the branch
mechanics	motion, forces, gravity and energy	Isaac Newton, Galileo, Nicolas Copernicus, Johannes Kepler, Robert Hooke, Blaise Pascal
thermodynamics	temperature, heat, matter and the combination of these to provide motion	James Joule, Ludwig Boltzmann, Sadi Carnot, Felix Wankel, Rudolf Diesel
waves	sound, light and how energy moves from one location to another	Isaac Newton, Max Planck, Christiaan Huygens, Christian Doppler, Heinrich Hertz
electromagnetism	electricity, current, voltage and magnets, motors and generating electrical power	James Clerk Maxwell, Michael Faraday, Nikolai Tesla, Andre-Marie Ampere
atomic and nuclear physics	the atom, nucleus, particles that make up the nucleus and how they interact with other matter and light	Marie Curie, Albert Einstein, Niels Bohr, Ernest Rutherford, Max Planck, Stephen Hawking, Richard Feynman
relativity	how the laws of physics above change when particles move very fast or when particles become close to a very large but dense object	Albert Einstein, Galileo, Hendrik Lorentz

WHAT PHYSICISTS DO

Physics uses mathematics to explain the natural world in terms of models, theories, laws and principles.

Physicists use models, theories and laws to explain the universe in terms of mathematical symbols. In order to check and refine their theories, they carry out experiments, collect data and analyse their results. Their theories are then changed or refined according to their results.

A physics **model** is a way of visualising a particular physical phenomenon that is quite often impossible to imagine in the real world. It may or may not be entirely correct.

Examples of models:

- the wave model of light
- the particle model of light.

A physics **theory** is a model that is more mathematically rigorous. It uses mathematical formulas to predict the behaviour of the model. Again, it may or may not be correct, but the phenomenon it describes is real.

Examples of theories:

- Newton's theory of gravity
- Einstein's general theory of relativity.

A physical **law** is a general statement that is found to be experimentally true over a large range of observed phenomena. It describes how nature behaves. A principle is a law but is more specific in its scope.

Examples of laws:

- Newton's three laws of motion
- Archimedes' principle.

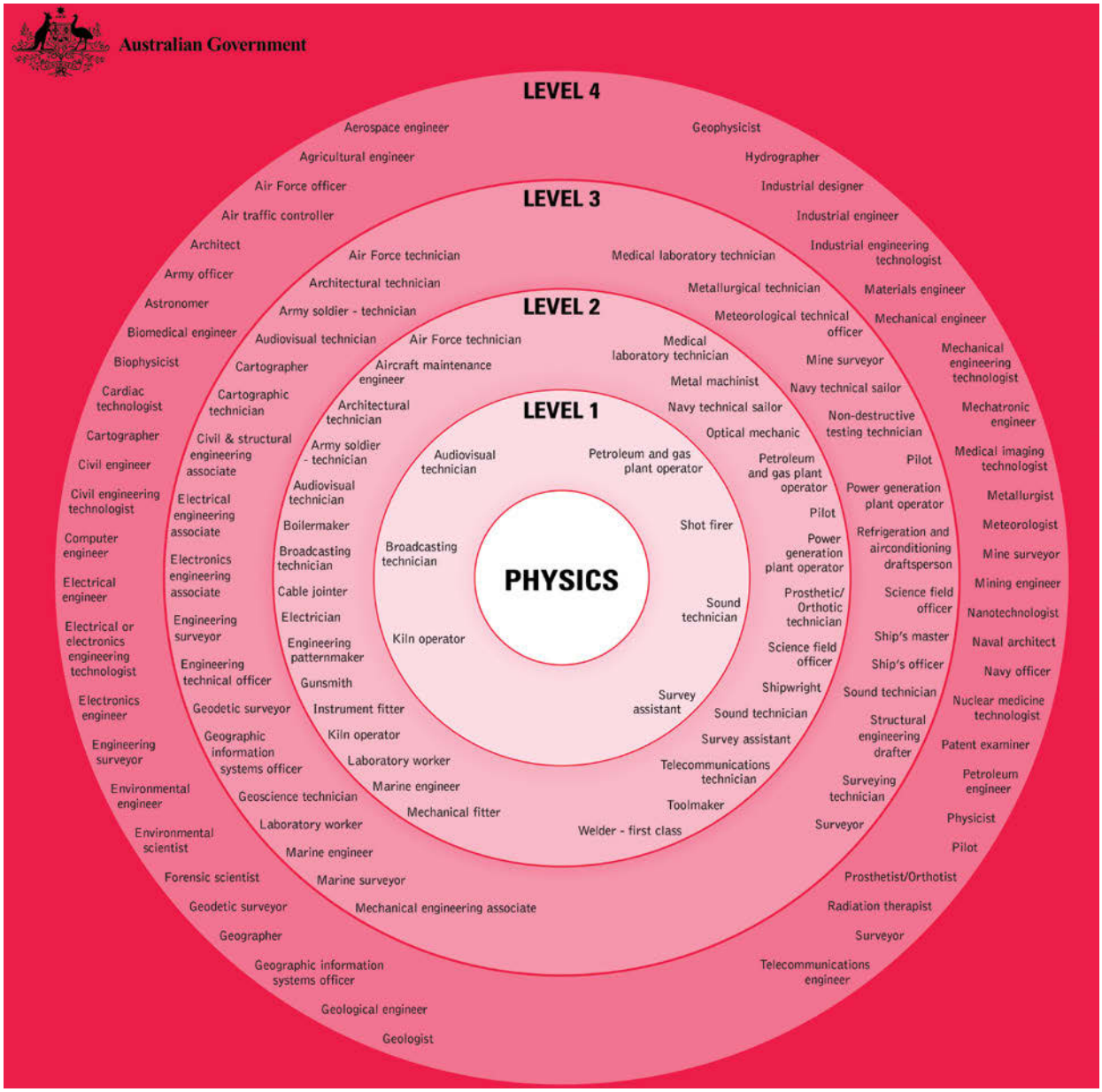
Who uses physics?

Physics is the most fundamental science and explains how the laws of nature work, so anyone that uses technology is using some aspect of physics. Examples of some of the many occupations that use physics either directly or indirectly are given in Table 1.1.2. Figure 1.1.8 lists examples for vocations related to physics.

TABLE 1.1.2 Some examples of the branches of physics used in various professions

Profession	Aspect of physics used
archaeologists	nuclear physics used in carbon dating
astronomers	all aspects of relativity, light and gravity
climate scientists	forces, thermodynamics
dentists	forces, thermodynamics and light
doctors	forces, nuclear physics, atomic physics, waves, electromagnetism (see Figure 1.1.9)
electricians	electromagnetism
engineers (civil, mechanical, electrical, sound, optical, aerospace, materials, mining)	all aspects of physics
geologists	gravity, thermodynamics, atomic physics
journalists	all aspects of physics
nurses	forces, nuclear physics, atomic physics, magnetism, waves
people in information technology	electromagnetism, atomic physics
people in sports medicine	forces, thermodynamics
people in the defence forces	forces, motion, electromagnetism, thermodynamics, waves
people in the film industry	forces, light, sound, electromagnetism
pilots	mechanics, thermodynamics, electromagnetism
police officers	electromagnetism, thermodynamics, waves, mechanics (Figure 1.1.10)
veterinarians	forces, nuclear physics, atomic physics, magnetism, waves
video game designers	waves, thermodynamics, mechanics, gravity (Figure 1.1.11)

Almost every profession on Earth uses some aspect of a law of physics.



Do you enjoy or are you good at physics?
Have you considered the occupations above?

FIGURE 1.1.8 Examples of careers in fields related to physics

FIGURE 1.1.9 A medical physicist prepares a patient for a scan in a magnetic resonance imaging (MRI) machine.

FIGURE 1.1.10 Police use physics to determine the speed and direction of vehicles involved in traffic accidents.

FIGURE 1.1.11 Physics plays a central role in the animation of many video games and developers need to know the laws of physics to accurately represent motion in their games.

Physics forms the basis of all of our technology, as shown in Figure 1.1.11. If it wasn't for a physicist somewhere, there would be no mobile phones, internet, cars, aircraft, TV, electricity, calendars, space exploration or fidget spinners!

THE WORK OF SCIENTIFIC RESEARCH

The foundation of all sciences, including physics, is scientific research. Scientific research works in the unknown to develop new understanding. To build evidence, it may take years and many experiments. In interpreting scientific evidence, scientists endeavour to establish models, theories, laws, principles and facts. These are illustrated in Figure 1.1.12. It is important to note that all these deductions change over time as knowledge develops.

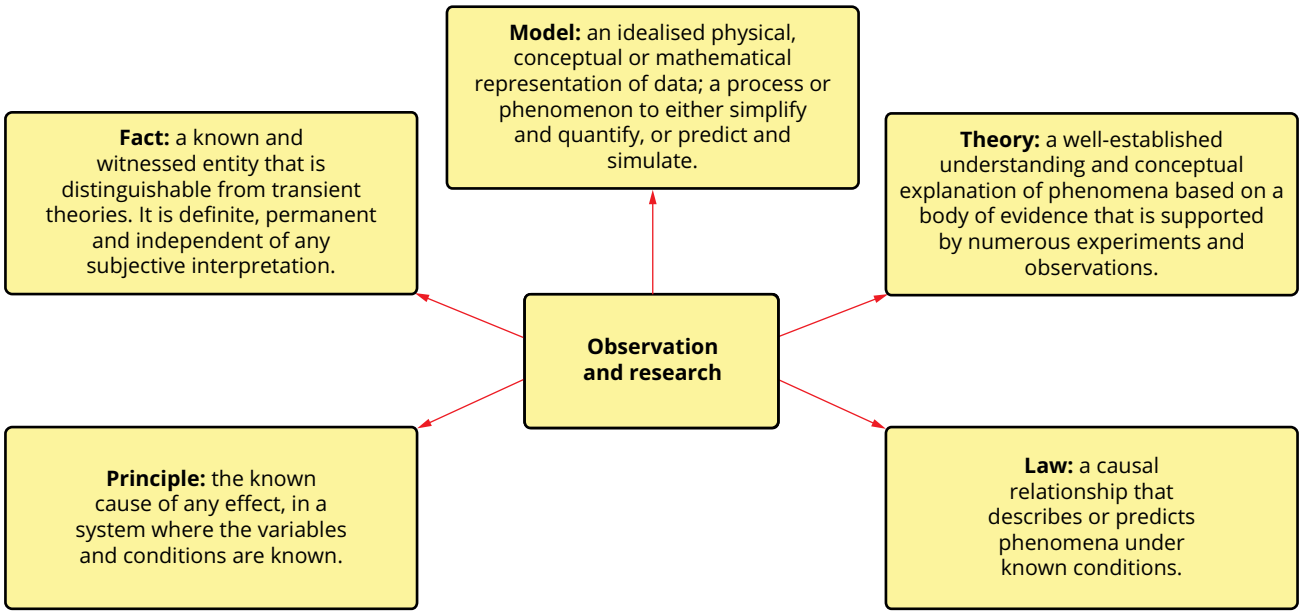


FIGURE 1.1.12 Scientific research and observations are used to develop facts, principles, laws, theories and models.

1.1 Review

SUMMARY

- Physics is the most fundamental science in the way it explains the basic laws of nature.
- Physics uses mathematics as its language.
- A physics model is a visual way of describing an invisible natural phenomenon.
- A physics theory is a mathematical description of a natural phenomenon.
- A law of physics is a general statement that is found to be experimentally true over a large range of observations.
- A physics principle is a law of physics that is more specific in its context.
- Major branches of physics are mechanics, thermodynamics, atomic and nuclear physics, electromagnetism, waves and relativity.
- A vast number of professions use some aspect of physics.
- Physics is a dynamic and evolving branch of science.

KEY QUESTIONS

Retrieval

1 Name a model used in physics.

2 Name a law of physics.

3 Name the six major branches of physics.

4 The concept of a field, as used in physics, describes a force exerted on an object without actual physical contact. Name as many different types of fields as you can.

Comprehension

5 Explain why mathematics is the language of physics.

6 Identify the major branch of physics that has been left out of the quantum aspects of physics, but is a major part of classical and relativistic mechanics.

7 Name a famous physicist who worked in the following branches of physics:

a gravity
b nuclear physics
c particle physics or black holes
d electromagnetism
e astronomy or astrophysics
f thermal physics or thermodynamics
g relativity.

8 Explain how police use physics.

9 Explain how doctors use physics.

10 Explain why light is linked to many branches of physics.

Analysis

11 Differentiate between a principle and a law.

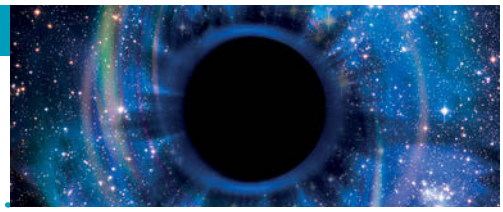
12 Explain why the captain of a ship must know some aspects of physics to keep the passengers safe.

The section focuses on the basic mathematical skills and applications that will be useful for the data test and required for a range of mandatory and suggested practicals as well as the student experiment.

1.2 Orders of magnitude and estimation

BY THE END OF THIS MODULE, YOU SHOULD BE ABLE TO:

- write numbers into and out of scientific notation
- estimate the value of a quantity using its order of magnitude
- estimate the value of a quantity of calculation.



Physics is a science that deals with very large and very small numbers. A number written using all of its zeros as placeholders is written in long form. For example:

- the mass of Earth has been *calculated*: 5 972 000 000 000 000 000 000 000 kg
- the mass of a carbon atom has been *measured*: 0.000 000 000 000 000 000 000 000 0199 kg.

Writing these numbers out the long way every time you do a calculation would be very inefficient, so physicists use scientific notation as a short cut to writing very big and small numbers.

Note that 'scientific notation', 'standard notation' and 'standard form' all have the same meaning.

SCIENTIFIC NOTATION

Recall from mathematics that a number in scientific notation is written as:

$$a \times 10^b$$

where

- a is the coefficient, and is a real number between 1 and 10
- b is the exponent, and is an integer (either positive or negative).

For $a \times 10^b$:

- if b is positive, then the number is greater than 1
- if b is negative then the number is less than 1.

Scientific notation, $a \times 10^b$, is used extensively in physics and is the way of writing very large or very small numbers in a short, convenient way.

Writing numbers in scientific notation

Table 1.2.1 shows how to write numbers from long form or basic numeral into scientific notation. Figure 1.2.1 shows that very large numbers sometimes occur in non-natural aspects of the world.

TABLE 1.2.1 How to write numbers from long form into scientific notation

If the number in long form is:	The exponent is:	The coefficient is:	Example
larger than 1	equal to the number of placeholders after the first digit and before the decimal point	equal to the digits in the number with a decimal point placed between the first and second digits	123 400 in long form is written as 1.234×10^5 in scientific notation
smaller than 1	equal to the negative value of the number of zeros before the first non-zero digit (including the zero to the left of the decimal place in the units column)	equal to the digits in the number after the first non-zero digit with a decimal point placed between the first and second digits	0.000 012 34 in long form is written as 1.234×10^{-5} in scientific notation

FIGURE 1.2.1 This is a Zimbabwean banknote from 2008 with a face value of one hundred trillion dollars, or \$100 000 000 000 000. Written in scientific notation this would be $\$1 \times 10^{14}$. This was equivalent to AUD$\$1 \times 10^{-16}$.

Worked example 1.2.1

WRITING QUANTITIES IN SCIENTIFIC NOTATION

Write the following values in scientific notation.	
a The number of seconds in 1 day is 86 400.	
Thinking	**Working**
This number is larger than 1, so the exponent will be a positive value. There are 4 placeholders after the first digit, so 4 becomes the exponent.	86 400 has 8 as its first digit. There are 4 placeholders between the 8 and the final zero, so 4 is the exponent.
The coefficient is then 864 with a decimal point placed between the 8 and the 6.	Coefficient is 8.64
Write in scientific notation.	8.64×10^4 seconds
b The Moon is moving away from Earth at a rate of 0.000 000 001 3 metres per second.	
Thinking	**Working**
This number is less than 1 so the exponent will be a negative number. There are 9 placeholders before the first non-zero digit, so the exponent is –9.	0.000 000 001 3 has 1 as its first non-zero digit. Including the zero in the units column, there are 9 zeros to the left of 1, so –9 is the exponent.
The coefficient is then 13 with a decimal point placed between the 1 and 3.	Coefficient is 1.3
Write in scientific notation.	1.3×10^{-9} metres per second

➤ Try yourself 1.2.1

WRITING QUANTITIES IN SCIENTIFIC NOTATION

Write the following quantities in scientific notation.

a 4 000 000 m

b 0.000 000 000 000 000 000 160 2 C

Writing numbers out of scientific notation

To write a number in long form from scientific notation:

- If the exponent is positive, write the coefficient without the decimal point. Then continue to write zeros after the last digit in the coefficient so that the number of placeholders after the first digit is equal to the exponent.
- If the exponent is negative, write a zero in the units placeholder, then a decimal point. Continue to write zeros until the total number of zeros (including the zero in the units placeholder) is equal to the positive value of the exponent. Then write the coefficient without the decimal place.

Worked example 1.2.2

WRITING QUANTITIES FROM SCIENTIFIC NOTATION

Write the following values in long form.

a The mass of the neutron is 1.6749×10^{-27} kg.

b A light year is 9.4607×10^{15} m.

Thinking	Working
a The exponent is negative, which means the number in long form will be less than 1. Write a zero in the units column and then a decimal point. After the decimal point, write another 26 zeros followed by the coefficient without the decimal place.	0.000 000 000 000 000 000 000 000 001 674 9 kg
b The exponent is positive, which means the number in long form is greater than 1. Write the coefficient, without the decimal point. There are 4 digits after the 9. So write 11 more zeros to complete the number. 15 – 4 = 11	9 460 700 000 000 000 m

In both examples the number in long form has been written with three digits grouped together using thin spaces. Sometimes commas are used. This is purely for ease of reading and counting and is not compulsory.

➤ Try yourself 1.2.2

WRITING QUANTITIES FROM SCIENTIFIC NOTATION

Write the following values in long form.

a The force on an electron in a hydrogen atom is 8.2×10^{-8} N.

b The mass of the Moon is 7.342×10^{22} kg.

Scientific notation is the preferred way of communicating measurements and information in physics. For convenience and ease of use, quantities in a physics problem must first be converted into scientific notation before any calculations can be carried out.

ORDERS OF MAGNITUDE

The order of magnitude of a quantity is the power of 10 that is closest to the quantity.

Sometimes you may not know a quantity exactly and have to estimate its value. To help you do that, you use the order of magnitude, or the power of 10 that the quantity is closest to, and the regular rules of rounding up if the coefficient is 5 or above. Orders of magnitude are only used to serve as a comparison of the size of quantities and do not represent exact values.

For example:

$7.86 \times 10^{-41} \approx 10 \times 10^{-41} = 1.0 \times 10^{-40} = 10^{-40}$

So the order of magnitude of 7.86×10^{-41} is –40.

Here are some orders of magnitude of three important dimensional quantities used in physics: mass, time and length.

- The smallest particle that has had its mass determined is the electron with a mass of 9.11×10^{-31} kg. The closest power of 10 is –30, so you say the order of magnitude of the mass of the electron in kg is –30.
- The age of the universe is generally accepted to be 13.8 billion years, or 4.35×10^{15} s. So, the order of magnitude of the age of the universe in seconds is 15.
- A proton, which is a particle in the centre of every atom, has a diameter thought to be 8.7×10^{-16} m. This means its order of magnitude in metres is –15.

Orders of magnitude are compared by subtracting the smaller from the larger.

Orders of magnitude allow physicists to compare two values of the same type measured in the same unit (e.g. masses in kg to masses in kg, lengths in m to lengths in m, etc.) to quickly see how much bigger or smaller one quantity is than the other. To do this, the orders of magnitude are subtracted.

If one quantity is an order of magnitude larger than another quantity, you say that it is about 10 times larger than the second quantity. If a quantity is three orders of magnitude larger than another quantity, then it is about 10^3, or one thousand times larger than the second quantity.

Worked example 1.2.3

USING ORDERS OF MAGNITUDE

The mass of a hydrogen atom is 1.6737×10^{-27} kg. The mass of Earth is 5.9736×10^{24} kg. Use the order of magnitude of each mass to quickly estimate how many times heavier Earth is than a hydrogen atom.

Thinking	Working
First, determine the order of magnitude of each quantity. Note that each quantity is in the same units, so no unit conversion is needed here. For the mass of the hydrogen atom, the coefficient is less than 5, so the order of magnitude of the hydrogen atom is the same as the exponent, or –27. The coefficient of the mass of Earth is larger than 5, so the order of magnitude is one more than the exponent, or 25.	Order of magnitude of the mass of the hydrogen atom is –27. Order of magnitude of the mass of Earth is 25.
The difference in the order of magnitude is: 25 – –27 = 52	So Earth is 52 orders of magnitude heavier than a hydrogen atom, or 10^{52} times heavier.

➤ Try yourself 1.2.3

USING ORDERS OF MAGNITUDE

The circumference of Earth is 4.02×10^4 km. A light-year is 9.4607×10^{15} m. Use order of magnitude to determine approximately how many times longer a light-year is than the circumference of Earth.

Orders of magnitude also give physicists a way of determining the range of values a particular quantity can have in the universe. Table 1.2.2 shows three fundamental quantities that have been measured or calculated in physics and their largest and smallest known examples.

TABLE 1.2.2 The orders of magnitude of the range of values that three fundamental quantities have in the universe

Quantity	Unit	Smallest known value	Order of magnitude	Largest known value	Order of magnitude	Difference in order of magnitude
length	metre	the smallest scale of the fabric of the universe, quantum foam, 1.6×10^{-35}	–35	the diameter of the observable universe, 9×10^{26}	27	62
mass	kg	the mass of the electron, 9.11×10^{-31}	–30	the mass of the observable universe, $\sim 5 \times 10^{52}$	53	83
time	second	the smallest possible time scale, Planck time, 5×10^{-44}	–43	the age of the universe, 4.4×10^{15}	15	58

ESTIMATION IN PHYSICS

Physics problem usually include enough information to calculate a precise and correct answer. Sometimes, however, not enough information is given or the information is not precise, so the answer will need to be estimated. To estimate the answer to a calculation, orders of magnitude are used. These types of problems, where an estimate is asked for, are called Fermi questions, named after the Italian physicist Enrico Fermi, who worked in nuclear physics in the 1930s.

Worked example 1.2.4

ESTIMATION IN PHYSICS

Estimate the answer to this calculation: $\frac{3728 \times 470165 \times 10^{-14}}{278146 \times 0.000713 \times 10^{-5}}$

Thinking	Working
An estimate is needed, so each quantity can be written as its closest power of ten.	$\frac{3728 \times 470165 \times 10^{-14}}{278146 \times 0.000713 \times 10^{-5}}$ is approximately: $\frac{10^3 \times 10^5 \times 10^{-14}}{10^5 \times 10^{-3} \times 10^{-5}}$
Now the index laws are applied.	$\frac{10^3 \times 10^5 \times 10^{-14}}{10^5 \times 10^{-3} \times 10^{-5}} = \frac{10^{3+5-14}}{10^{5-3-5}}$ $= \frac{10^{-6}}{10^{-3}} = 10^{-6--3} = 10^{-3}$
So the answer is approximately 10^{-3} or 0.001.	An estimate of the answer is 10^{-3} or 0.001.

➤ Try yourself 1.2.4

ESTIMATION IN PHYSICS

Estimate how many times your heart has beaten since you were born.

The Drake equation

Introduction

One of the most famous of all Fermi questions is: What is *N*, the number of intelligent and communicative alien civilisations in our galaxy, the Milky Way? The answer to this question can be estimated by using orders of magnitudes in the Drake equation, as shown in Figure 1.2.2. Frank Drake, an astronomer from the USA, first conceived this in 1961.

FIGURE 1.2.2 The Drake equation gives an estimate of how many intelligent and communicative alien civilisations are in our galaxy.

The factors contained in the Drake equation relate to variables that change the probability that an intelligent civilisation will arise on a given planet. This is shown in Table 1.2.3.

All scientists know is that the answer is at least 1, and could be anywhere from only 1 to millions.

Review

1. Identify the factor that has the largest variation, as a ratio, between minimum and maximum values.
2. Identify the factor that has the smallest variation, as a ratio, between minimum and maximum values.
3. Explain why the Drake equation only gives an estimate for *N*.
4. Using the minimum and maximum values for the factors in the Drake equation, determine a lower and upper estimate for *N*.
5. The first exoplanet, or planet orbiting another star, was discovered in 1995. Before then, the values of f_p and n_e were purely guesses. Explain why this is true.

TABLE 1.2.3 The factors used in the Drake equation to estimate the number of communicative, intelligent, alien civilisations in our galaxy

Factor	Description	Minimum value	Maximum value	Notes
R^*	the rate of star formation in the Milky Way galaxy at number of new stars per year	1.5	3	This is the most accurately known value of all factors.
f_p	the fraction of those stars that have planets orbiting	0.2	1	The thousands of exoplanets discovered in the last 10 years is evidence that this factor is very close to 1.
n_e	the number of those planets, per star, that can support life	0.1	5	This value is becoming more accurately known from the number of earth-like planets found as exoplanets each year.
f_L	the fraction of those planets on which life actually arises	10^{-4}	1	This factor is difficult to determine because you only have one data point and that is Earth.
f_i	the fraction of those planets on which intelligent life or civilisation develops	10^{-9}	1	This is the most unknown factor.
f_c	the fraction of those planets that develop technology that releases information about their existence into space	0.2	1	It is generally thought that once intelligent life arises, it will quickly develop advanced technologies.
L	the length of time, in years, that the civilisation releases information into space about its existence	300	10^9	This value can be estimated from a survey of all known civilisations that have existed, and still exist, on Earth.

1.2 Review

SUMMARY

- Scientific notation is a convenient way of writing very large numbers and very small numbers using the format $a \times 10^b$.
- The order of magnitude of a number is the power of 10 that the number is closest to.
- The difference in orders of magnitude of two quantities is a way of estimating how much bigger or smaller one quantity is than another.
- Estimation is used when values in a problem or calculation are not given precisely.

KEY QUESTIONS

Retrieval

1 Give a reason why physicists need to write numbers in scientific notation instead of long form.

2 Identify the two numbers between which the coefficient of a value expressed in scientific notation must lie.

3 Recall by approximately how much one number is larger than a second number if the difference between orders of magnitude is 2.

Comprehension

4 Explain why the order of magnitude is sometimes not the same as the exponent in scientific notation.

5 Write the following values in scientific notation:

a 6 370 000 m
b 0.003 19 s
c 7713 kg
d 45 N

6 Write each of the the following numbers as a basic numeral:

a 1.1×10^{-10} m
b 7.031×10^{6} m s^{-2}
c 3.0×10^{8} m s^{-1}
d 9.8×10^{0} N kg^{-1}

7 Determine the order of magnitude of the following values:

a 6.41×10^{9} m
b 1.201×10^{-3} m^3
c 6.67×10^{-11} Nm^2 kg^{-2}
d 1.732×10^{3} km

Analysis

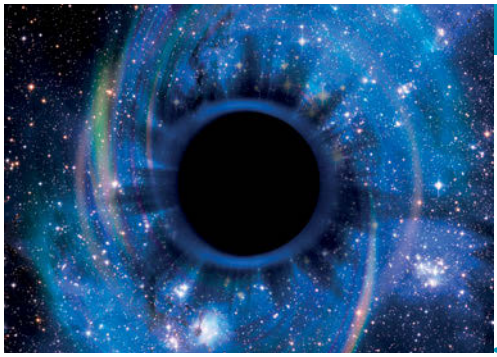
8 Compare the mass of Earth (5.972×10^{24} kg) to the mass of the Sun (1.99×10^{30} kg).

9 Determine which is the bigger difference in order of magnitude:

A the mass of a human being to the mass of the nucleus of a carbon atom (mass = 1.99×10^{-26} kg)
B the mass of the universe (estimated to be about 5×10^{52} kg) to the mass of a human being

10 Compare the mass of all of the 7.5 billion people on Earth to the mass of Earth itself.

1.3 Mathematical basics for physics



BY THE END OF THIS MODULE, YOU SHOULD BE ABLE TO:

- perform basic mathematical operations using percentages and fractions
- rearrange and substitute formulas using algebraic rules and the index laws
- use the trigonometric ratios to determine side lengths and angles of right-angled triangles
- use the formulas for curved shapes to approximate the areas, surface areas and volumes of more complex objects
- use the equation of a straight line to determine its gradient and *y*-intercept.

Mathematics has often been quoted as the language of physics. The theories, models, laws and principles used in physics all have their basis in mathematics. Physics extensively uses all aspects of mathematics, from the simplest application of percentage to the addition of three-dimensional magnetic field vectors. To do well in physics you must have knowledge of the following branches of mathematics.

Note that all physics formulas are written using algebraic representation. This means that the variables used in any formula are given symbols and their relationship to each other is linked by a set of mathematical operations that include addition, subtraction, multiplication, division, powers and roots.

PERCENTAGES

Percentages are used when calculating relative amounts of measurements, such as uncertainties and efficiencies.

To calculate a percentage, $P\%$, of an amount, x:

$$x \times \frac{P\%}{100}$$

To express x out of y as a percentage, $P\%$:

$$P\% = \frac{x}{y} \times 100$$

FRACTIONS

Fractions are used extensively throughout physics in such areas as electricity, optics and waves.

When adding or subtracting fractions, the denominators must be equal.

When multiplying fractions, multiply the numerators and write that as a fraction over the denominators multiplied together:

$$\frac{a}{b} \times \frac{c}{d} = \frac{ac}{bd}$$

When dividing fractions, write the divisor (the fraction to be divided) as its reciprocal (i.e. upside-down) and then multiply the fractions together:

$$\frac{a}{b} \div \frac{c}{d} = \frac{a}{b} \times \frac{d}{c} = \frac{ad}{bc}$$

Or, if a whole number, a, is divided by a fraction:

$$a \div \frac{c}{d} = a \times \frac{d}{c} = \frac{ad}{c}$$

INDEX LAWS

Indices, or powers, are also used extensively in physics in scientific notation as well as in many formulas.

$$a^x \times a^y = a^{x+y}$$
$$a^x \div a^y = \frac{a^x}{a^y} = a^{x-y}$$
$$\left(a^x\right)^y = a^{xy}$$
$$a^0 = 1$$
$$a^1 = a$$
$$a^{-1} = \frac{1}{a}$$
$$a^{-x} = \frac{1}{a^x}$$
$$a^{\frac{1}{2}} = \sqrt{a}$$
$$a^{\frac{1}{x}} = \sqrt[x]{a}$$

ALGEBRA

Algebra is a powerful tool in solving physics problems. Measurements and data often need to be substituted into a formula in order to obtain an answer. Remember that the data that is to be substituted should always be written without a prefix but in an SI unit, and preferably in scientific notation.

If an unknown variable in a formula needs to be evaluated, then two strategies can be employed:

- The formulas can be rearranged to make the unknown variable the subject of the equation, and then the values substituted in.
- Alternatively, the values can be substituted into the formula and then the formula can be rearranged to make the unknown variable the subject.

Worked example 1.3.1

USING ALGEBRA IN FORMULAS

The kinetic energy (E_k) of a 0.224 kg toy car, m, moving at an unknown speed, v, is 1.61×10^{-3} joules.

Kinetic energy is given by the formula:

$$E_k = \frac{mv^2}{2}$$

Calculate the velocity of the car by first substituting in the known values, and then rearranging the formula.

Thinking	Working
Substitute in the known values.	$E_k = \frac{mv^2}{2}$ $1.61 \times 10^{-3} = \frac{0.224 \times v^2}{2}$
Rearrange the equation so that v is the subject.	$1.61 \times 10^{-3} \times 2 = 0.224 \times v^2$ $v^2 = \frac{1.61 \times 10^{-3} \times 2}{0.224}$ $v = \sqrt{\frac{1.61 \times 10^{-3} \times 2}{0.224}}$
Then solve the equation for v.	$= \sqrt{\frac{3.22 \times 10^{-3}}{0.224}}$ $= \sqrt{0.014375}$ $= 0.12\,\text{m s}^{-1}$
State the answer using the correct units.	The toy car's velocity is $0.12\,\text{m s}^{-1}$.

➤ Try yourself 1.3.1

USING ALGEBRA IN FORMULAS

The formula relating how much energy per second, P, is released by the Sun is:

$P = \sigma A T^4$

where

A is the surface area of the Sun in m^2

T is the surface temperature of the Sun in kelvin

P is the energy released by the Sun per second in watts

σ is the Stefan–Boltzmann constant 5.67×10^{-8}.

If the surface area of the Sun is $6.1 \times 10^{18} m^2$, and it produces 3.8×10^{26} watts, determine its surface temperature by first rearranging the formula, then substituting known values.

QUADRATIC FORMULA

The quadratic formula is sometimes used in more difficult physics problems in which a question can have one, two or no solutions. It is used when the unknown variable is written in an equation with a power of one as well as a power of two. Examples of these questions occur in motion, gravity, electric fields and in electricity.

$$\text{If } ax^2 + bx + c = 0, \text{ then } x = \frac{-b \pm \sqrt{b^2 - 4ac}}{2a}.$$

PROBABILITY

In physics, probability is used in thermal, quantum and atomic physics. It is defined as the chance that an event, E, can occur:

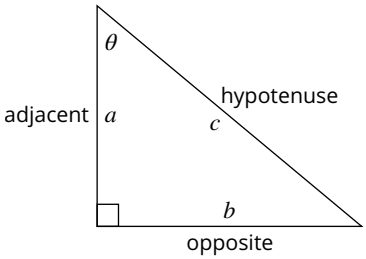
$$P(E) = \frac{\text{number of times } E \text{ can occur}}{\text{total number of possible events}}$$

GEOMETRY

Understanding the direction and shape of many abstract ideas in physics requires knowledge of the basics of angles, area, perimeter, volume and trigonometry. These concepts occur throughout every aspect of physics, especially where direction is important.

Pythagoras's theorem

Right-angled triangles are used extensively when vectors are being added or subtracted. Pythagoras' theorem can be used to find unknown side lengths in any right-angled triangle, as shown in Figure 1.3.1.

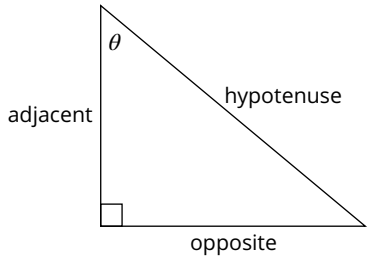


$c^2 = a^2 + b^2$

FIGURE 1.3.1 Pythagoras' theorem is used for right-angled triangles.

Trigonometry

The sine, cosine and tangent ratios are also used to determine the sizes and directions of vector quantities in physics. Using the triangle below, the trigonometry ratios can be calculated as follows:



$$\sin\theta = \frac{\text{opposite}}{\text{hypotenuse}}$$

$$\cos\theta = \frac{\text{adjacent}}{\text{hypotenuse}}$$

$$\tan\theta = \frac{\text{opposite}}{\text{adjacent}}$$

Measurement

Many concepts in physics require the use and calculation of perimeters, areas, surface areas and volumes. Complex objects are often approximated by circles and spheres.

Circumference, C, of a circle with radius r: $C = 2\pi r$

Area, A, of a circle with radius r: $A = \pi r^2$

Surface area, SA, of a sphere with radius r: $SA = 4\pi r^2$

Volume, V, of a sphere with radius r: $V = \frac{4\pi r^3}{3}$

Volume, V, of a cylinder with height h and base radius r: $V = \pi r^2 h$

STRAIGHT LINES

A straight line is the simplest relationship between two variables. In graphical analysis of physics phenomena, a straight line is very useful as the y-intercept and gradient can be easily calculated by hand or with technology. Figure 1.3.2 shows a typical straight-line relationship:

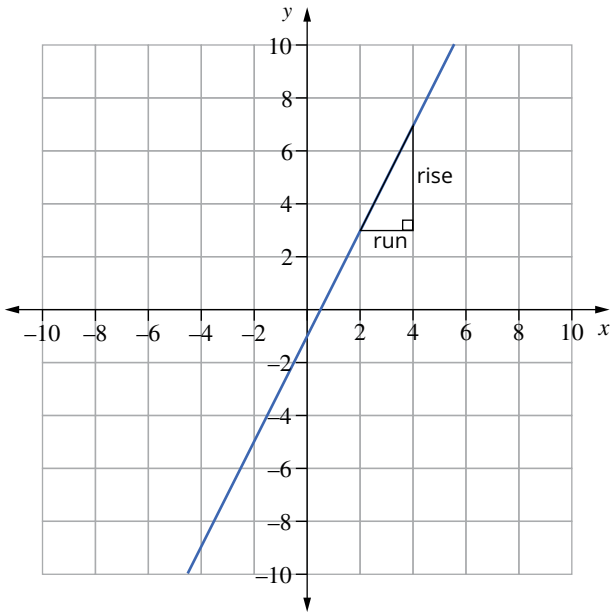


FIGURE 1.3.2 A graph showing a linear relationship.

The gradient, m, of any straight line is calculated using:

$$m = \frac{\text{rise}}{\text{run}} = \frac{y}{x}$$

And the y-intercept, c, is read off the y-axis.

The equation of any straight line is determined by the gradient and y-intercept:

$$y = mx + c$$

In the example above, the equation of the straight line is $y = 2x - 1$. It has a gradient of 2 and a y-intercept of -1.

1.3 Review

SUMMARY

- Percentages and fractions are basic mathematical skills that are applicable in all fields of physics.
- Performing substitution and rearranging of physics formulas is vital to solving numerical calculations.
- The trigonometric ratios of sine, cosine and tangent are used to determine directions of many physical quantities.
- Complex shapes can be approximated using circles, spheres and cylinders, and then calculating their area, surface area and volume using the appropriate formula.
- The analysis of a straight line is very important in physics as the gradient and *y*-intercept often contain useful information about physical relationships.

KEY QUESTIONS

Retrieval

1 Recall the base units for area, surface area and volume.

2 Write the three trigonometric ratios in terms of the sides of a right-angled triangle.

3 Write down three branches of physics in which probability is used.

Comprehension

4 Determine the gradient (m) and y-intercept of the following straight lines.

a $y = x - 7$

b $2y = 16 - 4x$

c $4.5y + 2.1x - 7 = 0$

5 Rearrange the following formulas so that the variable in brackets is the subject of the equation:

a $F = ma$ (a)

b $E_k = hf - \phi$ (f)

c $F = \frac{GMm}{r^2}$ (r)

Analysis

6 WASP-17b is an exoplanet discovered in 2009 that has a radius twice that of Jupiter. Determine how many times the volume of Jupiter this is. The relationship between the radius, r, and volume, V, of a sphere is given by the formula $V = \frac{4\pi r^3}{3}$.

7 Solve the following problems:

a $\frac{1}{2} + \frac{1}{8}$

b $10 \div \frac{4}{5}$

c 15% of 76.2 kg

8 Simplify each of the following:

a $\frac{t^3 \times t}{\sqrt{t}}$

b $c\left(\frac{c^2}{c}\right)^3$

9 Substitute the following values into the formula below to obtain a value and units for γ:

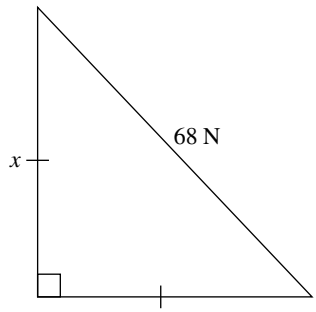
$c = 3.00 \times 10^8\,\text{m s}^{-1}$

$v = 2.99 \times 10^8\,\text{m s}^{-1}$

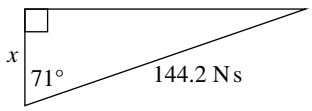
$\gamma = \frac{1}{\sqrt{1 - \frac{v^2}{c^2}}}$

10 Determine the value of x in the following triangles:

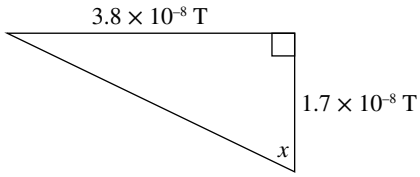
a



b



c

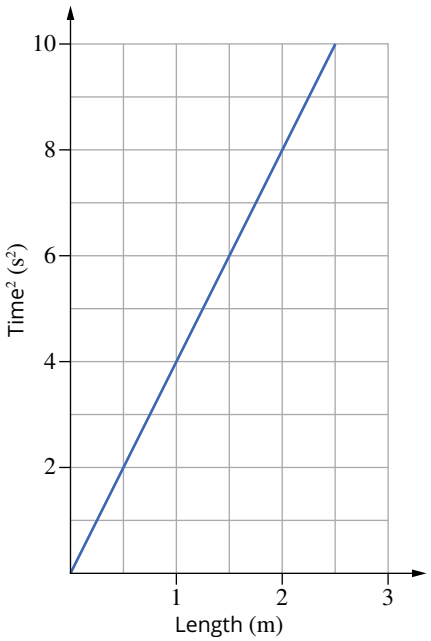


11 Solve the following equation for a positive value of x:

$$\frac{kq^2}{x^2} = \frac{4kq^2}{(1-x)^2}$$

where k and q are constants.

12 The following questions refer to the graph below of how the time for one complete swing of a pendulum, squared, changes with the length of a pendulum.

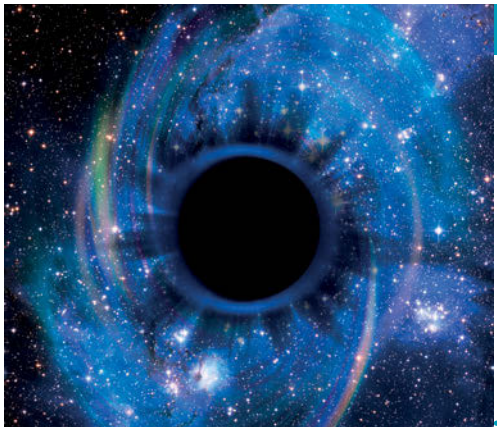


a Determine the gradient and y-intercept of the line.

b Identify the units of the gradient and y-intercept.

c If the gradient of the line is theoretically equal to $\frac{4\pi^2}{g}$, determine the value, and units, of g.

1.4 Units and prefixes



BY THE END OF THIS MODULE, YOU SHOULD BE ABLE TO:

- appreciate that physics uses the International System (SI) of units
- understand that the use of scientific knowledge may have beneficial and/or harmful and/or unintended consequences
- recall the seven fundamental units, their symbols and definitions
- differentiate between fundamental and derived units
- understand that the SI prefixes are multipliers of powers of 10 of the base units
- convert between various units of the same type using SI and some non-SI units.

Every science needs a system of units in order to describe the measurements that are made. In physics, measurements are made using the International System (SI) of units. This system was first developed in France in 1791 with the advent of the metric system, and then formally organised in 1960. Most countries around the world (Figure 1.4.1) use and understand these units, as they are internationally accepted in everyday life.

FIGURE 1.4.1 Only three countries are still yet to officially adopt the metric system: Myanmar (in Asia), Liberia (in Africa) and the USA.

Physicists use the International System (SI) of units in measurements and calculations.

FUNDAMENTAL UNITS

There are seven fundamental units used in physics. These units cannot be simplified into any other unit and describe the most basic measurements that can be made about phenomena in the universe. The seven fundamental units are listed in Table 1.4.1. Figure 1.4.2 shows the platinum-iridium alloy cylinder that is used as the standard definition for the kilogram.

TABLE 1.4.1 The seven fundamental SI units used in physics, along with their symbols and formal definitions

Quantity	SI Unit	Symbol	Definition	Date of definition
length	metre	m	the distance a ray of light, travelling at the speed of light, moves in $\frac{1}{299\,792\,453}$ of a second	1983
mass	kilogram	kg	the mass of a cylinder of a platinum-iridium alloy, kept in a vault in Sevres, France (Figure 1.4.2)	1901
time	second	s	9 192 631 770 oscillations of the ground state hyperfine electron transition of caesium-133 at rest at 0 K	1997
electric current	ampere	A	the current flowing in two straight infinitely long parallel conductors of negligible cross section such that there is a force of 2×10^{-7} N between them for each metre of length	1948
temperature	kelvin	K	$\frac{1}{273.16}$ of the thermodynamic temperature of the triple point of water (where H_2O exists as a solid, liquid and gas)	2005
amount of substance	mole	mol	the amount of substance of an object that contains as many particles as there are atoms in 0.012 kg of ground state carbon-12	1980
luminous intensity	candela	cd	the luminous intensity of a source that emits monochromatic radiation of a frequency of 540×10^{12} Hz and has a radiant intensity of $\frac{1}{683}$ watts per steradian (or solid angle).	1979

All of the units in Table 1.4.1 are commonly studied in secondary school physics courses, except for the mole and candela. The mole is extensively used in chemistry as a measure of a quantity of a substance. The candela is a measure of light intensity, as used in Chapter 11, and shown in Figure 1.4.3. Currently, plans are being made to redefine all of the fundamental units in terms of atomic or quantum aspects of nature.

The fundamental units have been chosen so that they:

- do not change over time
- are accessible to the entire world
- are easy to reproduce.

FIGURE 1.4.2 The international prototype kilogram is a cylinder of platinum-iridium alloy. It is expected that the definition will change in 2019. The new definition relates the kilogram to the equivalent energy of a photon.

FIGURE 1.4.3 The candela is about the same as the luminous intensity of light given off by a single candle.

Seven fundamental units are used in the SI. They are the metre, kilogram, second, kelvin, ampere, mole and candela.

DERIVED UNITS

Every other unit that is used in physics is a mathematical combination (such as division, multiplication, squaring) of one or more of the seven fundamental units, and are called derived units. Table 1.4.2 lists some of the most common units encountered in high school physics.

TABLE 1.4.2 Some of the most common derived units in high school physics

Quantity and symbol	SI Unit	Symbol	Notes
area, A	square metre	m^2	
volume, V	cubic metre	m^3	
amount of liquid, V	litre	L or l	$1\,L = 1000\,cm^3 = 0.001\,m^3$
density, ρ	kilograms per cubic metre	$kg\,m^{-3}$	
velocity, v	metres per second	$m\,s^{-1}$	
acceleration, a	metres per second squared	$m\,s^{-2}$	
current, I	ampere	A	
momentum, p	kilogram metres per second	$kg\,m\,s^{-1}$	$1\,kg\,m\,s^{-1} = 1\,N\,s$
force, F	newton	N	$1\,N = 1\,kg\,m\,s^{-2}$
energy, E	joule	J	$1\,J = 1\,N\,m$
power, P	watt	W	$1\,W = 1\,J\,s^{-1}$
charge, q	coulomb	C	$1\,C = 1\,A\,s$
frequency, f	hertz	Hz	$1\,Hz = 1\,s^{-1}$
pressure, P	pascal	Pa	$1\,Pa = 1\,N\,m^{-2}$
voltage, V	volt	V	$1\,V = 1\,J\,C^{-1}$
resistance, R	ohm	Ω	$1\,\Omega = 1\,V\,A^{-1}$
magnetic flux density, B	tesla	T	$1\,T = 1\,N\,A^{-1}\,m^{-1}$
magnetic flux, Φ	weber	Wb	$1\,Wb = 1\,T\,m^2$
activity, A	becquerel	Bq	$1\,Bq = 1$ decay s^{-1}

A derived unit is a unit that is a mathematical combination of one or more of the seven fundamental units.

Note that when a unit has a division implied, such as the unit for velocity of metres per second, its symbol is written as $m\,s^{-1}$ not m/s.

NON SI UNITS USED IN PHYSICS

Two non-SI units are used extensively in physics, the kW h and the eV, and they are both units of energy.

The kilowatt-hour, kWh, is used to describe the amount of energy used or supplied to homes by power stations. Note that this unit is NOT kilowatts *per* hour but kilowatts times hour.

$$1\,kWh = 3.60 \times 10^6\,J$$

The electron volt, eV, is used to describe the energies of subatomic particles.

$$1\,eV = 1.602 \times 10^{-19}\,J$$

SI PREFIXES

Two methods are used to write a physical measurement: prefixes and scientific notation. Scientific notation was discussed in Module 1.2.

An SI prefix is a symbol written at the front of a unit to indicate that the measurement is a power of 10 higher or lower than the unit itself.

There are 20 SI prefixes in use and most of them denote units that are one thousand (10^3) times larger or smaller than the previous prefix. Table 1.4.3 lists the 20 SI prefixes used in physics.

TABLE 1.4.3 The 20 official SI prefixes used in physics

Prefix	Symbol	Multiplier	Description	Decimal	Example
yotta	Y	10^{24}	septillion	1 000 000 000 000 000 000 000 000	The total power output of the Sun is 383 YW.
zetta	Z	10^{21}	sextillion	1 000 000 000 000 000 000 000	The diameter of the Milky Way galaxy is about 1 Zm.
exa	E	10^{18}	quintillion	1 000 000 000 000 000 000	1 EeV = 0.16 J
peta	P	10^{15}	quadrillion	1 000 000 000 000 000	1 light-year is approximately 10 Pm.
tera	T	10^{12}	trillion	1 000 000 000 000	1 TByte hard drives are now common (Figure 1.4.4).
giga	G	10^{9}	billion	1 000 000 000	3.16 Gs = 1 century
mega	M	10^{6}	million	1 000 000	1 MHz is close to the frequencies at which TV stations broadcast.
kilo	k	10^{3}	thousand	1000	1 kg = 1000 grams
hecto	h	10^{2}	hundred	100	1 hPa is a unit used in meteorology used to describe atmospheric pressure.
deca	da	10^{1}	ten	10	1 daN is approximately the force exerted by a 1 kg object on the surface of Earth.
-	-	1	unit	1	-
deci	d	10^{-1}	tenth	0.1	1 L = 1 dm^3
centi	c	10^{-2}	hundredth	0.01	1 cg of water takes up 1 mL of space.
milli	m	10^{-3}	thousandth	0.001	There are 1000 mm in 1 m.
micro	µ	10^{-6}	millionth	0.000 001	µg are commonly used as the unit for medicine dosage.
nano	n	10^{-9}	billionth	0.000 000 001	The wavelength of yellow sodium street lights is 550 nm.
pico	p	10^{-12}	trillionth	0.000 000 000 001	The diameter of the hydrogen atom is about 100 pm.
femto	f	10^{-15}	quadrillionth	0.000 000 000 000 001	Some lasers emit a pulse of light that lasts for 1 fs.
atto	a	10^{-18}	quintillionth	0.000 000 000 000 000 001	Quarks and electrons are believed to be 1 am in size.
zepto	z	10^{-21}	sextillionth	0.000 000 000 000 000 000 001	160 zJ is approximately 1 eV.
yocto	y	10^{-24}	septillionth	0.000 000 000 000 000 000 000 001	The mass of a proton is approximately 1.7 yg.

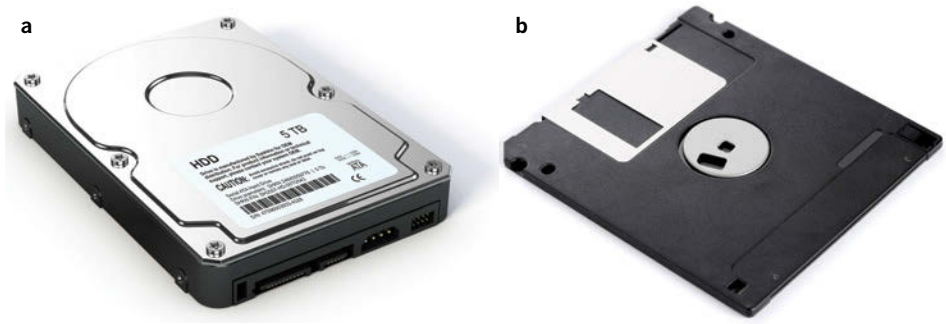


FIGURE 1.4.4 (a) A 1.0 terabyte hard drive (left) in 2016 compared to a 1.44 megabyte floppy disc (right) in the 1990s. (b) The hard disc drive holds more than 690 000 times the information that can be stored on the floppy disc.

An SI prefix is a symbol written at the front of a unit to that the measurement is a power of 10 larger or smaller than the unit.

The larger prefixes are written as a capital letter, whereas the smaller prefixes are written using a lower case letter. Note that the fundamental unit kilogram has itself a prefix, but all multiples of mass are written with the base unit grams. As an example, 1 million kilograms is not written as 1 megakilogram, but as 1 gigagram (Gg). Before any measurement with a prefix can be substituted into a formula, it must be converted into SI units without the prefix, in scientific notation. Figure 1.4.4 compares storage sizes in bytes using SI prefixes.

Worked example 1.4.1

UNIT CONVERSIONS

Determine how many litres there are in 1 cubic kilometre.	
Thinking	**Working**
Write each unit in terms of m^3. Remember that a km^3 is a cube that has sides of 1000 m by 1000 m by 1000 m.	$1\,L = 0.001\,m^3$ $1\,km^3 = 1000\,m \times 1000\,m \times 1000\,m = 10^9\,m^3$
Take the inverse of each equation to find the equivalent volume in m^3.	$1\,m^3 = \frac{1}{10^9} = 10^{-9}\,km^3$ $1\,m^3 = \frac{1}{0.001} = 10^3\,L$
Now equate them because they are both equal to $1\,m^3$.	$10^{-9}\,km^3 = 10^3\,L$ $\therefore \frac{10^3\,L}{10^{-9}\,km^3} = 10^{12}\,L\,km^{-3}$
State the answer.	There are 10^{12}, or one trillion, litres in 1 cubic kilometre.

Try yourself 1.4.1

UNIT CONVERSIONS

Determine how many am are in 5.91 Ym.

1.4 Review

SUMMARY

- Physics uses the International System (SI) of units.
- There are seven fundamental units: metre, second, kilogram, kelvin, mole, ampere and candela.
- Fundamental units cannot be written using any other combination of units.
- Derived units are units that can be written as a mathematical combination of the fundamental units.
- The SI prefixes are symbols that go before a unit and indicate multiplication of a power of 10 of the unit.
- Units with a prefix need to be converted into scientific notation before they can be used in a physics formula.

KEY QUESTIONS

Retrieval

1 Recall which fundamental unit has the oldest definition.

2 Give an example of a derived unit that is a combination of only one fundamental unit.

3 List the fundamental units.

Comprehension

4 Explain the difference between an ampere second and an ampere per second.

5 Explain the difference between fundamental units and derived units.

6 Explain why it is important for general society, not just the scientific community, to have a systematic and consistent set of units for measurement.

Analysis

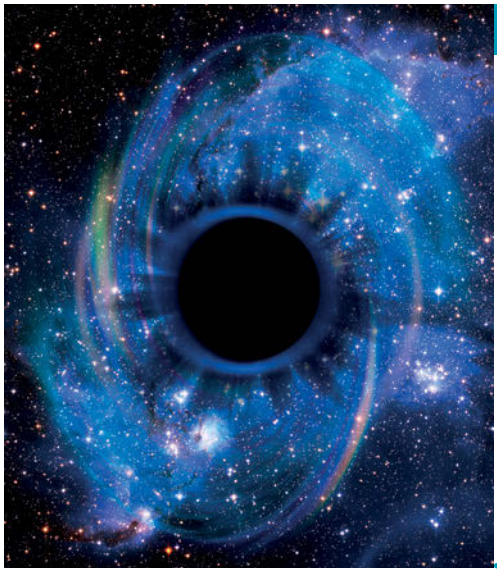
7 Determine how many metres there are in the 656 nm wavelength of red light emitted from hydrogen gas.

8 The Large Magellanic Cloud is the nearest large galaxy to our own Milky Way galaxy. It is located at a distance of 48.5 kiloparsecs. If 1 parsec is equal to 3.1×10^{13} km, calculate how far away the Large Magellanic Cloud is in km.

9 Show that the unit ohm can be written in fundamental units as:

$$1\ \Omega = 1\ \frac{\text{kg m}^2}{\text{A}^2\,\text{s}^3}$$

1.5 Uncertainties in measurement



BY THE END OF THIS MODULE, YOU SHOULD BE ABLE TO:

- understand that all measurements made in physics experiments are subject to a level of uncertainty
- differentiate between accuracy and precision, and know how to express this quantitatively using significant figures
- perform calculations using significant figures
- recognise the difference between mistakes, systematic uncertainties and random uncertainties
- determine the limit of reading and absolute uncertainty of analog and digital instruments
- convert between absolute, fractional and percentage uncertainties
- perform propagation of uncertainties including addition, subtraction, multiplication, division and powers of measurements and their uncertainties.

Advanced laws of physics do not allow any measurement made in science to be 100% exact. This means that all measurements made in science are subject to a level of doubt, or uncertainty.

ACCURACY AND PRECISION

The accuracy of a measurement is how close it is to an accepted value.

An accurate measurement is very close to an accepted value, and the accuracy of the measurement is how close it is to the accepted value.

The percentage error (or measurement error written as a percentage) in the measurement is the difference between the measurement and the accepted value, written as a percentage:

$$\text{Percentage error} = \left|\frac{\text{measured value} - \text{accepted value}}{\text{accepted value}}\right| \times 100\%$$

As an example, the speed of light is $299\,792\,453\,\text{m}\,\text{s}^{-1}$.

The precision of a measurement is how many digits can be written down to describe the measurement.

An accurate measurement for the speed of light is $300\,000\,000\,\text{m}\,\text{s}^{-1}$, which has only a 0.07% percentage error:

$$\left|\frac{300\,000\,000 - 299\,792\,453}{299\,792\,453}\right| \times 100\% = 0.07\%$$

An inaccurate measurement for the speed of light is $780\,000\,000\,\text{m}\,\text{s}^{-1}$, which has a 160% percentage error:

$$\left|\frac{780\,000\,000 - 299\,792\,453}{299\,792\,453}\right| \times 100\% = 160\%$$

Any measurement made in physics needs to be both accurate and precise.

Devices that use smaller and smaller units to measure in are also said to be precise. Common examples are Vernier callipers and micrometers.

To understand more clearly the difference between accuracy and precision, think about shooting arrows at an archery target, as shown in Figure 1.5.1. Accuracy is being able to hit the bullseye, whereas precision is being able to hit the same spot every time you shoot.

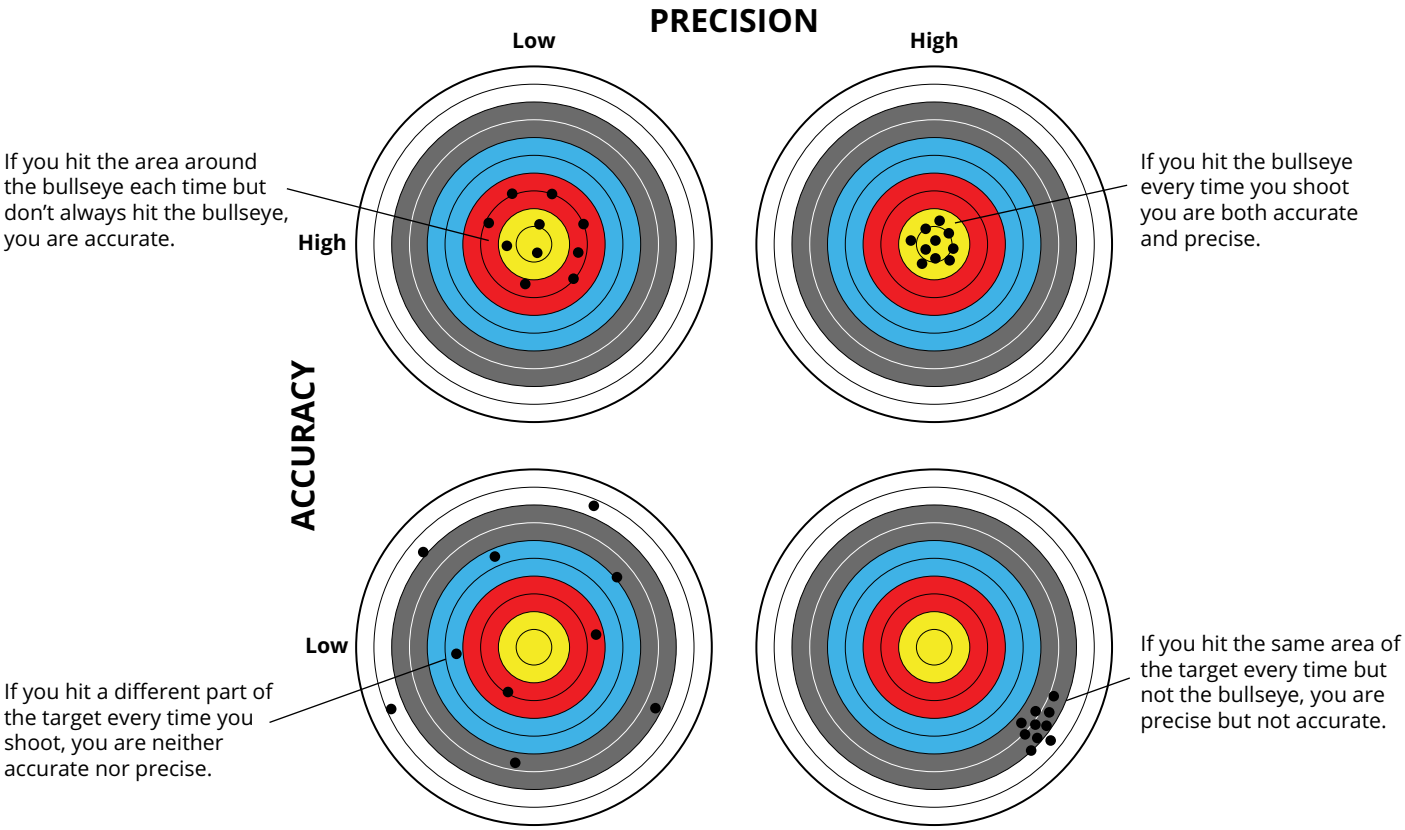


FIGURE 1.5.1 Using a dartboard with darts illustrates the difference between accuracy and precision. Measurements should be both precise and as accurate as possible.

SIGNIFICANT FIGURES

Another way of describing precision is by the number of significant figures in a measurement. The significant figures of a measurement are digits that are known exactly. The more significant figures a measurement has, the higher its precision.

> The precision of a measurement is how many significant figures can be written down to describe it.

Measurements written in scientific notation

In order to determine how many significant figures are in a measurement there are several rules:

- All digits (including 0) in the coefficient of a number written in scientific notation are significant.
- Digits in a number not written in scientific notation may or may not be significant.

Table 1.5.1 shows some examples of measurements written in scientific notation and the number of significant figures.

TABLE 1.5.1 Some examples of determining the number of significant figures in measurements written in scientific notation

Measurement	Number of significant figures
$\mathbf{4.2003} \times 10^{-5}\,\text{m}$	5
$\mathbf{1.9} \times 10^{23}\,\text{kg}$	2
$\mathbf{3.500} \times 10^{2}\,\text{N}$	4
$\mathbf{6} \times 10^{24}\,\text{kg}$	1

Always write measurements in scientific notation, as every digit in the coefficient is treated as a significant.

Measurements not written in scientific notation

Determining the number of significant figures in a measurement written in scientific notation is easy, but it is more problematic in measurements not written in scientific notation.

Several rules can be used to determine the number of significant figures in a measurement:

- The digits 1, 2, 3, 4, 5, 6, 7, 8, 9 are always significant.
  For example:
  5622.1 has 5 significant figures.
  6 has 1 significant figure.
- Any zeros between non-zero digits are significant.
  For example:
  1003 kg has 4 significant figures.
  30 602 s has 5 significant figures.
  23 000 001 km has 8 significant figures.
- Zeros that are placeholders are not significant.
  For example:
  23 000 000 J has 2 significant figures because all the zeros are considered to be placeholders and not actually measured. Measurements written like this are ambiguous, as there could be anywhere from 2 to 8 significant figures here, so the lowest number is used. The only way to be sure how precise the measurement is to write the measurement in scientific notation. **1**00 mm has 1 significant figure as the zeros are the units and hundreds placeholders. 0.000 000 0**3** m has 1 significant figure as all zeros are also just written to take a place value holder.
- Numbers less than one that have zeros to the right of a non-zero digit are significant.
  For example:
  0.0**310** m s^{-1} has 3 significant figures because the two leading zeros are taking the place of the units and hundredths placeholder. The final zero did not have to be written unless it was actually measured so therefore it must be significant. 0.00**4 002 000** J has 7 significant figures because the leading zeros are placeholders. The zeros between the 4 and the 2 are significant, as they are located between non-zero digits, and the final three zeros must have been measured otherwise they would not have be written down.
- Any constants, or numbers that have been defined or counted exactly (such as the speed of light or the number of years in a century) have an infinite number of significant figures and are generally not used to determine the precision of a calculation.

Worked example 1.5.1

SIGNIFICANT FIGURES

Determine how many significant figures there are in these measurements.

a 8.07×10^{14} kg

b 9.00 m

c 0.000 100 3 s

d 4560 N

Thinking	Working
a This measurement is written in scientific notation therefore all digits in the coefficient are significant.	3 significant figures
b The final zeros are significant, as they did not need to be written down unless they were specifically measured.	3 significant figures
c The first four zeros are not significant as they are just placeholders. The middle zeros are significant because they are located between two non-zero digits.	4 significant figures
d The final zero is not significant, or is ambiguous, so it is not counted.	3 significant figures

➤ Try yourself 1.5.1

SIGNIFICANT FIGURES

Determine how many significant figures there are in these measurements.

a 77 000 T

b 0.000 000 422

c 2.76×10^{-17} C

d 20.040 m s^{-2}

Calculations with significant figures

It is important to keep track of the number of significant figures in any calculation with measurements, because the final answer cannot be more precise than any of the measurements used in the calculation.

Addition and subtraction

When adding or subtracting measurements, the answer is written to the least number of decimal places in the question. If a measurement has no decimal places, then the answer is written to the largest number of placeholders in the question. If the answer has more than the required number of significant figures, then it must be rounded up or down to the correct number of significant figures.

Worked example 1.5.2

ADDITION AND SUBTRACTION WITH SIGNIFICANT FIGURES

Determine the answer to these calculations to the correct number of significant figures.	
a 212 g + 2.1 g + 1.88 g – 0.02 g	
Thinking	**Working**
Perform the calculation keeping all decimal places.	212 g + 2.1 g + 1.88 g – 0.02 g = 215.96 g
Determine the measurement with the least number of decimal places.	212 g has no decimal places, so it has the least number of decimal places in the question.
The answer must then be rounded up or down to match the least number of decimal places.	The answer of 215.96 g must therefore be rounded up to 216 to have no decimal places.
Write the final answer.	216 g
b 3600 mL + 111 mL + 55.5 mL – 0.5 mL	
Thinking	**Working**
Perform the calculation keeping all decimal places.	3600 mL + 111 mL + 55.5 mL – 0.5 mL = 3766 mL
Determine the measurement with the least number of decimal places or with the greatest number of placeholders.	3600 mL has 2 placeholders (i.e. to the hundreds placeholder), and this is the number of placeholders in the question. The answer must therefore be written to the nearest hundred.
The answer must then be rounded up or down to match the least number of decimal places or largest number of placeholders.	The answer of 3766 mL must therefore be rounded up to the nearest hundred.
Write the final answer.	3800 mL

➤ Try yourself 1.5.2

ADDITION AND SUBTRACTION WITH SIGNIFICANT FIGURES

Determine the answer to these calculations to the correct number of significant figures.

a 0.042 16 m – 0.000 413 4 m + 0.0033 m

b 564 321 s – 264 321 s

Multiplication and division

When multiplying or dividing measurements, the answer is written to the same number of significant figures as there are in the measurement that has the least number of significant figures. If the answer has more than the required number of significant figures, then it must be rounded up or down to get the correct number of significant figures.

Worked example 1.5.3

MULTIPLICATION AND DIVISION WITH SIGNIFICANT FIGURES

Determine the answers to the correct number of significant figures.	
a 3.22 cm × 12.34 cm × 1.8 cm	
Thinking	**Working**
Perform the calculation keeping all decimal places.	3.22 cm × 12.34 cm × 1.8 cm = 71.522 64 cm^3
Determine the measurement with the least number of significant figures.	1.8 cm has the least number of significant figures with 2.
The answer must then be rounded up or down to match the least number of significant figures.	The answer of 71.522 64 cm^3 must therefore be rounded up to 72 cm^3 to have 2 significant figures.
Write the final answer.	72 cm^3
b 1500.0 m ÷ 253.2 s	
Thinking	**Working**
Perform the calculation keeping all decimal places.	1500.0 m ÷ 253.2 s = 5.924 17 $m\,s^{-1}$
Determine the measurement with the least number of significant figures.	253.2 s has the least number of significant figures with 4.
The answer must then be rounded up or down to match the least number of significant figures.	The answer of 5.924 17 $m\,s^{-1}$ must therefore be rounded down to have 4 significant figures.
Write the final answer.	5.924 $m\,s^{-1}$

➤ Try yourself 1.5.3

MULTIPLICATION AND DIVISION WITH SIGNIFICANT FIGURES

Determine the answers to the correct number of significant figures.

a Use the rule $V = h\pi r^2$ to calculate the volume (in cm^3), and units, of a cylinder of a height 1.49 m and circular radius 9.9 cm.

b Use the formula $\lambda = \frac{h}{p}$ with $h = 6.626 \times 10^{-34}$ J s and $p = 5.9 \times 10^{-23}$ N s to determine λ and its fundamental unit.

UNCERTAINTIES

Every measurement made in a physics laboratory or during an experiment is subject to some uncertainty. This means that no matter how good or experienced the experimenter is, or how sophisticated the equipment is, it is impossible to know a measurement exactly. This is a law of physics!

Uncertainties, or errors, can be divided into three types:

- systematic errors
- random errors
- actual mistakes, as shown in Figure 1.5.2.

Note that the word 'error' when used in physics, does not mean that a blunder has been made in a measurement, but rather it is a statement of the precision of the measurement. Thus a measurement stated without an uncertainty is meaningless. The smaller the uncertainty in a measurement the more precise it is.

> **i** A measurement stated without an uncertainty is meaningless.

Mistakes

These are actual mistakes made using equipment, mathematical blunders, or misunderstandings of the physics theory. As such, they are not considered to be a measurement uncertainty and, with practice, can be eliminated entirely.

FIGURE 1.5.2 An example of a mistake, rather than an uncertainty, that occurred in Paris in 1895.

Systematic errors

Systematic errors are errors in the way the equipment or experimenter measures a particular phenomenon. Examples of where these types of errors occur include:

- poorly designed equipment
- poorly calibrated equipment (the scale on the equipment does not match the actual values)
- parallax errors, as shown in Figure 1.5.3
- zero error (the equipment not being reset to zero before use), as shown in Figure 1.5.4.

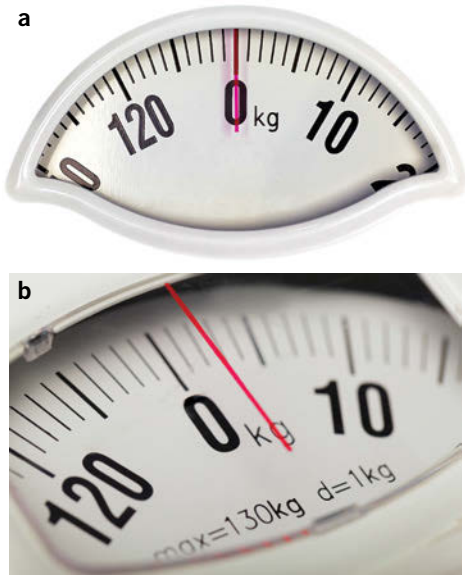


FIGURE 1.5.3 (a) The correct reading of 0 kg is obtained when the scale is viewed from directly in front. (b) An incorrect reading of 2 kg is obtained because of parallax error when reading an analog scale at an angle.

FIGURE 1.5.4 Three examples of zero error on analog instruments: (a) voltmeter (b) ammeter and (c) a digital instrument (an electronic balance).

Systematic errors are caused by incorrectly using or setting up equipment.

Systematic errors cannot be reduced by repeated measurements. The only way to reduce these errors is to use more precise and correctly calibrated equipment.

Systematic errors do not affect the precision of a series of measurements, but they do affect the accuracy. A low value of systematic error indicates that a measurement is very accurate.

Random errors

These errors are naturally occurring and are always present even if the equipment and techniques are perfect. Examples of where these types of errors occur include:

- not taking enough measurements
- not rejecting any outliers
- not averaging the measurements.

Random errors cannot be eliminated, but can be reduced by repeating the experiment many times, removing any outliers, and finding the average of the values.

Random errors are always present in any measurement and they cannot be totally eliminated.

Random errors do not affect the accuracy of a series of measurements, but they do affect the precision. Low values of random errors indicate that a measurement is very precise.

Determining an uncertainty in a single measurement

When using an instrument to measure a property of an object, there will always be a limit as to how precise the reading can be. In a physics experiment, analog and digital instruments are both used and measurements are determined slightly differently depending on which device is used.

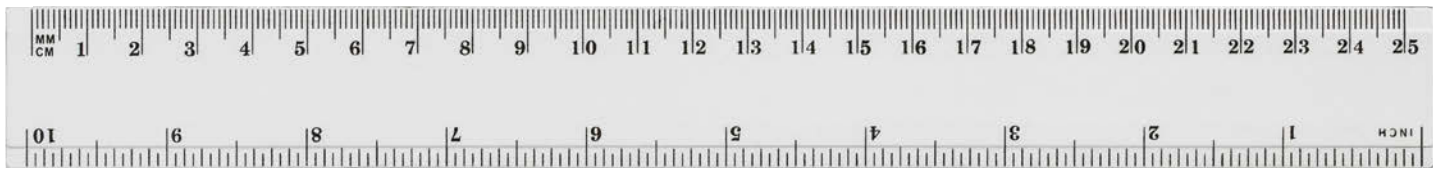
The precision that can be read off a single instrument is called the limit of reading. This is the smallest visible graduation on an analog instrument, or, if a digital instrument is used, then the limit of reading is usually the smallest decimal place given on the screen.

For most analog instruments, the absolute uncertainty, Δx, in a measurement of x is exactly half of the limit of reading for each part of the measured object that has to be lined up. This means that the actual measurement could be anywhere from half of the smallest graduation too big to half of the smallest graduation too small.

Some analog instruments have a zero mark and a reading mark, such as the ruler shown in Figure 1.5.5a. The object to be measured has to be lined up at both ends, therefore doubling the absolute uncertainty. For rulers and protractors the absolute uncertainty is equal to the limit of reading, not half of it.

For a digital instrument, Δx is typically the limit of reading, or the smallest decimal place given on the screen. An example of this is a high-precision electronic balance, as shown in Figure 1.5.5b.

a



b

FIGURE 1.5.5 (a) The ruler has a limit of reading of 1 mm and (b) the electronic balance has a limit of reading of 0.001 g.

Usually, the absolute uncertainty in a measurement will have 1 significant figure, or 2 significant figures if the first digit is 1. This is because the uncertainty of a measurement is an estimate, and writing more than 2 significant figures is therefore meaningless.

When the absolute uncertainty has been determined, the measurement should be rounded so that it and the absolute uncertainty have the same number of decimal places. This is to keep the measurement and its uncertainty to the same precision.

Table 1.5.2 lists several examples of measurements and their absolute uncertainties.

TABLE 1.5.2 Examples of writing a measurement and its absolute uncertainty

Measurement and absolute uncertainty	Comments
48.2 ± 1.0°C	The absolute uncertainty is written to 2 significant figures because the first digit is 1. The measurement and uncertainty have the same number of decimal places.
99.99 ± 0.01 s	The measurement and absolute uncertainty are written to 2 decimal places, with 1 significant figure for the uncertainty. This measurement of time may have been recorded using a digital device such as a datalogger because the precision is quite high.
0.000 000 031 ± 0.000 000 005 kg	This is technically a correct way of writing a measurement and its absolute uncertainty, but it is normally written in scientific notation so that the measurement and uncertainty have the same power of 10, i.e. $(3.1 \pm 0.5) \times 10^{-8}$ kg.

Table 1.5.3 summarises the limit of reading and absolute uncertainty of common analog instruments used in a high school physics lab.

For analog instruments that have one scale to line up (such as a measuring cylinder, thermometer or voltmeter), the absolute uncertainty, Δx, in a measurement of x is exactly half of the limit of reading for each part of the measured object that has to be lined up.

For analog instruments that have two scales to line up (such as rulers and protractors) the absolute uncertainty, Δx, is equal to the smallest graduation scale, or limit of reading.

For digital instruments the absolute uncertainty, Δx, is equal to the smallest decimal place displayed.

TABLE 1.5.3 A summary of common instruments and their uncertainties used in a physics laboratory

Instrument	Type of instrument	Limit of reading	Absolute uncertainty	Example	Notes
mm ruler	analog	1 mm	± 1.0 mm	123.8 ± 1.0 mm	Half of the limit of reading is 0.50 mm, but the object to be measured has to be lined up at both ends, so the uncertainty is double this, or ±1.0 mm.
cm ruler	analog	1 cm	± 1.0 cm	31.4 ± 1.0 cm	As for a mm ruler.
Vernier callipers	analog	0.05 mm	0.05 mm	19.44 ± 0.05 mm	Vernier callipers and micrometers use screws to determine the measurement (shown in Figure 1.5.6).
micrometer	analog	0.01 mm	± 0.01 mm	7.13 ± 0.01 mm	
thermometer	analog	1.0°C	± 0.5°C	24.4 ± 0.5°C	Only the top part of the liquid in the thermometer has an uncertainty, so the uncertainty is exactly half of the limit of reading.
measuring cylinder	analog	1.0 mL	± 0.5 mL	15.7 ± 0.5 mL	The limit of reading and absolute uncertainty depend on the size of the measuring cylinder.
protractor	analog	1.0°	± 1.0°	30.1 ± 1.0°	The two lines that make up the angle have to be lined up, so the uncertainty is twice half of the limit of reading, similar to that in mm and cm rulers.
stopwatch	digital	0.01 s	from ± 0.1 to ± 0.4 s	9.6 ± 0.2 s	The limit of reading is not the absolute uncertainty for a stopwatch because the user's reaction time (usually between 0.1 and 0.4 s) needs to be taken into consideration.
electronic balance	digital	typically 0.01 g	± 0.01 g	7.03 ± 0.01 g	The absolute uncertainty is the smallest possible decimal place displayed.

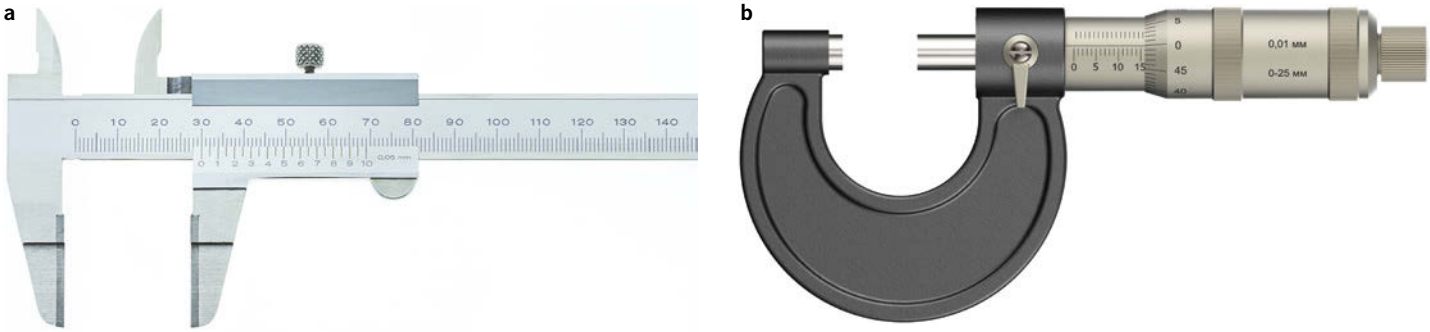


FIGURE 1.5.6 (a) A Vernier calliper and (b) micrometer use screws to determine the measurement.

How to write a measurement and its absolute uncertainty is summarised below:

1 Determine the absolute uncertainty from the type of instrument used to measure the quantity.
2 Measure the quantity, including an estimate of the final significant figure.
3 If the first digit of the absolute uncertainty is 1, then one more significant figure can be quoted. Usually this extra digit is zero.
4 The measurement is then rounded up or down to the same number of decimal places, or place value holders, as the uncertainty.
5 Do not forget the unit of measurement for the quantity.

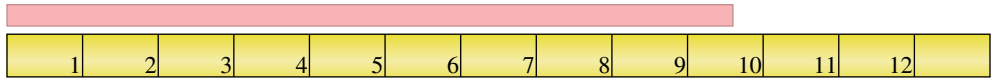
> **i** The absolute uncertainty should be written to 1 or 2 significant figures, which then determines to how many decimal places the measurement is written.

Worked example 1.5.4

READING MEASUREMENTS

For each of the following objects, determine its measurement and uncertainty.

a The length of the pink rectangle is measured with a ruler calibrated in cm.



Thinking	Working
The pink rectangle is between 9 cm and 10 cm in length, so the best estimate for this is 9.6 cm.	Length $L = 9.6\,\text{cm}$
The limit of reading is 1.0 cm so this is the uncertainty in a cm ruler.	$\Delta L = \pm 1.0\,\text{cm}$
Write the measurement and the uncertainty.	Length = 9.6 ± 1.0 cm

b The temperature of tap water is measured using an analog thermometer.

Thinking	Working
The temperature is between 40.1°C and 40.2°C, with the best estimate of 40.14°C.	Temperature $T = 40.14°\text{C}$
The limit of reading is 0.1°C so the uncertainty is half of this: 0.05°C.	$\Delta T = \pm 0.05°\text{C}$
Write the measurement and uncertainty.	$T = 40.14 \pm 0.05°\text{C}$

c The temperature of a bucket of tap water is measured using a digital thermometer.

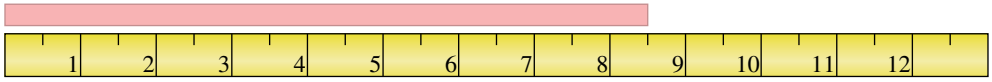
Thinking	Working
This temperature measurement is done using a digital thermometer, so the temperature is simply read off the screen at 36.4°C.	Temperature $T = 36.4°C$
The uncertainty in this measurement is then 1 of the smallest decimal value: ± 0.1°C.	$\Delta T = \pm 0.1°C$
Write the measurement and uncertainty.	$T = 36.4 \pm 0.1°C$

➤ Try yourself 1.5.4

READING MEASUREMENTS

For each of the following objects, determine its measurement and uncertainty.

a The length of the pink rectangle is measured with a ruler calibrated in half-cm intervals.



b The volume of the liquid is measured in a measuring cylinder calibrated in mL.

c The mass of this apple is measured on an electronic balance.

Determining an uncertainty in a number of trials of a measurement

The information above described how to determine the absolute uncertainty in a single measurement. To reduce the absolute uncertainty of a measurement, take as many trials as possible of the same measurement.

Once a series of trials of a single measurement has been taken, the best estimate of the value of the quantity is the average, or mean:

$$x_{best} = \bar{x} = \frac{\text{sum of the individual trials, } x_1, x_2 \ldots}{\text{number of trials, } n} = \frac{\sum x}{n}$$

The absolute uncertainty of the mean, $\bar{x}$, is found by finding the difference between the smallest and largest individual trials, then dividing by 2:

$$\Delta\bar{x} = \pm\left(\frac{x_{max} - x_{min}}{2}\right)$$

Note that if the absolute uncertainty of the mean gives a smaller value than the individual absolute uncertainties, then the absolute uncertainty of the mean should be the absolute uncertainty of the individual measurements.

For a series of trials of a single measurement, the best estimate of the measurement is the mean, or average, and the best estimate of its uncertainty is the absolute uncertainty of the mean.

Worked example 1.5.5

UNCERTAINTIES IN THE MEAN OF A SET OF MEASUREMENTS

The thickness, *t*, of a copper wire was measured along six points and recorded in mm (using a micrometer with an uncertainty of ± 0.01 mm) as:

5.84, 5.83, 5.82, 5.85, 5.79, 5.81

Calculate the mean (average) value for the thickness of the copper wire and its absolute uncertainty.

Thinking	Working
First, calculate the mean of the set of measurements. Note that the mean is not rounded to the correct number of decimal places at this stage.	$t = \frac{5.84 + 5.83 + 5.82 + 5.85 + 5.79 + 5.81}{6}$ $= \frac{34.94}{6}$ $= 5.8233333\,\text{mm}$
Find the uncertainty in the mean using the difference between the maximum and minimum values, divided by 2.	$t = \pm \frac{5.85 - 5.79}{2}$ $= \pm \frac{0.06}{2}$ $= \pm 0.03\,\text{mm}$
This value is larger than each individual uncertainty, so it will now be the final absolute uncertainty of the mean. This has 1 significant figure, so no rounding of the uncertainty needs to be done. It also has 2 decimal places, so the mean will be rounded to also have 2 decimal places as the final value.	$t = 5.82 \pm 0.03\,\text{mm}$

➤ Try yourself 1.5.5

UNCERTAINTIES IN THE MEAN OF A SET OF MEASUREMENTS

The masses, *m*, of five pendulum bobs taken from the same batch were measured using an electronic balance set to grams:

24.66 g, 24.59 g, 24.51 g, 24.76 g, 24.75 g

Calculate the mean (average) mass of the pendulum bobs and the absolute uncertainty in the mean.

PROPAGATING UNCERTAINTIES

Propagating uncertainties means combining the uncertainties in one set of data and with the uncertainties in another data set. To help with these calculations, an uncertainty can be written three ways:

- Absolute uncertainty: $\Delta\overline{x} = \pm\left(\frac{x_{max} - x_{min}}{2}\right)$
- Fractional uncertainty = $\frac{\text{absolute uncertainty}}{\text{measurement}}$
- Percentage uncertainty = $\frac{\text{absolute uncertainty}}{\text{measurement}} \times 100\%$

Note that only the absolute uncertainty has the same units as the measurement and should only have the rules for significant figures and decimal places applied to it. When quoting a final value of the uncertainty of a measurement, the absolute uncertainty should always be used.

Table 1.5.4 shows some examples of writing the absolute uncertainty as a fractional uncertainty and percentage uncertainty.

The percentage uncertainty is a way of writing the uncertainty of a measurement as a percentage of the measurement.

TABLE 1.5.4 Conversions between the absolute, fractional and percentage uncertainties

Measurement and absolute uncertainty	Fractional uncertainty	Percentage uncertainty
20.2 ± 0.5 cm	$\frac{0.5}{20.2} = 0.0248$	$\frac{0.5}{20.2} \times 100\% = 2.48\%$
116.48 ± 0.01 g	$\frac{0.01}{116.48} = 8.59 \times 10^{-5}$	$\frac{0.01}{116.48} \times 100\% = 0.00859\%$
5.0 ± 1.0°	$\frac{1.0}{5.0} = 0.2$	$\frac{1.0}{5.0} \times 100\% = 20\%$

In physics, is it often necessary to calculate values with two or more measurements using a formula. Not only do the measurements need to have some mathematical operation performed on them, but so do the uncertainties.

Adding or subtracting uncertainties

If an operation involves an addition or subtraction of two or more measurements, then you must also add the absolute uncertainties.

- If a and b are two measured values with absolute uncertainties of Δa and Δb, and their sum is $y = a + b$, then $y = a + b$.
- If a and b are two measured values with absolute uncertainties of Δa and Δb, and their difference is $y = a - b$, then $y = a + b$.

This means that it doesn't matter whether the operation is addition or subtraction, the absolute uncertainty is the total sum of the individual uncertainties.

If measurements are being added or subtracted, their absolute uncertainties are always added.

Worked example 1.5.6

ADDING OR SUBTRACTING UNCERTAINTIES

Perform the following calculation:
(2.6 ± 0.5) cm + (2.8 ± 0.5) cm

Thinking	Working
First ignore each uncertainty and add the measurements.	Let x be the sum of the two quantities. $x = 2.6 + 2.8 = 5.4$ cm
This is an addition operation, so add the absolute uncertainties.	$\Delta x = 0.5 + 0.5 = 1.0$ cm
The absolute uncertainty can have 2 significant figures here because the first digit is 1. The absolute uncertainty also has 1 decimal place so x will also have 1 decimal place.	$x = 5.4 \pm 1.0$ cm

➤ Try yourself 1.5.6

ADDING OR SUBTRACTING UNCERTAINTIES

Perform the following calculation:
$(4 \pm 2)\,\text{N} - (5.33 \pm 0.05)\,\text{N}$

Multiplying or dividing uncertainties

If an operation involves a multiplication or division, then the percentage or fractional uncertainties always add. The percentage uncertainty is then changed back into an absolute uncertainty as the final step.

- If a, b and c are three measured values with absolute uncertainties of Δa, Δb and Δc, and y is given by $y = \frac{ab}{c}$, then $\frac{\Delta y}{y} = \frac{\Delta a}{a} + \frac{\Delta b}{b} + \frac{\Delta c}{c}$, where $\frac{a}{a}$ is the fractional uncertainty in a.
- If a, b and c are three measured values with absolute uncertainties of Δa, Δb and Δc, and y is given by $y = \frac{ab}{c}$, then $\frac{y}{y}\% = \frac{a}{a}\% + \frac{b}{b}\% + \frac{c}{c}\%$, where $\frac{a}{a}\%$ is the percentage uncertainty in a.

This means that it doesn't matter whether the operation is multiplication or division, the percentage or fractional uncertainties always add. Uncertainty calculations must all be done as fractional uncertainties, or all done as percentage calculations; never mix the two types.

Note that if a measurement is multiplied or divided by a constant then the uncertainty is also multiplied or divided by the same constant.

If measurements are being multiplied or divided, their percentage uncertainties always add.

Any constants have an absolute and percentage uncertainty of exactly zero.

Worked example 1.5.7

MULTIPLYING OR DIVIDING UNCERTAINTIES

Perform the following calculation:
$(6.2 \pm 0.5)\,\text{cm} \times (2.81 \pm 0.01)\,\text{cm}$

Thinking	Working
First ignore each uncertainty and multiply the measurements. Do not forget to operate on the units as well.	Let x be the product of the two quantities: $x = 6.2 \times 2.81 = 17.422\,\text{cm}^2$
This is a multiplication operation, so the absolute uncertainties will need to be converted into percentage uncertainties.	$6.2 \pm 0.5\,\text{cm} = 6.2 \pm \frac{0.5}{6.2} \times 100\%\,\text{cm} = 6.2 \pm 8.06\%\,\text{cm}$ $2.81 \pm 0.01\,\text{cm} = 2.81 \pm \frac{0.01}{2.81} \times 100\%\,\text{cm} = 2.81 \pm 0.356\%\,\text{cm}$
The percentage uncertainties are now added.	$\Delta x\% = 8.06\% + 0.356\% = 8.416\%\,\text{cm}^2$
And the percentage uncertainty is now converted back into an absolute uncertainty.	$x = 8.416\%$ of $17.422\,\text{cm}^2$ $= \frac{8.416}{100} \times 17.422$ $= 1.466\,\text{cm}^2$
The absolute uncertainty has 1 as its first digit, therefore one more digit can be quoted: $\Delta x = 1.5$. The absolute uncertainty also has 1 decimal place so x will also have 1 decimal place.	$x = 17.4 \pm 1.5\,\text{cm}^2$

➤ Try yourself 1.5.7

MULTIPLYING OR DIVIDING UNCERTAINTIES

Perform the following calculation:
$(2.0 \pm 0.2)\,\text{cm} \div (3.0 \pm 0.6)\,\text{s}$

Squaring, square root or other powers with uncertainties

If an operation involves an index or power, then the percentage uncertainty is multiplied by the absolute value of the power. The percentage uncertainty is then changed back into an absolute uncertainty as the final step.

Remember that any index or square root can be written as a single power.

For example, $\sqrt{x} = x^{0.5}$, and $\frac{1}{x} = x^{-1}$

If a is a measured value with an absolute uncertainty of Δa, and y is $y = a^n$, then:

$$\frac{y}{y}\% = |n|\frac{a}{a}\%$$

This means that the percentage uncertainty in y is the percentage uncertainty of a multiplied by the positive value of the power, n. The absolute value $|n|$ is the magnitude of n and does not include the sign.

Note that addition, subtraction, multiplication, division, powers and square roots are the only operations that require you to work out the uncertainties. Other functions such as sin, cos and tan require the use of calculus, so you will not need to directly calculate the uncertainties of these operations in this course.

When propagating uncertainties with a mixture of addition, subtraction, multiplication, division and indices, perform the addition and subtraction calculations first, then the multiplication, division and power calculations.

i When raising a measurement to an index, the percentage uncertainty is multiplied by the absolute value of the index.

i When propagating uncertainties, perform the addition and subtraction calculations first.

Worked example 1.5.8

MIXED UNCERTAINTY CALCULATIONS

If $a = 4.52 \pm 0.02$ m and $b = 2.0 \pm 0.2$ s, then calculate c and its uncertainty when $c = a^2b^3$.

Thinking	Working
First ignore each uncertainty and perform the calculation for c. Don't forget the units.	$c = 4.52^2 \times 2.0^3$ $= 163.4432\ \text{m}^2\text{s}^3$
This is a multiplication operation, so the absolute uncertainties will need to be converted into percentage uncertainties.	$a = 4.52 \pm 0.02\ \text{m}$ $= 4.52 \pm \frac{0.02}{4.52} \times 100\%\ \text{m}$ $= 4.52 \pm 0.4425\%\ \text{m}$ $b = 2.0 \pm 0.2\ \text{s}$ $= 2.0 \pm \frac{0.2}{2.0} \times 100\%\ \text{s}$ $= 2.0 \pm 10\%\ \text{s}$
To obtain the final percentage uncertainty the individual percentage uncertainties are multiplied by the powers of a and b given in the formula.	$c\% = 2 \times 0.4425\% + 3 \times 10\%\ \text{m}^2\text{s}^3$ $= 0.885\% + 30\%\ \text{m}^2\text{s}^3$ $= 30.885\%\ \text{m}^2\text{s}^3$
Now convert the percentage uncertainty into an absolute uncertainty.	$c = 30.885\%$ of 163.4432 $= \frac{30.885}{100} \times 163.4432$ $= 50.48\ \text{m}^2\text{s}^3$
The absolute uncertainty does not have 1 as its first digit, therefore it must be rounded to 1 significant figure: $\Delta c = 50$. The absolute uncertainty therefore is written to the 10s placeholder, so c will also be written to the nearest 10s placeholder. An alternative to this is to write c and its uncertainty to the same power of 10.	$c = 160 \pm 50\ \text{m}^2\text{s}^3$ $= (1.6 \pm 0.5) \times 10^2\ \text{m}^2\text{s}^3$

➤ Try yourself 1.5.8

MIXED UNCERTAINTY CALCULATIONS

If $a = 3.6 \pm 0.6$ m, $b = 9.91 \pm 0.01$ m, and $c = 4.9 \pm 0.5$ kg, calculate d when $d = \frac{a+b}{\sqrt{c}}$.

1.5 Review

SUMMARY

- All measurements made in physics experiments are subject to a level of uncertainty, or doubt, to the precision of that measurement.
- A measurement without an uncertainty is meaningless.
- Accuracy is a description of how close a measurement is to an accepted value.
- Precision is a description of how many digits can be written down for a single measurement, or how close together a group of measurements are.
- Significant figures are a way of communicating the precision of a measurement. There are specific rules governing how many significant figures there can be in any measurement.
- Systematic errors or uncertainties arise due to mistakes in calibrating or using equipment the wrong way for every measurement.
- Random errors or uncertainties are naturally occurring and cannot be eliminated.
- The limit of reading of an instrument is the smallest graduation on the device.
- The absolute uncertainty of a measurement is determined by the limit of reading of an instrument.
- Uncertainties can be written as an absolute, a fraction or a percentage.
- Propagation of uncertainties involves the mathematical combination of uncertainties from a range of variables.
- When adding or subtracting measurements, the individual absolute uncertainties are added.
- When multiplying or dividing measurements, the individual percentage uncertainties are added.
- When raising a measurement to a power, the percentage uncertainty is multiplied by the absolute value of the power.
- When using measurements in a formula, perform any addition and subtraction propagations first, followed by multiplication, division and indices.

KEY QUESTIONS

Retrieval

1 State the type of error associated with:
- **a** inaccurate measurements
- **b** imprecise measurements.

2 Identify whether each of the situations below is a mistake, a systematic error or a random error.
- **a** A student measured the lengths of three different wires using a cm ruler but did not check that the wire was lined up at the zero mark on the ruler.
- **b** A student was measuring the mass of approximately 2 g samples of 5-cent pieces using a balance that was accurate to the nearest 1 g.
- **c** A student sometimes forgot to re zero the balance between weighing trolleys used in a motion experiment.

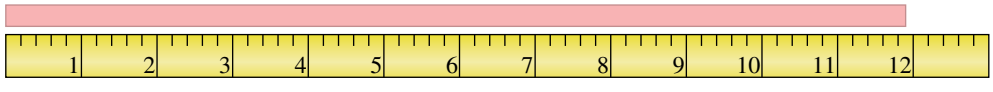
3 State the absolute uncertainty of the following instruments.
- **a** a cm ruler
- **b** a protractor graduated in degree intervals
- **c** an electronic balance giving a reading down to the nearest 0.001 g
- **d** an analog needle voltmeter graduated in 10 volt intervals

Comprehension

4 Explain why it would be unreasonable to state that the absolute uncertainty in a handheld stopwatch is ± half of the limit of reading, or ± 0.005 s.

5 Explain why repeated measurements do not change the systematic error.

6 Determine the length, and absolute uncertainty, of the pink rectangle using the given scale calibrated in cm.



7 Write these measurements and uncertainties to the correct number of significant figures and decimal places.

a $(9.11 \times 10^{-31}) \pm (2.2345 \times 10^{-31})$ kg

b $(0.0023456 \pm 1.623 \times 10^{-4})$ s

Analysis

8 Differentiate between precision and accuracy.

9 A friend asks to borrow your precious diamond for a day to show her family. You are a bit worried, so you carefully weigh your diamond on a scale that reads 8.17 g. The scale's precision is claimed to be ±0.05 g. The next day you weigh the returned diamond again, getting 8.09 g. Determine if this is your diamond.

10 The electrical power, P, dissipated by a resistor in an electrical circuit is given by:

$P = I^2R$

where

I is the current (A)

R is the resistance (Ω).

If the percentage uncertainty in I is ±7% and the percentage uncertainty in R is ±10%, calculate the percentage error in P.

11 If $a = 20.0 \pm 0.5$ m and $b = 5 \pm 1$ m, calculate the value and absolute uncertainty of $c = 2a - b$.

12 Calculate C and ΔC, if $C = 2\pi r$ and $r = 4.12 \pm 0.05$ m.

13 The density of an object is found by dividing its mass by its volume. An iron cube had its side length and mass measured five times.

Mass (±0.01 g)	121.37	121.40	121.39	121.36	121.38
Side length (±0.05 cm)	2.47	2.49	2.48	2.47	2.50

Calculate:

a the average mass (with its uncertainty)

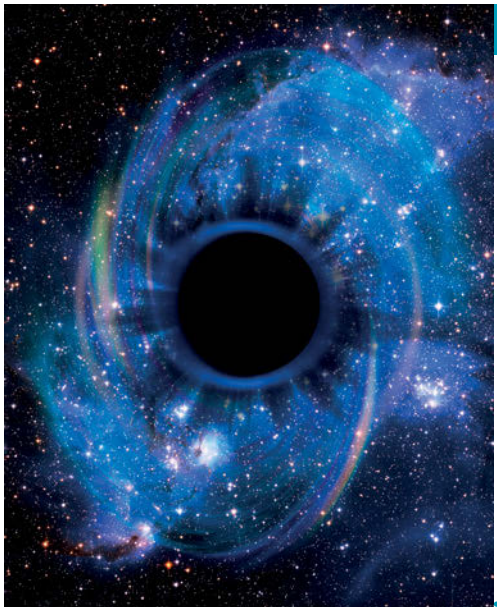
b the average side length

c the volume of the cube

d the density of the cube.

14 If $w = 4.52 \pm 0.02$ m, $x = 2.0 \pm 0.2$ m, and $y = 3.0 \pm 0.6$ m, determine z when $z = wx + y^2$.

1.6 Graphing



BY THE END OF THIS MODULE, YOU SHOULD BE ABLE TO:

- appreciate that graphs can show a wealth of information relating two or more variables and constants, including their uncertainties
- understand that graphs can be used to predict relationships between variables or used to find outliers in data
- display data, including error bars, line of best fit, minimum and maximum lines of primary and secondary data
- recognise the common types of graphs or relationships seen in physics and know examples of each
- linearise data that is not already producing a straight line graph
- use the equation of a straight line of best fit to determine the gradient and *y*-intercept
- use the gradient and *y*-intercept in further processing of data
- use the minimum and maximum lines to calculate an uncertainty in the gradient and *y*-intercept.

USING GRAPHS IN PHYSICS

A graph is a very useful tool. In physics, data is plotted using a line or curved graph and it is sometimes called a scatterplot. In graphs:

- data can be seen visually
- incorrect data points can be ignored
- constants can be determined from the properties of the line or curve
- uncertainties can be seen as error bars
- a line of best fit or trend line can be drawn to show the trend of the data points
- any known relationship between the dependent and independent variables can be supported or rejected, especially by the use of uncertainties.

Figure 1.6.1 shows an example of a typical graph used in physics complete with error bars and line of best fit.

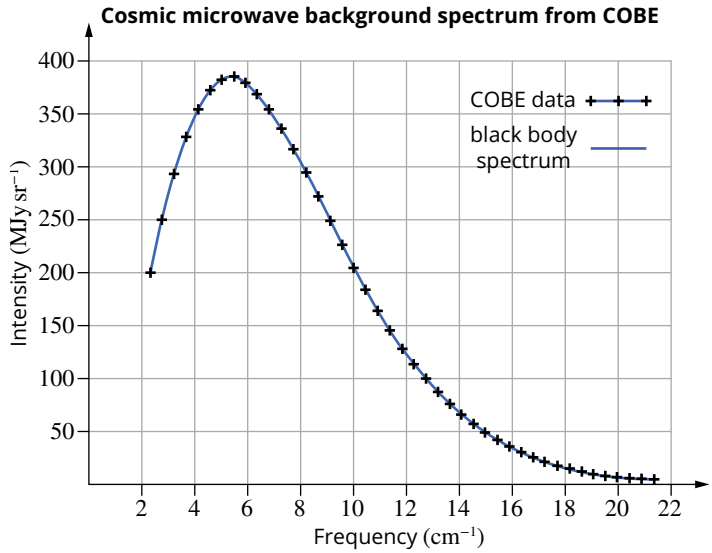


FIGURE 1.6.1 One of the best fits of data to theory is the intensity of microwaves coming from deep space against their frequency measured by the COBE satellite in the 1990s.

The shape of a curve can be used to suggest a possible relationship between the dependent and independent variables. Figure 1.6.2 shows a hypothetical relationship between Bloxists and Dubars. The number of Bloxists measured against the rate of Dubars in the graph suggests there is an inverse relationship from the shape of the graph and from the index of the trend line. The trend line passes through each error bar, so the inverse relationship between Bloxists and Dubars appears to be real.

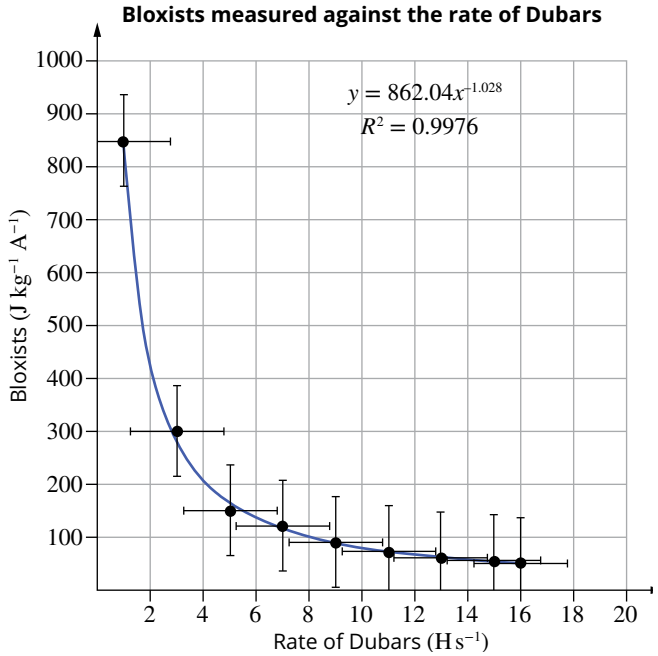


FIGURE 1.6.2 This hypothetical graph of Bloxists versus rate of Dubars shows how the shape of a graph and its error bars can suggest a particular relationship between variables.

Graphs can display 'holes' or missing data, and therefore where more measurements need to be taken, especially around rapidly changing values. Figure 1.6.3 shows many data points located around the 0.5 phase value in order to confirm the curvature of the data.

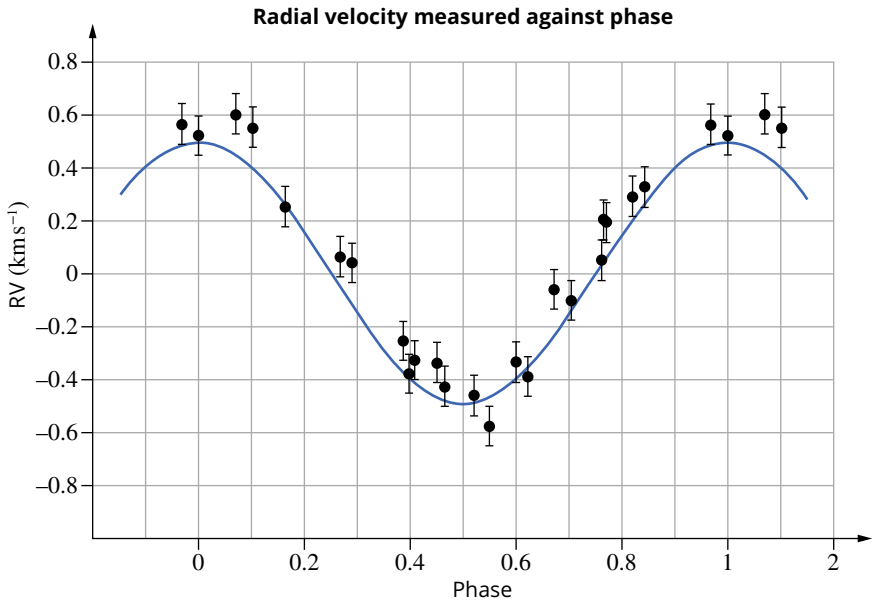


FIGURE 1.6.3 The radial velocity curve and *y*-axis error bars for an exoplanet orbiting the star Tau Boötis. Many data points were taken around the 0.5 phase values in order to confirm that that point was an important part of the best-fit curve.

DRAWING GRAPHS IN PHYSICS

General rules to follow when drawing a graph in physics:

1 Use a suitable set of axes for the independent and dependent variables.

Most physics graphs are only drawn in the first quadrant, but some graphs use all four quadrants (i.e. have negative values for the independent and dependent variables).

- The independent variable is the variable that you deliberately change and always goes along the *x*-axis.
- The dependent variable is the variable that depends on the variable you change and always goes on the *y*-axis.

2 Use a suitable scale that allows information to be seen easily and quickly.

For most graphs it is important to choose a scale that is linear and has tick marks at common intervals (e.g. 2, 5, 10, 100 units).

3 Add a title and labels for the axes.

Make sure that the axis labels show information about the quantity and units. Give a descriptive title that is not just a repeat of the labels of the axes.

4 Plot data points as a small circle or small cross indicating their position.

5 Include error bars drawn for each point.

These indicate the absolute uncertainties in the independent and dependent values. They are drawn as a horizontal line centered on the data point indicating the uncertainty of the the independent variable left and right of the value, and as a vertical line centered on the data point above and below the value, indicating the the uncertainty of the dependent variable. The error bars for *x* and *y* form an error rectangle that the true measurement is located within. This is all shown in Figure 1.6.4.

The smaller the errors bars for a given point, the more precise the measurement is.

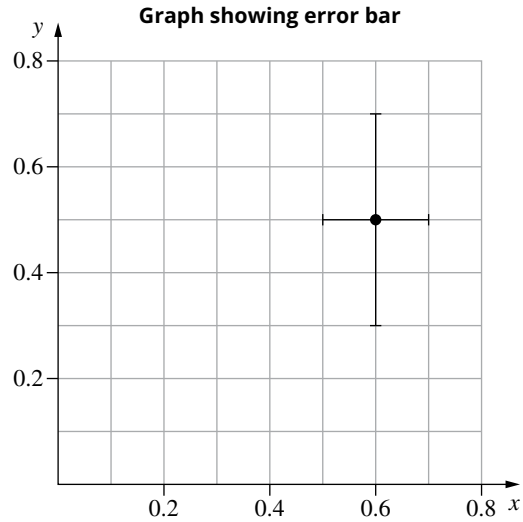


FIGURE 1.6.4 This data point has an *x*-value of 0.6 ± 0.1, and a *y*-value of 0.5 ± 0.2.

Error bars are the graphical representation of the uncertainties in the independent and dependent variables.

6 Draw a line of best fit.

This is the straight line or a curve that best summarises the data. This line does not have to pass through every point nor the origin, but does have to be one smooth continuous line or curve and not a 'join the dots'. Typically the line of best fit should have as many points on the line as possible, but if this is not possible then it should have as many points above the line as there are below the line or curve.

Figure 1.6.5 shows that the line of best fit should normally pass through the error bars of each point, and be extrapolated so that it intersects the *y*-axis.

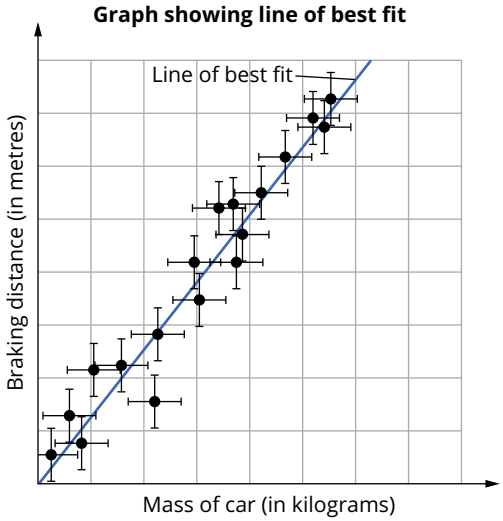


FIGURE 1.6.5 A graph showing the line of best fit passing through the data, as well as the *y*-intercept.

TYPES OF GRAPHS SEEN IN PHYSICS

In physics, many relationships that exist between two variables can be represented using formulas and graphs. The following types of graphs are common in the study of physics. You will encounter all of these graphs at some stage during the course.

> The line of best fit is a straight line or curved line that best summarises the general pattern of the data on the graph.

Linear graphs

Straight line or linear graphs represent variables that have a constant rate of change and the power of each variable is 1. The gradient and *y*-intercept of a linear graph are calculated easily, as shown in Figure 1.6.6. The general equation of a straight line is:

$$y = mx + c$$

where

m is the gradient

c is the *y*-intercept.

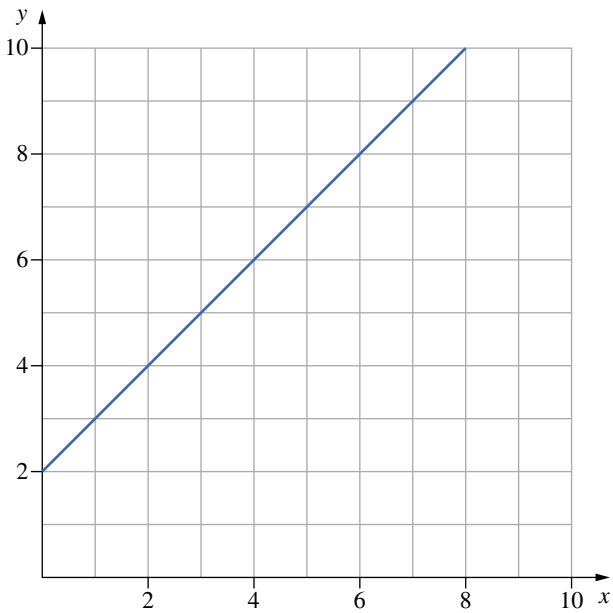


FIGURE 1.6.6 The linear, or straight line, graph. In this example, the equation of the line is $y = x + 2$, with a gradient of 1 and *y*-intercept of 2.

Examples of linear relationships in physics include force against acceleration and momentum against velocity. Note that, if the y-intercept of the equation is zero, then the relationship between the x- and y-variables is said to be directly proportional and the equation is $y = mx$. The equation of the line in Figure 1.6.7 is $y = 2x$.

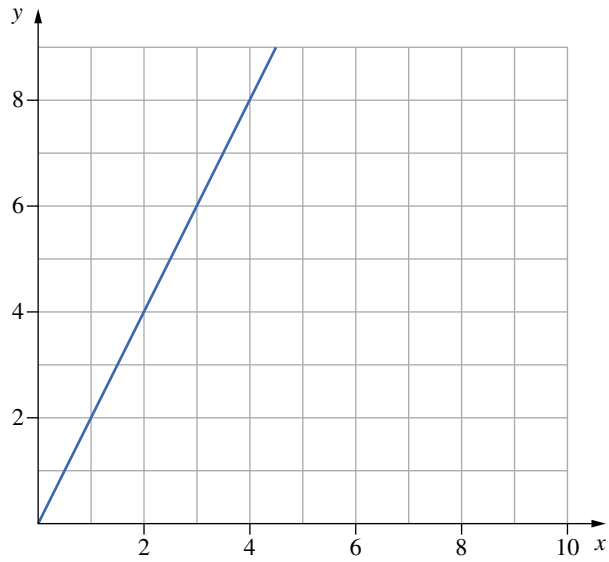


FIGURE 1.6.7 An example of a direct proportion. The equation of the line is $y = 2x$. The line passes through the origin and has a gradient of 2.

Linear graphs of the form $y = mx + c$ either increase (if the gradient is positive) at a constant rate, or decrease (if the gradient is negative) at a constant rate.

Parabolas

Parabolas represent relationships in which the independent variable is squared and the dependent variable increases at an increasing rate, as shown in Figure 1.6.8. The general equation of a parabola is:

$$y = kx^2$$

where k is a constant.

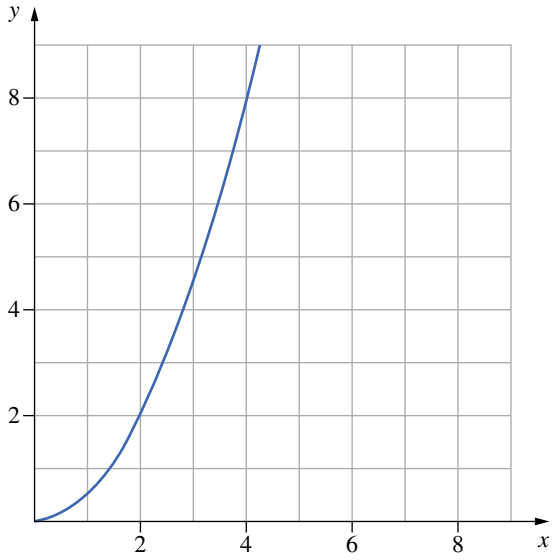


FIGURE 1.6.8 An example of a parabolic or squared graph. The equation of the parabola is $y = 0.5x^2$.

Examples of parabolic relationships in physics include kinetic energy against velocity and the position of a projectile against time, when launched at an angle to the horizontal.

Inverse functions or hyperbolas

These graphs represent variables with an inverse or $\frac{1}{\text{independent variable}}$ relationship. The curves decrease at a decreasing rate and do not intersect the x- or y-axes. When one variable increases, the other variable decreases, as shown in Figure 1.6.9. The general equation of a hyperbola is:

$$y = \frac{k}{x}$$

where k is a constant.

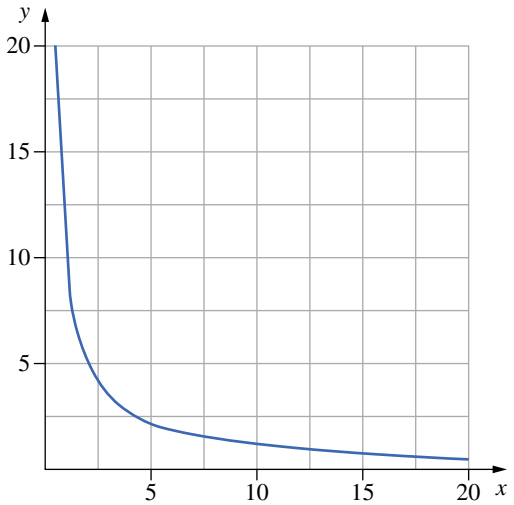


FIGURE 1.6.9 An example of a hyperbola, or inverse, graph. The equation of the hyperbola is $y = \frac{10}{x}$.

Examples of hyperbolic relationships in physics include pressure against volume, and object distance against image distance for a lens.

Periodic or sine and cosine graphs

These graphs represent relationships that oscillate between a maximum and minimum value over a period of time, as shown in Figure 1.6.10. The general equations of a sine graph and a cosine graph are, respectively:

$$y = A\sin\omega x$$
$$y = A\cos\omega x$$

where

A is the amplitude, or the maximum value of y

ω is the angular frequency of the motion ($\omega = 2 \times \pi \times$ frequency).

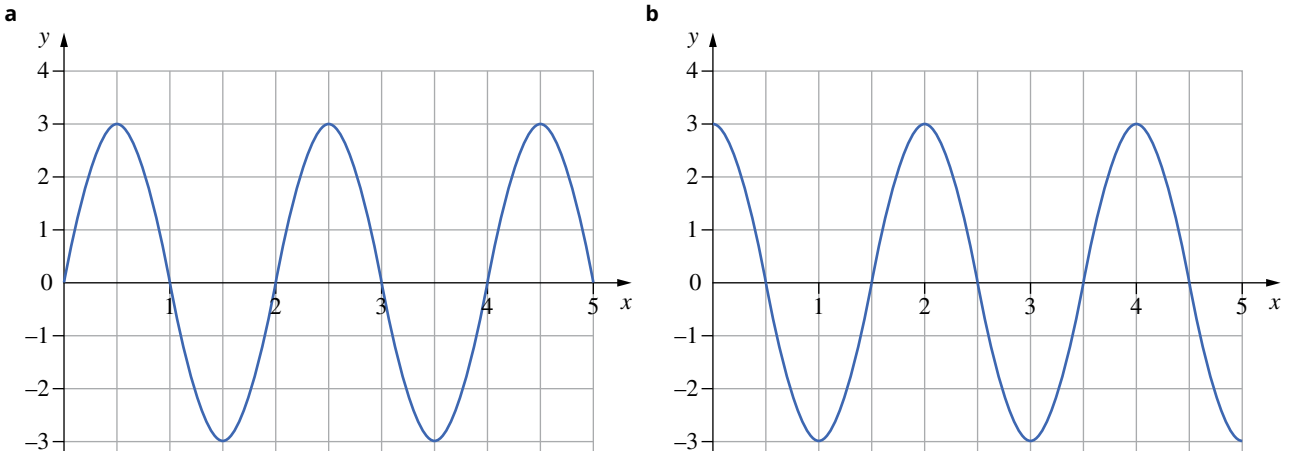


FIGURE 1.6.10 Examples of (a) a sine graph with equation $y = 3\sin\pi x$ and (b) a cosine graph with equation of $y = 3\cos\pi x$. The variable x is measured in radians in both cases.

Examples of sine and cosine relationships in physics include position versus time for a mass on a spring and current versus time for an alternating current supply.

Exponential decay

These graphs represent variables that decrease from an initial value over a period of time but never reach zero. The curves decrease at a decreasing rate, as shown in Figure 1.6.11. The equation of an exponential decay graph is:

$$y = Ae^{-kx}$$

where

A and k are constants

e is the mathematical constant 2.718 28…

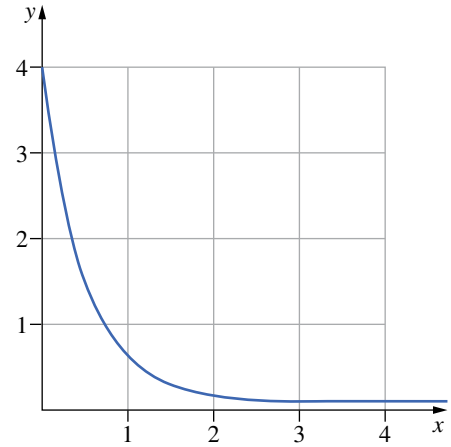


FIGURE 1.6.11 An exponential curve. In this example the equation of the curve is $y = 4e^{-2x}$, indicating that the initial value of the graph is 4.

Note that the exponential graph is different from an inverse relationship because an exponential relationship has a y-intercept, an inverse relationship does not.

An example of an exponential decay relationship in physics is the amount of decaying nuclear material remaining after a given time.

Square root graphs

These represent variables that increase but at a decreasing rate. This means that the dependent variable gets larger as the independent variable gets larger, but the difference becomes smaller and smaller. The equation for a square root graph (Figure 1.6.12) is:

$$y = k\sqrt{x}$$

where k is a constant.

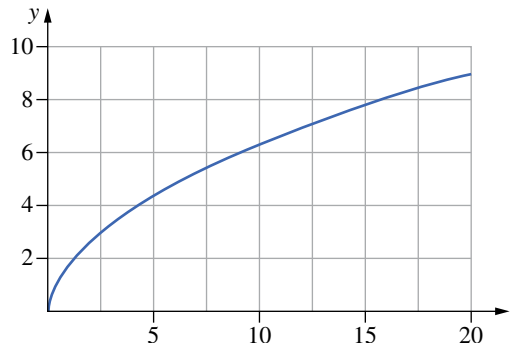


FIGURE 1.6.12 The square root curve. In this example the equation of the curve is $y = 2\sqrt{x}$.

Examples of where square root curves are used in physics are in the theoretical equation of the period of a pendulum and in many equations of relativity.

Table 1.6.1 summarises the common graphs seen in physics.

TABLE 1.6.1 A summary of the features of commonly encountered graphs and relationships seen in physics

Graph type	Basic equation	How y changes with x	Rate of change of y
directly proportional	$y = mx$	increasing if $m > 0$ decreasing if $m < 0$	constant
linear	$y = mx + c$	increasing if $m > 0$ decreasing if $m < 0$	constant
parabolic	$y = kx^2$	increasing if $k > 0$, decreasing if $k < 0$	increasing
hyperbolic	$y = \frac{k}{x}$	decreasing	decreasing
periodic	$y = A\sin\omega x$ $y = A\cos\omega x$	oscillating between maximum and minimum	N/A
exponential	$y = Ae^{-kx}$	decreasing	decreasing
square root	$y = k\sqrt{x}$	increasing	decreasing

LINEARISING DATA

A linear relationship is easy to analyse when processing raw data. The y-intercept and constant gradient are both readily calculated and the values often represent physical quantities. For example, the gradient of a graph of force against acceleration gives us the mass of the object from $F = ma$.

So, what happens if your raw data graph is *not* a straight line?

There are ways of processing the curved raw data to obtain values of constants, but they are not easy. A way around this is to convert the raw data into straight-line data via a process called linearisation.

Linearisation involves changing what is graphed along the horizontal and/or vertical axes so that a linear graph is produced. Note that this process does not alter the raw data in any way; it just changes how it is displayed as a graph and is a legitimate way of processing data.

For example, in an experiment the vertical displacement of a dropped rock was measured at various times from an initial height of 24.0 m. The data is shown below in Table 1.6.2 and are used to find a value for the acceleration due to gravity, g. Note that uncertainties were noted but have been removed for this example.

A graph of the raw data, with time on the x-axis and displacement on the y-axis, shows a parabolic relationship (Figure 1.6.13).

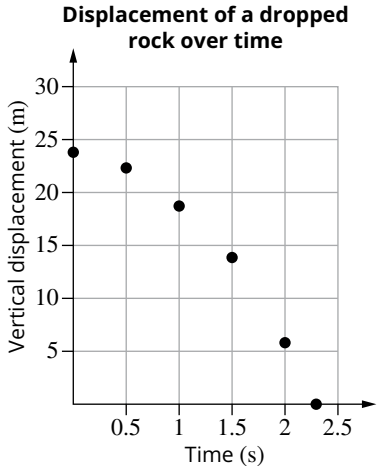


FIGURE 1.6.13 The graph shows a parabolic relationship between vertical displacement of an object falling under Earth's gravity and time.

Linear graphs are the easiest to analyse in physics as they have a y-intercept and a constant gradient.

If raw data does not show a linear trend, the data can be linearised. This involves modification of what is displayed along the independent and dependent axes to show a linear trend.

TABLE 1.6.2 Raw data of the height above the ground of a dropped rock at various times

Time (s)	Height above ground or displacement (m)
0.0	24.0
0.5	22.5
1.0	18.9
1.5	13.9
2.0	5.9
2.3	0.0

As this graph is not linear, it is not immediately apparent how to obtain information about the acceleration due to Earth's gravity. To analyse this data, the graph needs to be linearised to produce a straight line. The data 'looks' parabolic and this is backed up by the quadratic equation that relates the vertical displacement, s, of a falling object under Earth's gravity, g, over time, t:

$$s = \frac{1}{2}gt^2 + 24.0$$

This is a parabolic relationship between s and t because the independent variable, t, is squared.

To linearise this equation, you transform it into the straight-line equation $y = mx + c$, as shown in Figure 1.6.14. You then match the variables s to y and t^2 to x (shown in blue). You can see the gradient and y-intercept of the linearised t^2 graph (shown in red).

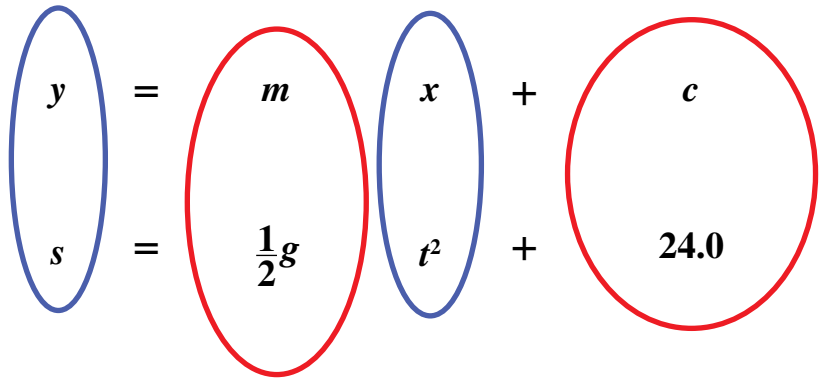


FIGURE 1.6.14 Linearising an equation

To linearise the quadratic equation $s = \frac{1}{2}gt^2 + 24.0$, you equate it to the general equation of a straight line $y = mx + c$:

s is plotted on the y-axis.

t^2 is plotted on the x-axis.

The gradient is $m = \frac{1}{2}g$.

The y-intercept is $c = 24.0$.

For the linearised version of the data, s is still on the y-axis, but the x-axis will now be t^2 rather than t. Time is squared, so insert a new column in the table of data. The y-intercept is the displacement when t is zero. From the table you can see that y-intercept is 24.0 m.

Note that in Table 1.6.3, the time^2 column is inserted immediately to the right of the original time data and that the unit of time is also squared. No change has been made to the displacement column.

TABLE 1.6.3 Processed data including time^2 to be used for the linearised version of the relationship between displacement and time

Time (s)	Time^2 (s^2)	Height above ground or displacement (m)
0.0	0.00	24.0
0.5	0.25	22.5
1.0	1.00	18.9
1.5	2.25	13.9
2.0	4.00	5.9
2.3	5.29	0.0

A graph of displacement versus time^2 should now be a straight line. Figure 1.6.15 shows this as a very good linear fit to the data (R^2 of 0.9994). The linear trend line is also shown.

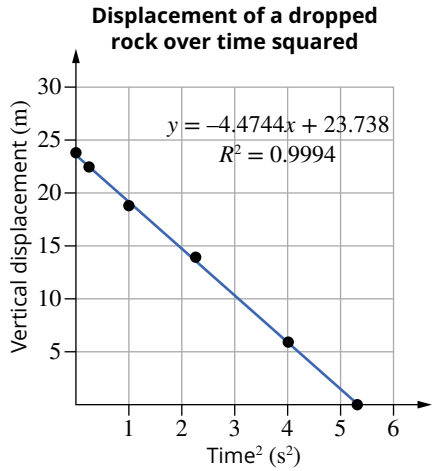


FIGURE 1.6.15 The linearised graph of vertical displacement against time^2, allowing the gradient and *y*-intercept to be used to calculate the acceleration due to Earth's gravity.

From the trend line, the gradient is $-4.4744\,\text{m s}^{-2}$, and *y*-intercept is 23.738 m.

The *y*-intercept value of 23.738 m is close to the actual *y*-intercept of 24.0 m, so it is an accurate result.

The gradient value of $-4.744\,\text{m s}^{-2}$ is much lower than the expected value of the acceleration due to Earth's gravity, *g*, which is $-9.80\,\text{m s}^{-2}$, so what went wrong? Remember that:

$$\text{Gradient} = \frac{1}{2}g$$
$$\therefore g = \text{gradient} \times 2$$
$$g = -4.4744 \times 2$$
$$= -8.9488\,\text{m s}^{-2}$$

This value is still slightly inaccurate but that is probably due to air resistance encountered by the falling rock.

This example showed that from non-linear raw data, a linear trend line could be used to find the values of the gradient and *y*-intercept.

Note that you can only linearise data if there is a relationship between the *x*- and *y*-variables in the first place, otherwise the linearisation process is meaningless. Figure 1.6.16 shows that linearisation is not possible if there is no relationship between the variables.

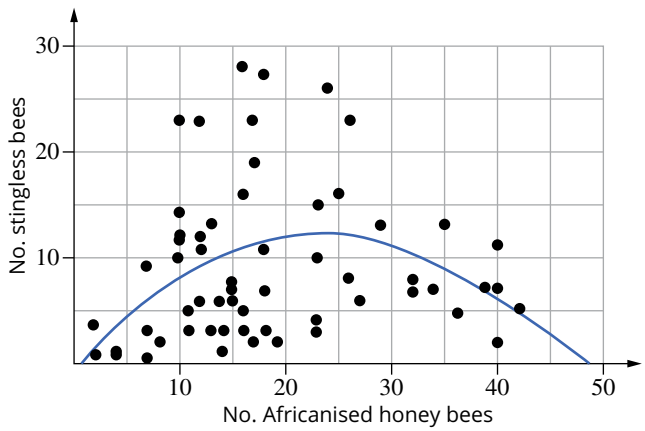


FIGURE 1.6.16 An extremely poor best fit line to the data that was actually published in the journal *Science* in 1978. Can you see the duck?

Sometimes the relationship between the x- and y-variables is known, but often it is unknown. This is what makes data analysis in physics exciting: using data and uncertainties to find an otherwise hidden relationship between the dependent and independent variables.

Worked example 1.6.1

LINEARISING DATA

Below are two formulas used in physics. Descriptions of the shapes of the graphs when the raw data is graphed are given in brackets. Assume that all other symbols are constant. For each formula:

i state the variable that would need to be graphed on each of the horizontal and vertical axes of a graph to linearise these equations

ii state the values of the gradient and y-intercept.

a $E_k = \frac{m}{2}v^2$ (E_k on the y-axis and v on the x-axis produce a parabola.)

Thinking	Working
i v is on the x-axis and the graph is a parabola, so the new x-axis variable will be v^2. The y-axis variable, E_k, will not be modified.	New x-axis variable = v^2 New y-axis variable = E_k (unchanged)
ii $E_k = \frac{m}{2}v^2 + 0$ The y-intercept is zero. The coefficient of v^2 is $\frac{m}{2}$.	y-intercept = 0 Gradient = $\frac{m}{2}$

b $F = \frac{GmM}{r^2}$ (F on the y-axis and r on the x-axis produce a hyperbola.)

Thinking	Working
i r is on the x-axis and the graph is a hyperbola, so the new x-axis variable will be $\frac{1}{r^2}$. The y-axis variable, F, will not be modified. Note that technically a hyperbola is proportional to $\frac{1}{r}$, but the general shape and linearisation process is the same for $\frac{1}{r^2}, \frac{1}{r^3}$, etc.	New x-axis variable = $\frac{1}{r^2}$ New y-axis variable = F (unchanged)
ii $F = GmM\ \frac{1}{r^2} + 0$ The y-intercept is zero. The coefficient of $\frac{1}{r^2}$ is GmM.	y-intercept = 0 Gradient = GmM

➤ Try yourself 1.6.1

LINEARISING DATA

Below are two formulas used in physics. Descriptions of the shapes of the graphs of the raw data are given in brackets. Assume that all other symbols are constant.

i State the variable that would need to be graphed on each of the horizontal and vertical axes of a graph to linearise these equations.

ii For each formula, state the values of the gradient and y-intercept.

a $T = 2\pi\sqrt{\frac{L}{g}}$ (T on the y-axis and L on the x-axis produce a square root graph.)

b $\frac{1}{d_i} = \frac{1}{f} - \frac{1}{d_o}$ (d_i on the y-axis and d_o on the x-axis produce a hyperbola.)

Table 1.6.4 summarises the commonly encountered relationships in physics and shows how to linearise each equation. Note that you will not be expected to linearise periodic relationships.

TABLE 1.6.4 A summary of common relationships in physics, and how to linearise the raw data to produce a straight line. Note that for parabolic, hyperbolic and square root relationships there is more than one way to linearise the raw data.

Graph type	Basic equation	New *x*-axis	New *y*-axis	New gradient	New *y*-intercept
directly proportional	$y = mx$	already linear	already linear	no change	no change
linear	$y = mx + c$	already linear	already linear	no change	no change
parabolic	$y = kx^2$	x^2	no change	k	no change
		x	$\sqrt{y}$	$\sqrt{k}$	no change
hyperbolic	$y = \frac{k}{x}$	$\frac{1}{x}$	no change	k	
		x	$\frac{1}{y}$	$\frac{1}{k}$	
exponential	$y = Ae^{-kx}$	x	$\ln y$	$-k$	$\ln A$
square root	$y = k\sqrt{x}$	$\sqrt{x}$	no change	k	no change
		x	y^2	k^2	no change

USING UNCERTAINTIES IN GRAPHS

Graphs can reveal systematic and random uncertainties. Systematic errors will reveal themselves on linear graphs if the actual measurements do not match the predicted values, but there is an obvious pattern. Random uncertainties show as error bars, and these can be used to determine the uncertainty in the gradient and *y*-intercept of the line of best fit.

Systematic errors in graphs

Incorrectly calibrated equipment will give the type of graph shown in Figure 1.6.17. This type of systematic error comes from an incorrectly scaled instrument.

For example, a ruler that has an incorrectly calibrated scale could read 1.2 cm when it should read 1.0 cm, and read 2.4 cm when it should read 2.0 cm.

Incorrectly zeroed equipment will give the type of graph shown in Figure 1.6.18. All measurements along the *y*-axis are offset by the same value.

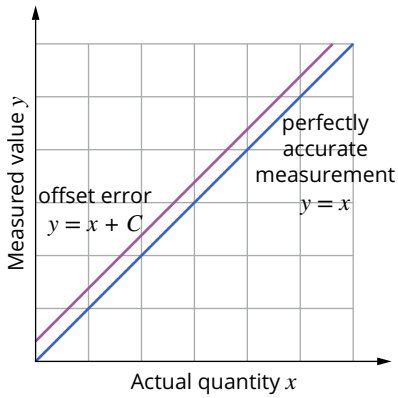


FIGURE 1.6.18 The recorded measurements need to be reduced by *C* to give the real values. This means that the instrument was not fully reset to zero before measurements were made.

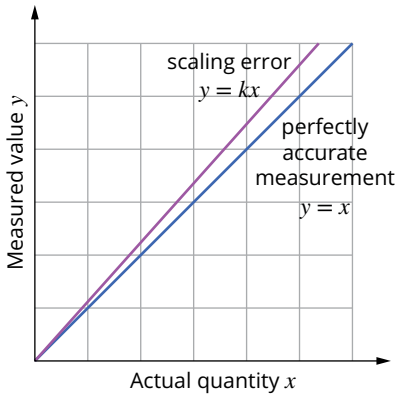


FIGURE 1.6.17 The recorded measurements are *k* times their real values. This means that the instrument's scale did not match the scale indicated on the display or on the graduated marks.

Systematic errors are seen in graphs when every data point is shifted out of its theoretical position by the same amount or same ratio.

For example, an electronic balance incorrectly zeroed could read 1.4 g when it should read 1.1 g, and 23.7 g when it should read 23.4 g.

Random errors in graphs

Any graph showing the relationship between two variables should also include uncertainties as error bars. When raw or processed data yields a straight line, the uncertainties can be used to determine the uncertainty in the gradient and *y*-intercept of the line of best fit. This is done via the use of the lines of maximum gradient and minimum gradient.

- The maximum gradient line is found by lining up a straight line such that it passes through all of the error boxes (at least part of either the error bars for *y* or *x* of every data point) at the steepest possible gradient.
- The minimum gradient line is found by lining up a straight line such that it passes through all of the error boxes at the shallowest possible gradient.

Note that this can be tedious to do by hand and software is available that will do this automatically.

Graph of distance travelled by toy car

Figure 1.6.19 shows an example of a linear graph, the best fit trend line and the maximum and minimum lines.

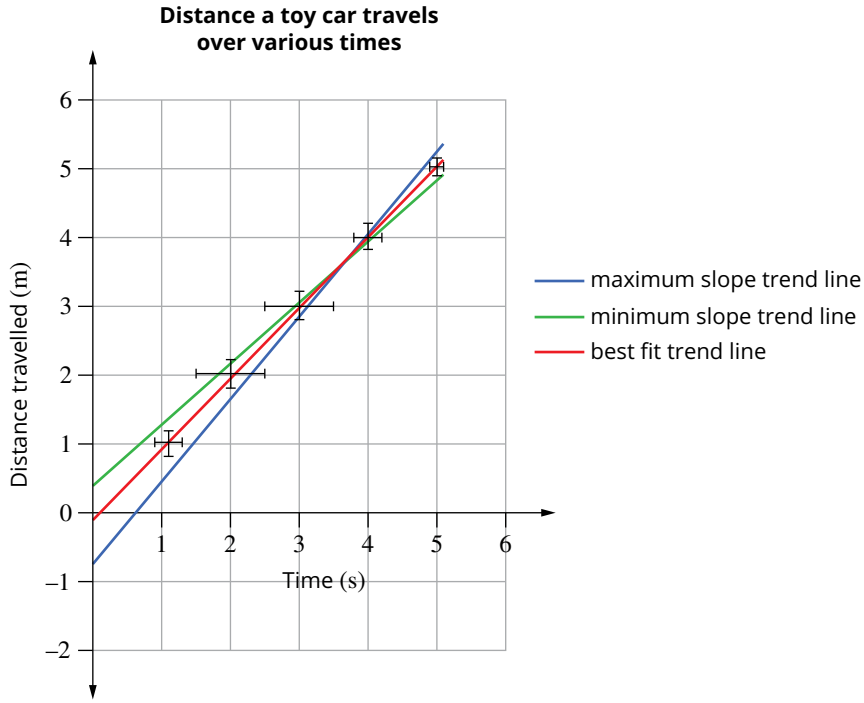


FIGURE 1.6.19 An example of a linear graph showing the best fit line, error bars, and maximum and minimum lines. The minimum and maximum lines are used to determine the uncertainty in the gradient and *y*-intercept.

If calculations are to be done manually, determine the values of the three slopes (line of best fit, maximum line and minimum line) by choosing two points on each line, not the data points. The *y*-intercept of each of the three lines can be read off the *y*-axis. Remember to also include units in your calculations.

If the gradient and *y*-intercepts are done automatically, they can be read off from the equations of the lines generated by the software. In Figure 1.6.19, the three equations are:

Equation of best fit line: $y = 1.02x - 0.0803$
Equation of the maximum line: $y = 1.19x - 0.753$
Equation of the minimum line: $y = 0.881x + 0.407$

Maximum and minimum gradient lines show the uncertainty in the gradient and *y*-intercept in linear data.

These data tell us that the difference between the maximum and minimum gradients, and maximum and minimum y-intercepts, are not very large, so the data is quite precise. The line of best fit also lies between the maximum and minimum lines.

Using the same procedure for calculating the absolute uncertainty of the mean on page 44, the uncertainty of the gradient can be found by using:

$$\text{gradient} = \frac{\text{maximum gradient} - \text{minimum gradient}}{2}$$

And, similarly, the uncertainty in the y-intercept can be fund using:

$$(y\text{-intercept}) = \frac{\text{maximum } y\text{-intercept} - \text{minimum } y\text{-intercept}}{2}$$

Using the data from Figure 1.6.19, the uncertainties of the gradient and y-intercept are:

$$\begin{aligned}\text{gradient} &= \frac{1.19 - 0.881}{2}\\ &= 0.1545\,\text{m s}^{-1}\\ &= 0.15\,\text{m s}^{-1}\\ (y\text{-intercept}) &= \frac{0.407 - -0.753}{2}\\ &= 0.58\,\text{m}\\ &= 0.6\,\text{m}\end{aligned}$$

Finally, using the correct significant figures and decimal places of uncertainties, the final values of the gradient and y-intercept are:

gradient = $1.02 \pm 0.15\,\text{m s}^{-1}$

y-intercept = $-0.08 \pm 0.6\,\text{m}$.

Note that in this example:

- the gradient represents speed. The toy car is travelling at a constant speed of $1.02 \pm 0.15\,\text{m s}^{-1}$.
- the y-intercept represents the initial distance travelled. This is expected to be zero, because at time zero the toy car is at the start. The value of the y-intercept has a range of values from +0.5 m to −0.7 m, which includes the expected 0 m. This indicates that the data is quite accurate for this variable.

Graph of volume versus mass of a copper cube

Table 1.6.5 shows data from an experiment in which the masses and volumes of solid copper cubes were measured in order to find the density, and its uncertainty, of copper.

TABLE 1.6.5 Raw data of the masses and volumes of five different solid copper cubes that will be graphed and used to determine the density of copper and its uncertainty

Volume of copper cube (±5 mL)	Mass of copper cube (±10 g)
1	10
8	70
24	220
53	480
125	1120

This data is now graphed with volume on the x-axis and mass on the y-axis. Each error bar is shown, but the y-axis error bars are very small and difficult to see. Figure 1.6.20 shows the line of best fit as the red dotted line, with the blue and purple dotted lines being the maximum and minimum lines respectively. The equations of each line is also shown, along with the R^2 value for the line of best fit.

From the line of best fit (red):

gradient = $8.958\,\text{g mL}^{-1}$

y-intercept = 1.9725 g.

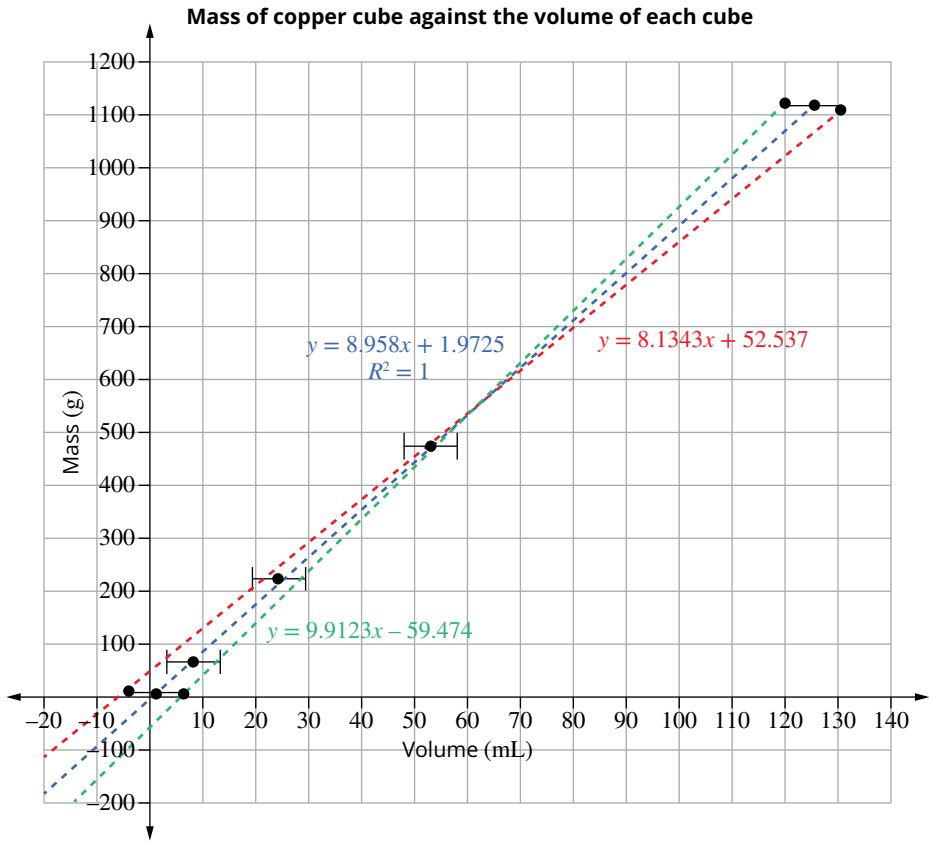


FIGURE 1.6.20 The complete graph, error bars and maximum and minimum lines for mass and volume data of copper cubes. The dots at the extremities of the lines were used to help draw the maximum and minimum lines.

From the graph:

$$\text{gradient} = \frac{9.9123 - 8.1343}{2}$$
$$= 0.889\ \text{g mL}^{-1}$$
$$= 0.9\ \text{g mL}^{-1}$$
$$(y\text{-intercept}) = \frac{52.537 - -59.474}{2}$$
$$= 56.006\,\text{g}$$
$$= 60\,\text{g}$$

Note that in this example:

- the gradient represents the density of copper, which is $9.0 \pm 0.9\,\text{g mL}^{-1}$. This is a reasonably precise measurement with a 10% uncertainty, and the discrepancy between this value and the accepted value ($\rho_{\text{copper}} = 8.96\,\text{g mL}^{-1}$) is only 0.4%.
- the y-intercept represents the mass of a copper cube with zero volume, which is 2 ± 60 g. You would expect this to be zero because any solid with no volume has no mass. The value of the y-intercept (2 ± 60 g) contains the expected value of zero in its range from –58 g to 62 g.

The trend line passes through every error bar, so the data is free of mistakes and matches theory. The precision of the data can be increased by using a higher resolution balance and callipers to reduce the uncertainty in mass and volume, although it was the uncertainty in volume that was the main source of uncertainty in the calculations. Systematic error can be eliminated because the value of the y-intercept contains the expected value of zero in its range.

1.6 Review

SUMMARY

- Graphs show a wealth of information relating two or more variables and constants, including their uncertainties.
- Graphs can be used to predict relationships between variables or to find outliers in data.
- Graphs drawn in physics should display:
  - a title
  - labels, scales and units on each axis
  - plotted data
  - error bars in the *x*- and *y*-direction
  - line of best fit for linear and nonlinear graphs
  - maximum slope line for linear graphs only
  - minimum slope line for linear graphs only.
- Systematic errors appear in graphs where the data for *x* or *y* are shifted or multiplied by the same value.
- Commonly used graphs in physics are linear, parabolic (squared), hyperbolic (inverse), sine and cosine, and exponential decay curves.
- A linear graph is the easiest to analyse because it is straightforward to calculate the gradient and *y*-intercept, and these are used in further processing of the data.
- Any graph that is not linear can be linearised to produce a graph that has modified *x*- and *y*-axes.
- The minimum and maximum lines are used to calculate the uncertainty in the gradient and *y*-intercept.

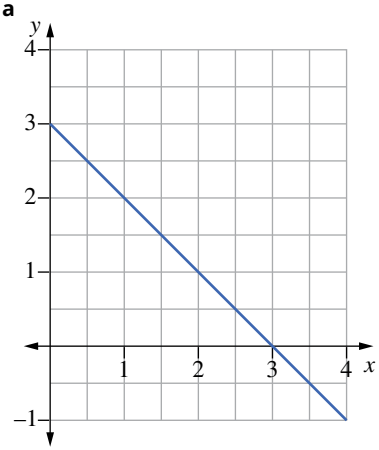
KEY QUESTIONS

Retrieval

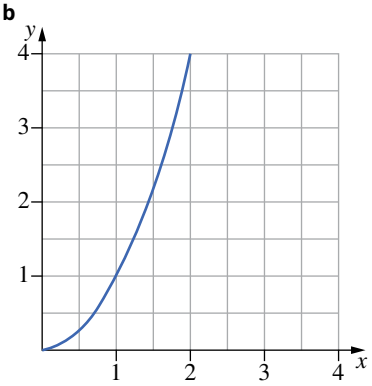
1 Recall how systematic errors are shown on a graph.

2 Identify the type of relationship between the *x*- and *y*-variables that is shown in the following graphs.

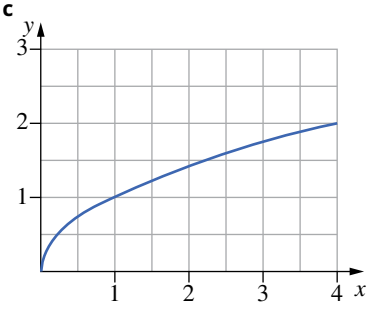
a



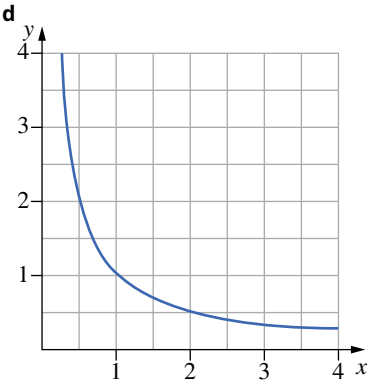
b



c

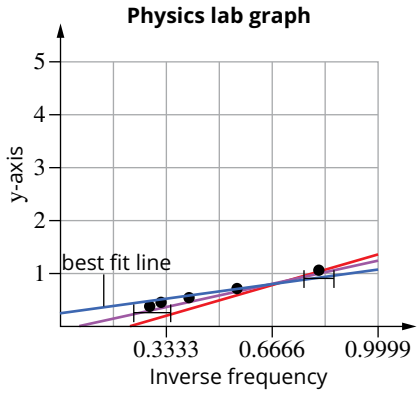


d



1.6 Review *continued*

3 Consider the graph shown below.



a List the mistakes or poor techniques in this graph.

b For each mistake in your list, identify how the graph could be corrected or improved.

Comprehension

4 Melissa draws a straight line graph of data, including error bars, from an experiment she has just completed. She finds that it is not possible to draw a straight line of best fit through every error bar. Explain to Melissa why this is the case and suggest some improvements to her data.

5 If a theory suggests that the *y*-intercept of a line is zero, describe how this should appear on a linear graph.

6 Explain why linear graphs are much easier to analyse than curved graphs, such as parabolic or hyperbolic graphs.

7 Describe what a graph of a variable that decreases at an increasing rate would look like.

8 Describe what a graph of a variable that increases at a decreasing rate would look like.

Analysis

9 Below are two formulas used in physics. A description of the shape of the graph of the raw data is given in brackets. Assume that all other variables are constant.

i Describe what modified variables, if any, need to be plotted on each axis to produce a linear graph.

ii Identify the gradient and *y*-intercept in each case.

a $P = \frac{nRT}{V}$ (*P* on the *y*-axis and *V* on the *x*-axis produce a hyperbola.)

b $B = \frac{\mu_0 I}{2\pi r}$ (*B* on the *y*-axis and *I* on the *x*-axis produce a straight line.)

10 The resistance, *R*, of an unknown, constant resistor can be found by using voltage, *V*, and current, *I*, data in a circuit. The theoretical relationship between voltage and current is given by $V = IR$.
The results of the experiment are recorded in the table.

Voltage *V* ± 0.5 V	2.0	4.0	6.0	8.0	10.0
Current *I* ± 0.03 A	0.19	0.44	0.55	0.68	0.94

a Identify the independent and dependent variables.

b Draw a graph of this data, using suitable axes, scales, labels and error bars.

c Draw the line of best fit.

d Draw the maximum and minimum lines.

e Determine the gradient of the line of best fit, maximum line and minimum line.

f Calculate the value of the resistor and its uncertainty.

g Comment on the value of the *y*-intercept and its uncertainty.

PART B STUDENT EXPERIMENT

The QCAA makes the following statement relating to the student experiment in Unit 2 Physics: 'It is suggested that student performance on Unit 2 is assessed using a student experiment modelled on the technique used in Unit 3.'

The QCAA requires students to complete a student experiment in Unit 3 Physics. In preparation for Unit 3, teachers may choose to assign a similar assessment task in Units 1 or 2. The student experiment assessment task requires students to research a question or hypothesis. Students use research conventions to investigate the question or hypothesis by collecting, analysing and synthesising primary data. The experiment requires students to locate and use information beyond the scope of their knowledge and what they have been given.

The student experiment requires students to undertake the full scientific method. The syllabus states that this process begins with a practical conducted during class, either a mandatory or suggested practical. This in-class practical will be altered to conduct the student experiment. It is recommended that during the class practical students record their observations, queries and thoughts in a logbook. These notes can be used to lead to a research question or hypothesis for the student experiment.

The student experiment constitutes 20% of the total assessment in Unit 3 Physics.

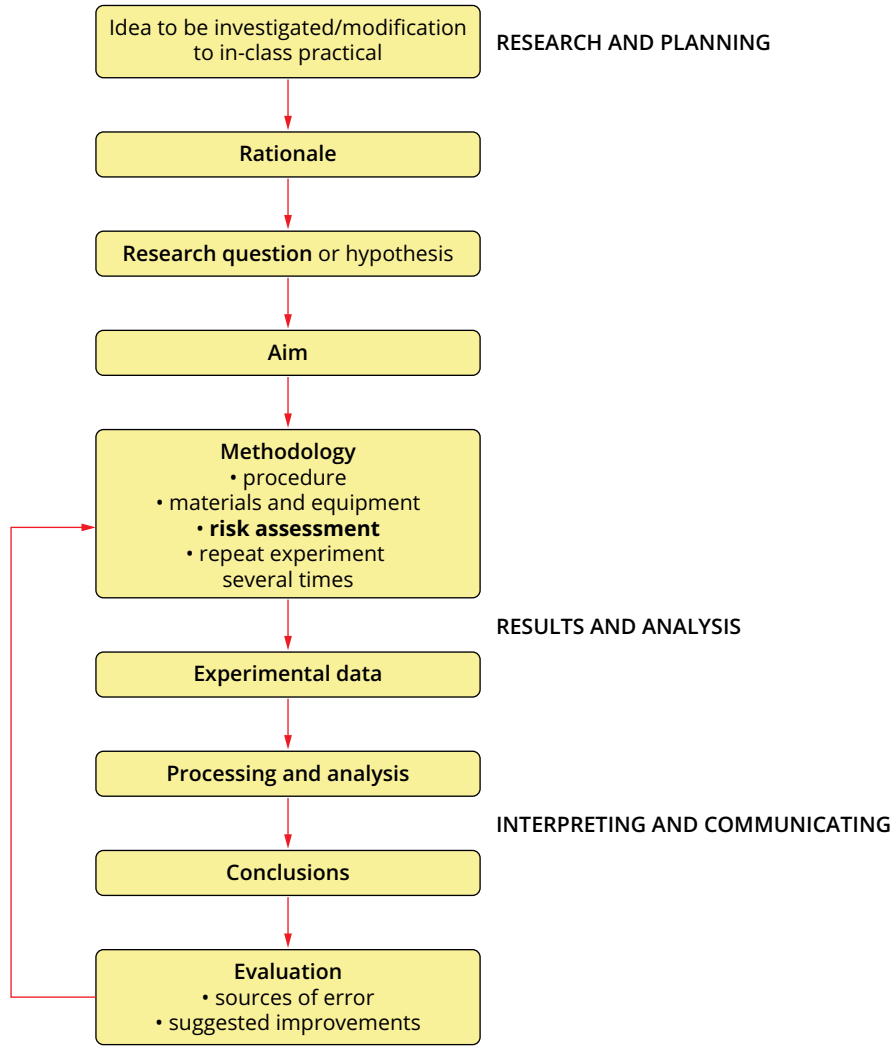
A summary of the objectives and marking for the summative internal assessment: student experiment, IA2, (Unit 3) is provided below.

The student experiment may be presented in:

- written form (e.g. scientific report), 1500–2000 words, or
- multimodal presentation form (e.g. poster presentation), 9–11 minutes.

Criteria	Assessment objectives	Demonstrated by	Marks
Research and planning	• Apply understanding. • Investigate.	• a considered rationale for the experiment • justifications for the experiment • a research question that is specific and relevant • collected data that is sufficient and relevant • considered risks and issues (ethical and environmental) and their management	6
Analysis of evidence	• Apply understanding. • Analyse evidence. • Investigate through experimentation.	• use of relevant algorithms and correct data processing • detailed and careful coverage of relevant trends, patterns and relationships in the evidence • detailed and careful coverage of uncertainty and limitations of evidence • collection of relevant raw data and sufficient data	6
Interpretation and evaluation	• Interpret experiment evidence. • Evaluate experimental processes and conclusions.	• a conclusion that is justified and addresses the research question • a discussion about the reliability and validity of the experiment that is supported by evidence • providing possible improvements and extensions to the experiment based on examination of evidence	6
Communication	• Present the experiment's findings, including methodology, conclusions, evaluation.	• scientific language and representations that are concise and fluent • suitable use of genre conventions • appropriate referencing conventions to acknowledge sources	2
Total			20

The scientific inquiry is not a linear process. Scientists will not necessarily complete these steps in the stated order and some steps may need to be repeated or altered in order to more accurately address the research question, as shown in the flow chart.



Instrument-specific marking guide

Student responses are assessed against an instrument-specific marking guide (ISMG). In developing your experiment and planning your response, it is important to always have in mind the assessment objectives and, in particular, the characteristics that are described in the performance level descriptors.

The major features of the ISMG are outlined below and shown for the Analysis of evidence criterion.

The ISMG has:

- four criteria (criterion): research and planning, analysis of evidence, interpretation and evaluation, and communication
- performance levels, against which the qualities of the response are assessed.
  - A performance level is comprised of a performance level mark, which may be a single mark or 2-mark range, and a performance level descriptor.
  - The performance level descriptor describes the characteristics that are demonstrated by a response at this level.

The QCAA criterion 'Analysis of evidence' stipulates the characteristics of the top performance level. The interpretation of these characteristics is shown in the table below.

In order to be awarded a mark of 5 or 6 for this criterion, you need to show a thorough, thoughtful and comprehensive engagement with the task. For example, appropriately applying algorithms and representations of data through correct and relevant data processing is working at the highest performance level. However, adequate application and basic data processing is working at the next, lower performance level. If the application is rudimentary and data is incorrect and irrelevant, the performance level is lower again.

Criterion: Analysis of evidence

These are the objectives that the assessment is assessing. Student work must demonstrate these objectives. The definition of the objectives is in the syllabus glossary. How they will be assessed is described below by the characteristics.

Objectives of assessment task

2 apply understanding of… to modify experiments and process primary data
3 analyse evidence from experiment
5 investigate… through an experiment

Key features that distinguish between marking levels:	Marks
• Processing relevant data correctly to demonstrate the appropriate application of algorithms and representations of data • Thoroughly identifying relevant relationships, trends and patterns to demonstrate systematic and effective analysis of evidence • Thoroughly and appropriately identifying the uncertainty and limitation of evidence to demonstrate systematic and effective analysis of evidence • Collecting sufficient and relevant data to demonstrate an effective and efficient investigation	5–6
• Processing basic data to demonstrate an adequate application of algorithms and representations of data • Identifying obvious relationships, trends, patterns to demonstrate effective analysis of evidence • Identifying the basic uncertainty and limitations of evidence to demonstrate effective analysis of evidence • Collecting relevant data to demonstrate an effective investigation	3–4
• Processing incorrectly or irrelevant data to demonstrate a rudimentary application of algorithms and representations of data • Identifying incorrect or irrelevant relationships, trends, patterns to demonstrate ineffective analysis of evidence • Identifying incorrect or insufficient uncertainty and limitations of evidence to demonstrate ineffective analysis of evidence • Collecting insufficient and irrelevant data to demonstrate an ineffective investigation	1–2
• Descriptors not addressed	0

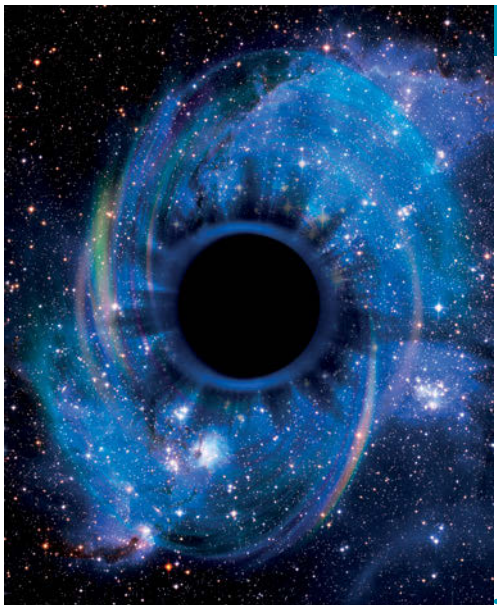
Performance level

Performance mark: the performance indicator describes requirements to achieve marks.

Performance level and characteristics: The descriptor contains all the characteristics required to achieve this level of performance. These characteristics outline the evidence in the student work for teachers to search for and identify. If these characteristics are found in the student work, then the associated marks will be awarded.

In the modules that follow, you will find a guide to a scientific method (Modules 1.7–1.10) followed by an outline on producing a scientific report (Module 1.11).

1.7 Research and planning



BY THE END OF THIS MODULE, YOU SHOULD BE ABLE TO:

- identify and explain the difference between controlled, measured, independent and dependent variables
- develop a research question or hypothesis
- evaluate a research question or hypothesis
- use a scientific journal to record experiments and experimental data
- plan, evaluate and refine scientific experiments
- explain what validity and reliability mean in relation to experimentation
- explain the difference between, and identify, qualitative and quantitative data
- characterise qualitative data as either nominal or ordinal
- characterise quantitative data as either discrete or continuous
- explain the difference between replication and repeat trials
- conduct risk assessments for planned experiments
- recognise common chemical GHS codes and symbols
- understand the criteria against which research and planning will be assessed.

All scientific work begins with research and planning. This includes understanding the relationship between controlled or measured variables as well as the independent and dependent variables. Research and planning is the foundation of the scientific method and is always recorded in a journal.

The journal will show a chronological record of ideas, development of knowledge and understanding, planning and refinement. Even though the journal will be in chronological order, it most likely will not be entirely in a conceptually logical order. The journal is an ongoing draft of scientific work from which the final scientific report is written.

IDENTIFYING AN EXPERIMENT AND DEVELOPING A RESEARCH QUESTION OR HYPOTHESIS

Identifying an experiment for the student experiment requires you to modify, refine, extend or redirect a practical undertaken in class. Therefore, the experiment will be similar to the class practical, with an alteration to investigate something slightly different, as shown in Figure 1.7.1.

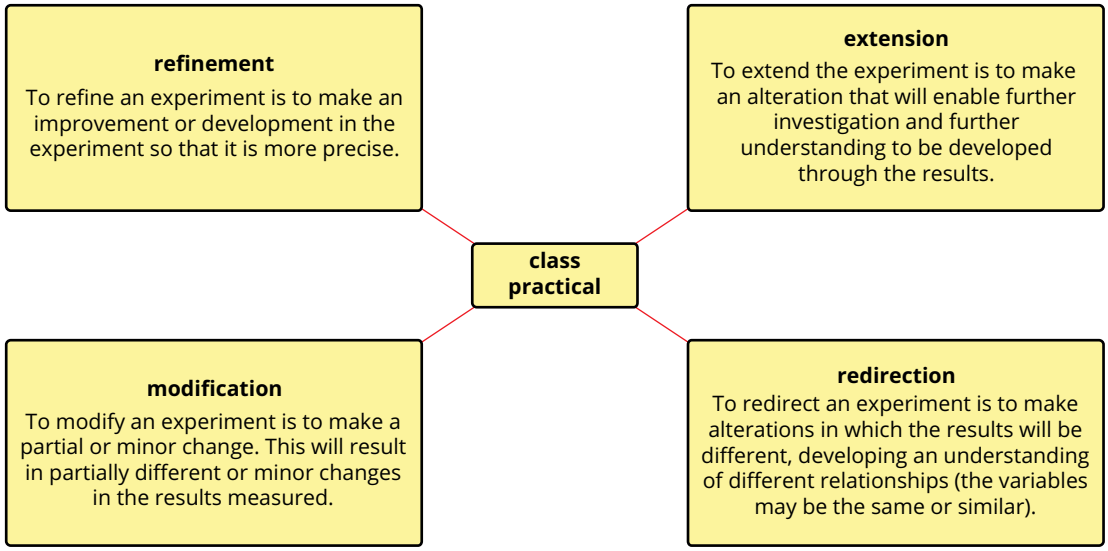


FIGURE 1.7.1 Changes that can be made to a class practical when developing a student experiment

Identify an experiment

During the class practical, record observations, points of interest, errors, ideas for improvement, or variables that you believe are significant to the experiment. Choose one of these observations to alter. When choosing a topic or observation to alter, consider the following:

- Select an observation/topic of which you already have some knowledge or understanding.
- Choose an observation/topic you find interesting.
- Check that your school laboratory has the resources for you to perform the experiment or investigate the topic.
- Choose a topic that can provide clear, measurable data that shows how variable y depends on variable x.

Table 1.7.1 shows examples of modifying, refining, extending or redirecting practicals into a topic of interest for a student experiment.

TABLE 1.7.1 Examples of ideas for changes to a class practical

Class practical	Modification, refinement, extension or redirection	Student experiment idea
Measure the velocity of falling objects under air resistance or high viscosity.	Extension and modification	Measure the terminal velocity of an object falling through a liquid.
	Modification and refinement	Measure the value of Earth's acceleration using apparatus other than a stopwatch and ruler/tape measure.
Conduct experiments to explore the voltage and current characteristics of a diode.	Extension and modification	Investigate how temperature affects the voltage or current characteristics of a diode.
	Modification and redirection	Measure the intensity of light produced from a diode when voltage or current are changed.
Use a laser and diffraction grating or slit to show that light behaves as a wave, to collect data to calculate its wavelength.	Extension	Use a laser and diffraction grating to measure the width of a human hair.

The Queensland Physics syllabus requires the student experiment report to justify the alteration of the methodology from the class practical. This is addressed further in Module 1.9.

When altering the class practical to identify a student experiment, it is best to think of a single variable that might influence the outcome (independent variable). This will require some research. The more variables that are altered (including measured and controlled variables), the more research required and the more complex the task becomes. Note that some alterations of variables may require the alteration of other variables.

- If only one variable is changed (the independent variable), then the class practical can be used as the control and the data collected can be used to compare results.
- If both the independent and dependent variables are altered, then the data of the class practical and the student experiment are not comparable. The student experiment will need to determine its own control.

Defining the variables

The factors that can change during your experiment or investigation are called the variables. An experiment or investigation determines the relationship between variables. There are four categories of variables, as shown in Figure 1.7.2. You should have only one independent variable, otherwise you could not be sure which independent variable was responsible for changes in the dependent variable (the results).

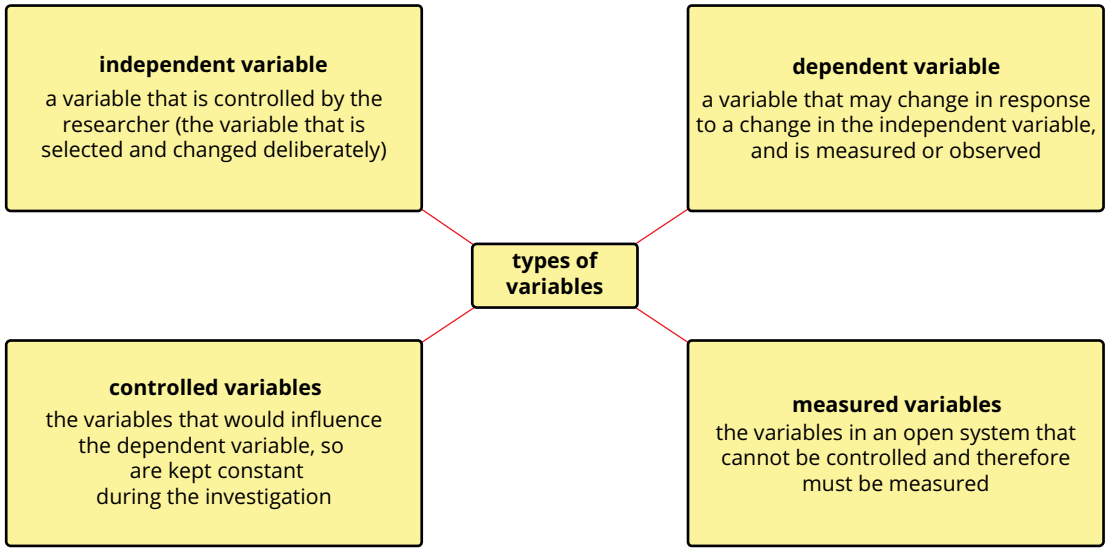


FIGURE 1.7.2 The four types of variables in experiments

Developing a research question

A research question is defined as a question that directs the scientific inquiry activity. Its purpose is to focus the research investigation or student experiment, inform the direction of the research, and to guide all stages of inquiry, analysis, interpretation and evaluation. The question determines the experiment and the experiment is testing the question. A research question should:

- be specific and relevant to the class experiment
- clearly identify the subject matter of the experiment
- specify the scope or conditions of the inquiry
- aim to find trends, patterns or relationships between two variables.

Consider the example in Figure 1.7.3.

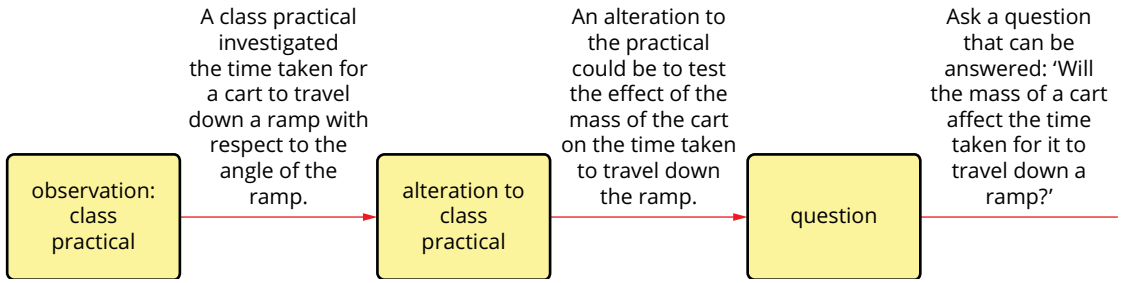


FIGURE 1.7.3 The process from class observation of a practical, to altering the practical and developing a possible question

Background research for the student experiment can refine the question. The research could include:

- information about the variables
- correlations between variables
- ideas for refining the question. Do not reject ideas that might seem improbable at this stage.

Figure 1.7.4 demonstrates the process of question refinement and the resultant question that will guide the student experiment.

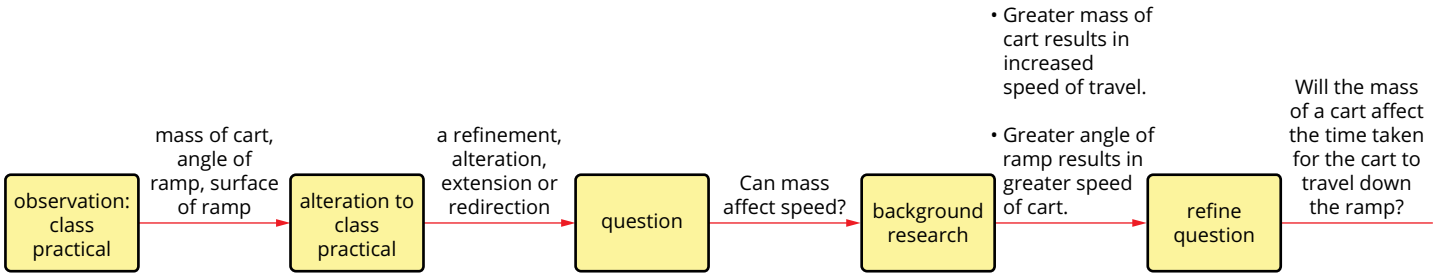


FIGURE 1.7.4 The process of refining a question in a student experiment

The structure of a research question

All research questions should state the independent and the dependent variables. Each question should ask whether the independent variable affects the dependent variable. It must specifically outline variables in a way that is measureable; this also allows the question to be answered. For example:

'Will the mass of a cart affect the time taken for the cart to travel down the ramp?'

As the research question is constructed, it should:

- include measurable variables—the independent and dependent variable
- have a guiding word, such as *who*, *what*, *why* or *will*
- be phrased so that a definitive answer can be developed
- be able to link the guiding word to command verbs such as *identify*, *describe*, *compare*, *contrast*, *distinguish*, *analyse*, *evaluate* or *create* so that a task can be determined.

Table 1.7.2 shows examples of research questions and the links between guiding words and command verbs.

TABLE 1.7.2 Examples of constructed research questions

Guiding word	Example research questions	What are you being asked to do? What are the command verbs?
What	**What** difference does cross-sectional area have on resistance?	Identify and describe specific evidence, reasons and examples from a variety of possibilities. *Identify* and *describe*
Will	**Will** a diver rotate faster with her arms tucked in or her arms outstretched?	Identify and describe giving reasons for effectiveness. *Identify* and *describe*
How	**How** does the angle of release affect the range of an arrow?	Identify and describe in detail a process or mechanism. Give examples using evidence and reasons. *Identify* and *describe*
Why	**Why** does the number of turns of wire change the magnetic field inside a solenoid?	Explain in detail the causes, reasons, mechanisms and evidence for. *Identify* and *explain*
Is/are	**Are** Kepler's laws valid for planets outside of our solar system? **Is** the speed of sound the same value at different air temperatures?	Evaluate. Justify, giving reasons and evidence. *Evaluate*, *assess*, *justify*
Can	**Can** you hit a cricket ball further with one hand or two hands on the bat?	Evaluate and assess. Is it possible? Give reasons, suggest possible alternatives. *Evaluate*, *assess*, *justify*, *create*
Do/does	**Does** your body weight change when you go up or down in a lift?	Evaluate. Justify using reasons and evidence for and against. *Evaluate*, *assess*, *justify*

The writing of a hypothesis is an optional inclusion that might support the development of your research question.

A hypothesis is not an assessed component of the ISMG, and not every research question will lead to the development of a hypothesis.

Formulating a hypothesis

A hypothesis can be developed from the research question. A hypothesis is a statement that proposes a relationship between variables, as it is based on some level of understanding. This statement must be testable, meaning it must specifically and clearly state a change in variables that can be tested through measurement.

The student experiment does not necessarily require a hypothesis, which is not always appropriate or beneficial. A hypothesis, if it is suitable, requires the control of variables to be more stringent during the experiment, resulting in an analysis of raw data that can specifically address the original inquiry of the observation. More stringent controls for errors may reduce uncertainties and produce results that are more straightforward to interpret.

Scientists use literature reviews and background research to develop an understanding of an observation and then infer a reason for their observation. The inference is then tested using experimentation to determine if it is true (verified or supported) or false (falsified or refuted).

Because the hypothesis proposes a specific relationship between the independent and dependent variables, the hypothesis can either be supported or refuted by the results. To be able to propose a specific relationship, the scientist must have some knowledge and understanding of the variables.

To develop a hypothesis, similar steps are undertaken to those listed for developing a research question. Refer to Figure 1.7.5.

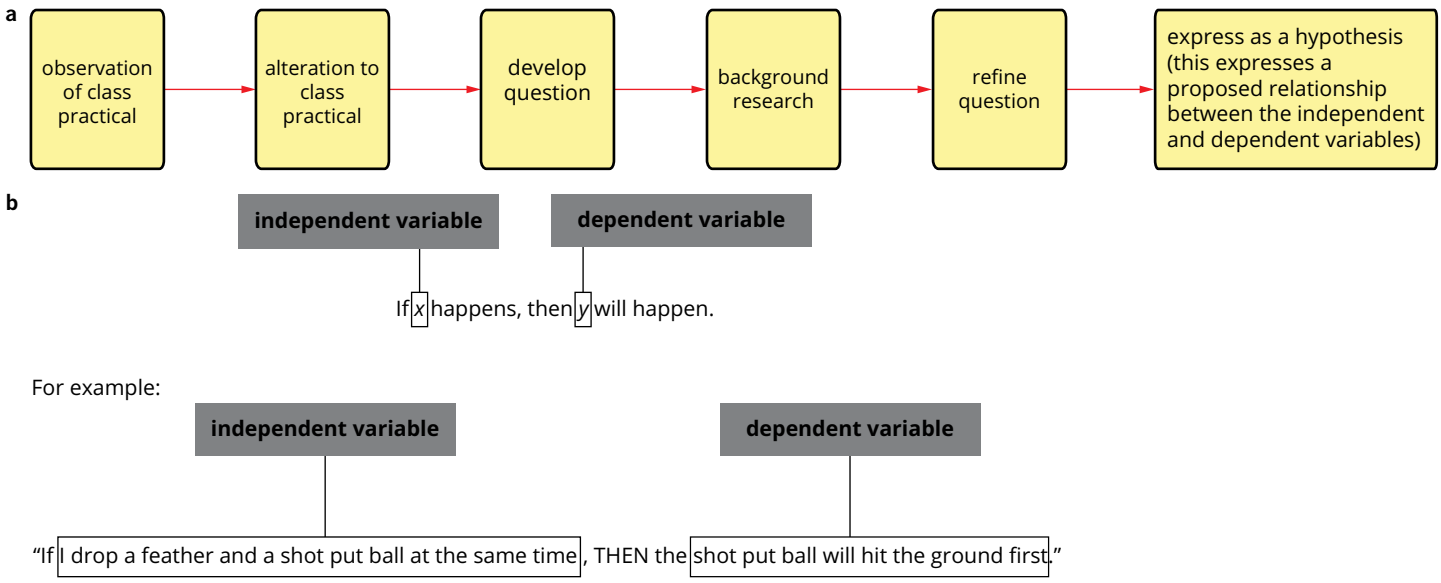


FIGURE 1.7.5 (a) Steps to refining a research question or hypothesis. (b) To formulate a hypothesis, write it in terms of the dependent and independent variables.

In a hypothesis for an experiment:

- the 'if' part refers to the independent variable, which is the variable you alter
- the 'then' part relates to the dependent variable, which is the variable you measure or observe.

A hypothesis does not need to include 'if' and 'then' in its wording. For example, the hypothesis in Figure 1.7.5b could also be worded in the following ways:

1 A shot-put ball will hit the ground before a feather.
2 When dropped at the same time from the same height, a shot-put ball will hit the ground before the feather.

A good hypothesis can be tested to be true (verified or supported), or false (falsified or refuted) by investigation.

Benefits of a hypothesis include:

- methodology guidance—provides specific limitations and guidance (due to the proposed relationship) directing the planning of the experiment
- methodology guidance—suggests specific variables to control and measure
- results—offers guidance in an analysis (processing data to determine if the proposed relationship exists)
- results analysis is specific—gives direction for the display of results to be specific to the hypothesised relationship between the variables
- evaluation is specific—directs what should be considered for adjustments in the methodology to improve or extend the experiment.

Evaluating your research question or hypothesis

When a research question or hypothesis has been developed, it should be evaluated and refined before progressing. Follow the prompts in the flow chart in Figure 1.7.6 to refine and improve the research question or hypothesis.

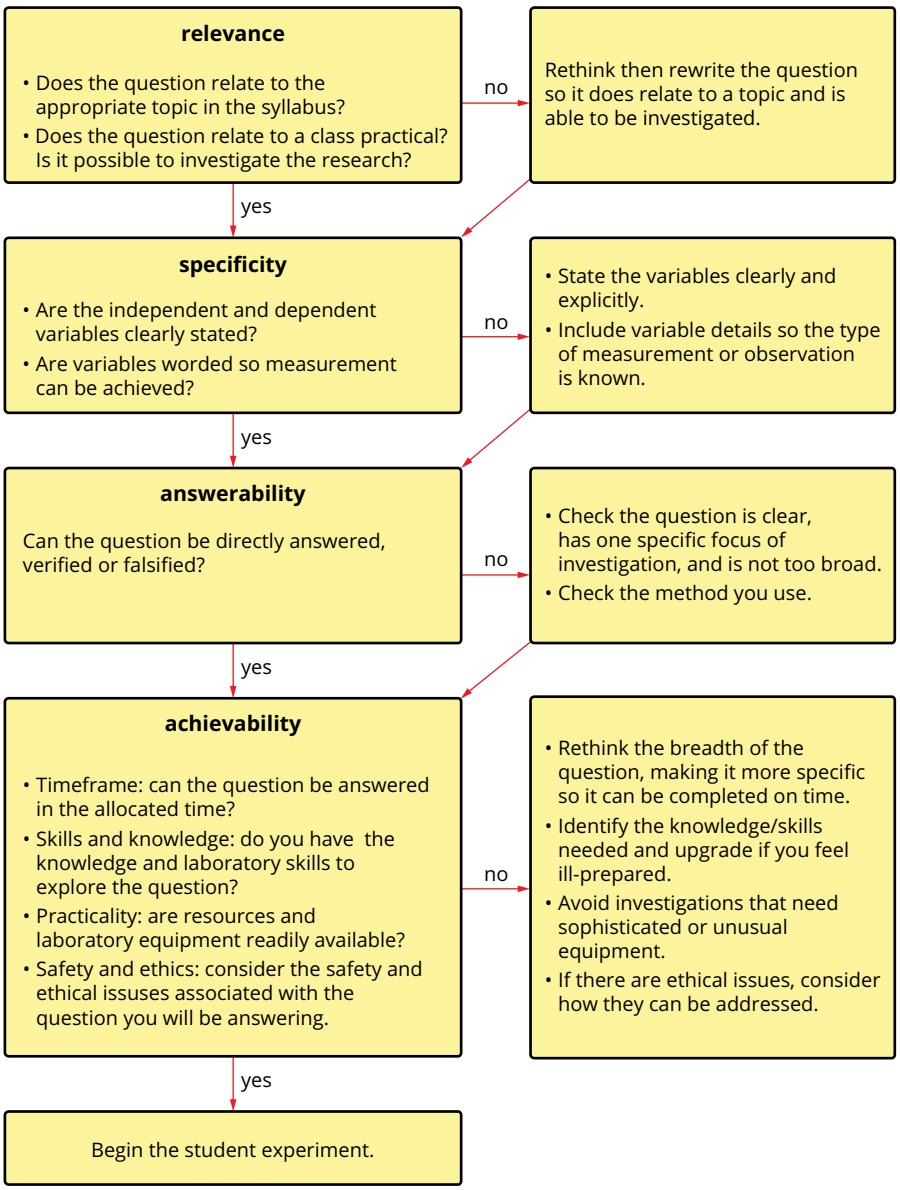


FIGURE 1.7.6 Steps to refine and improve the hypothesis or question

Examples of a research question or hypothesis

The following examples demonstrate that the student experiment may be expressed as either a hypothesis or a question to be investigated.

Hypothesis: The relationship between resistance and temperature of a resistor is linear. **Research question**: Is the relationship between resistance and temperature linear?
Hypothesis: Increasing the length of a pendulum string will increase the period of the pendulum. **Research question**: Will increasing the length of a pendulum string increase the period of the pendulum?
Hypothesis: Thick cardboard will stop most of the alpha, beta and gamma radiation when placed at a constant distance from the radiation source. **Research question**: Does cardboard have radiation shielding properties?

DEVELOPING THE RATIONALE

When you have decided on an experiment to modify (refine, extend or redirect), you will need to create your own related research question or hypothesis. The rationale is where you explain the scientific concepts appropriate to the research question.

Research relevant scientific information

The student experiment in the syllabus requires students to:

- research what is currently known about the relationship between the dependent and independent variables
- create a methodology that allows sufficient, relevant data to be collected that enables the research question to be answered
- manage the risks and issues associated with the experiment.

The student experiment ISMG (IA2) outlines the characteristics for background research as:

- informed application to modify experimental methodologies demonstrated by
  - a considered rationale for the experiment
  - justified modifications to the methodology
- effective and efficient investigation demonstrated by
  - a considered methodology that enables the collection of sufficient, relevant data
  - considered management of risks and ethical or environmental issues.

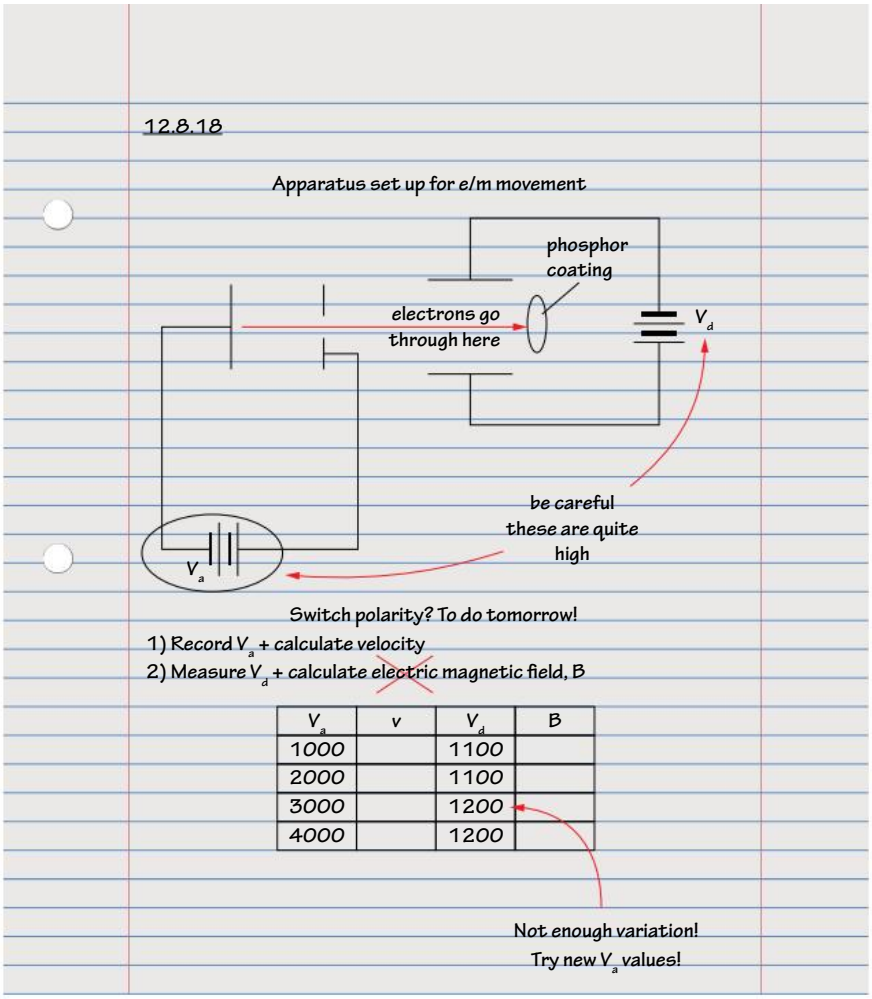
Furthermore, the syllabus expects background scientific information to be used in a rationale for the experiment to:

- explicitly justify the modifications to the methodology (alterations to the class practical)
- explain how the methodology will enable the research question to be answered through the collection of the data
- inform risk and identify how the risks associated with the experiment will be mitigated through personal protective equipment or specific features of the methodology.

The rationale is also expected to inform the interpretation of the evidence (results) and conclusion.

A lot of information needs to be recorded during a student experiment, so keep it all in a single document. Scientists always record their ideas, questions, background research and literature reviews, methodology drafts and revisions, results, refinements etc. in a single document called a **scientific journal**.

Taking notes and recording in the scientific journal keeps a record of all information that arose during the process of the scientific method, shown in Figure 1.7.7. You never know how vital some information will become throughout the process until it is complete and summarised into the scientific report. Collected information could be used in a rationale for the experiment, to explicitly justify the modifications to the methodology (alterations to the class practical), to provide a reason for collecting data, to inform risk, ethical and environmental management or in the interpretation of the evidence (results) and conclusion.



V_a	v	V_d	B
1000		1100	
2000		1100	
3000		1200	
4000		1200	

FIGURE 1.7.7 A journal entry with the journal entry date, titles, apparatus used and preliminary data. There will be numerous journal entries on any given date, and they should each have their own title. Also, the same titles will appear on different entry dates as research continues on specific topics.

The purpose of researching background scientific information in the scientific method is to develop understanding and knowledge. It must be relevant to the independent and dependent variables in the research question. As the variables become known, this will direct the research. The scientific method specifically requires scientists to demonstrate understanding and knowledge of the direct, and possibly indirect, relationship between the independent and dependent variables and perhaps controlled or measured variables. The background research is essential to achieve all this.

PLANNING AND REFINING METHODOLOGY

This section is a guide to some of the key steps that should be taken when planning and refining an investigation.

Planning experiments

When you have formulated your research question or hypothesis, defined the variables, developed knowledge and understanding of concepts and relationships, you will need to develop your experiment. You will also need to consider the ethical and safety implications of the testing during the experiment.

Create a work schedule that outlines the time frame of your experiment (including all trials and/or samples), being sure to include sufficient time to repeat experiments if necessary. Check with your teacher that your protocol and schedule (methodology) are appropriate, and that others will be able to repeat your experiment exactly by following the methodology you have written. If you have planned well, you will be able to test your methodology and run trials. You need to be able to perform your experiment independently, in the time available in the school laboratory, and with minimal support from your teachers and school laboratory staff.

The methodology of your experiment is a specific step-by-step procedure. (However, when written in the final scientific report, it may be written in paragraph form.) You must ensure that the methodology is valid, specific, reliable and accurate. All of these factors need to be considered when planning.

Validity

Validity refers to whether an experiment or investigation is in fact testing the set research question or hypothesis. Is the experiment obtaining data that is relevant to the question?

Factors influencing validity include:

- whether your experiment measures what it claims to measure; in other words, your experiment should test your research question or hypothesis
- the certainty that something observed in your experiment was the result of your experimental conditions and not some other cause that you did not consider; in other words, whether the independent variable influenced the dependent variable in the way you have concluded and by keeping all other variables constant (except those being measured)
- the degree, or scope, to which your findings can be generalised to more broad physics phenomena from which your experiment is taken; in other words, how does your experiment fit in to the big ideas in physics?

To ensure an investigation is valid, it should be designed so that only one variable is being changed at a time. The remaining variables must remain constant so that meaningful conclusions can be drawn about the relationship between variables. Also, the raw data collected during the experiment must be appropriate to ensure the data is valid. To ensure validity, carefully determine the:

- independent variable
- dependent variable
- controlled and/or measured variables
- appropriate raw data that will be collected (quantitative or qualitative), and that each will be measured, collected or controlled appropriately.

Qualitative data is descriptive and cannot be measured. It uses descriptions or adjectives to record observations.

Quantitative data is empirically measurable and uses instruments to record observations as numbers with units and uncertainties. Qualitative and quantitative data have further subsets in each category, as shown in Figure 1.7.8.

Qualitative data: can be observed but not measured.

They can only be sorted into groups or categories such as the colour of light or shape of a magnetic field.

Quantitive data: can be measured.

Height, mass, volume, temperature, intensity and time are all examples of quantitative data.

Nominal data

Variables are categorical variables in which the order is not important.

Example 1: the type of metal, type of apparatus

Example 2: the planets in our solar system

Discrete data

Variables consist of only integer numerical values, not fractions.

Example 1: the number of springs connected together

Example 2: the energy levels in atoms

Ordinal data

Variables are categorical variables in which order is important and groups have an obvious ranking or level.

Example 1: the level of brightness of light globes

Example 2: the apparent brightness of stars as seen from Earth

Continuous data

Variables allow for any numerical value within a given range.

Example 1: the measurement of height, temperature, volume, mass and intensity

Example 2: time for cart to slide down a ramp

FIGURE 1.7.8 Qualitative and quantitative data

Measurement of temperature requires an instrument and provides quantitative data. It is not appropriate to record qualitative data for temperature (e.g. cold, warm or hot), as shown in Figure 1.7.9.

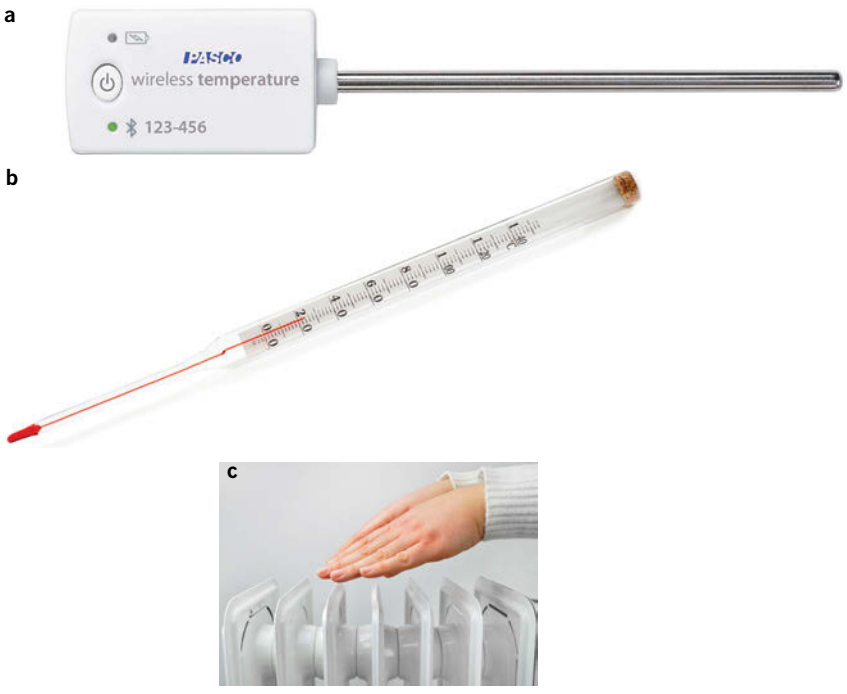


FIGURE 1.7.9 (a) Using a thermometer or a wireless temperature sensor will measure temperature empirically and provides quantitative data that can be analysed statistically. Processing empirical data can produce discrete, explicit and comparative analysis. (b) A liquid thermometer for measuring water temperature. (c) Feeling heat radiating from a heater is an example of qualitative data, based on personal observation. Qualitative data cannot be statistically analysed.

FIGURE 1.7.10 (a) When recording qualitative data, describe in detail how each variable will be defined. For example, if recording the brightness of light globes, photographs are a good way of clearly defining what each assigned term represents. (b) This multimeter is measuring a DC voltage of 8.9 volts. This is an example of a continuous variable that is quantitative data.

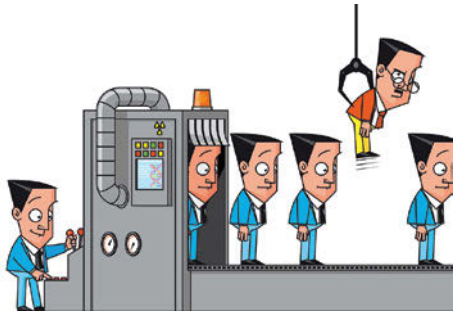


FIGURE 1.7.11 If you can reproduce your results, they are reliable.

Depending on the experiment, it may be appropriate to record a qualitative observation (e.g. brightness of light), or to measure quantitative results (e.g. voltage), as shown in Figure 1.7.10.

Controls

You should control as many variables as possible so you can determine which variable influenced the results and provide accurate and precise data.

It is difficult—sometimes impossible—to eliminate all variables that might affect the outcome of an experiment. Such variables in physics include time of day, temperature, amount of light, local gravity and strength of magnetic field. (A way to eliminate the possibility that random factors affect the results and cause uncertainty is discussed in Module 1.5.) One way to overcome this is to use a second group within the experiment (the control group) that is identical in every way to the first group (the experimental group) except for the single experimental (independent) variable that is being tested. This allows the examination of one variable at a time (the independent variable), which is required to validly test a research question or hypothesis.

Reliability

Reliability refers to the notion that if the experiment is repeated many times, the results obtained should be consistent. Reliability (repeatability) is the ability to obtain the same results if an experiment is repeated (Figure 1.7.11). The closer the results to the true value, the more reliable (and accurate) they are. Because a single measurement or experimental result could be affected by errors, replication of samples within an experiment and repeat trials are key components of reliability. To improve reliability you should:

- specify the materials and methods in detail, including precision (Module 1.5)
- include several replicate samples within each experiment or several observations within an investigation
- take repeat readings of each sample
- run the experiment or trial more than once.

Sample size is extremely important in scientific experiments. The sample size impacts:

- the representation of the phenomenon
- the natural variation, errors and uncertainty
- the results by offering more evidence to support the experimental results
- the repeatability and therefore reliability.

The greater the sample size, the more reliable the data. Reasons why a measurement or observation could vary include:

- natural variation
- random error
- uncalibrated instruments or instrumental error
- influence from unforeseen variables.

Accuracy and precision is also important in obtaining reliable (repeatable) data.

Sourcing appropriate equipment and materials

When planning an experiment you will need to decide on the materials, technology and instrumentation that will be used to carry out your investigation. It is important to find the right balance between items that are easily accessible and those that will obtain accurate and precise results. When conducting your investigation, the precision of the chosen instrumentation and how this affects the accuracy and validity of the results will have to be recorded in the journal and discussed in the scientific report.

ELECTRONIC DATA ACQUISITION IN SCHOOLS

Data collection has come a long way in the past 20 years. Historically, discrete measurements were recorded from manual tools and human readings over short periods of time. Now you can connect independent sensors to any device, which enables simple and highly effective electronic data acquisition over extensive periods of time, anywhere.

Data acquisition can be achieved by using sensors, or probes, recording data to a standalone device, computer, tablet (Figure 1.7.12) or even a phone. The software will generally graph the data and perform the uncertainty propagation automatically. This specialised software allows for many analysis functions not found in standard spreadsheets. There are many different probes available, which allows many applications.

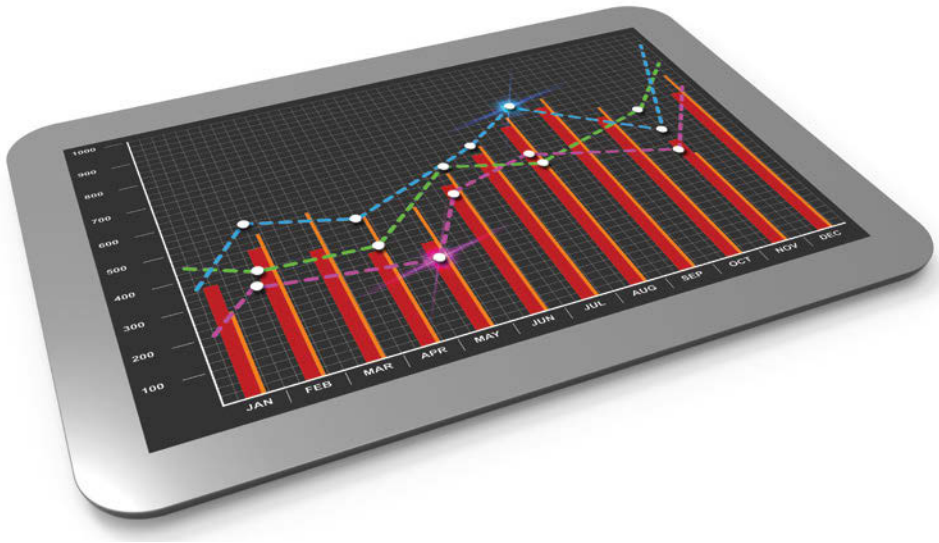


FIGURE 1.7.12 Data acquisition software produces real-time graphs that can be downloaded or printed.

Many smart watches (Figure 1.7.13) and apps in phones include digital sensors that can be accessed and used for some class practicals and experiments. The video camera of a phone or tablet is also an excellent means of capturing data, particularly for investigations in kinematics and dynamics.

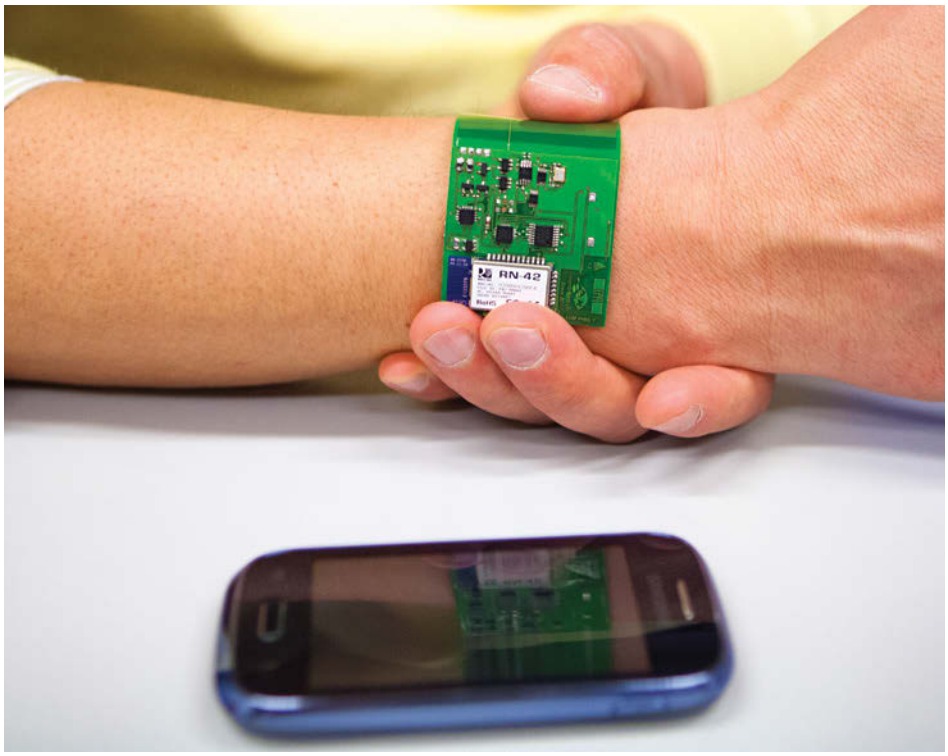


FIGURE 1.7.13 Many smart watches and phones have digital sensors and in-built data loggers.

Electronic data acquisition and data logging

Electronic data acquisition takes advantage of highly accurate sensors to collect data direct to a computing device. There are many sensors, probes and instruments available that can measure a vast variety of phenomena in a single device, as shown in Figure 1.7.14a.

You will need to decide which quantities are the independent and dependent variables. Usually, the independent variable is time, and the dependent variable can be set to be almost anything that the attached probe can measure, as shown in Figure 1.7.14b.

In physics, probes can measure temperature, distance, velocity, acceleration, force, magnetic field strength, current, voltage, brightness of light and many more physical quantities. A common probe (the motion detector) measures the movement of an object by detecting tiny variations in the pressure of air, as shown in Figure 1.7.14c. Video provides an excellent means of investigating high-speed movement in more than one dimension, as do accelerometers.

Most probes give immediate results that can be displayed on the screen or in the device itself, as shown in Figure 1.7.14d. Video can be linked directly for synchronising with data or used separately where it can be imported into suitable software after the event for detailed analysis.

FIGURE 1.7.14 (a) Sensors connected to computing devices such as phones and tablets are readily used in the field. This one is being used to measure the periodic nature in the movement of a playground swing. (b) Many different probes and sensors can attach to a single device, such as in the use of accelerometers and angle sensors to measure the lift of a bar. (c) They can be very precise and measure multiple times per second, such as the frequency and amplitude of air vibrations in sound to record motion. (d) They are usually easy to use and produce results immediately; for example, this sensor measures the temperature of skin on contact.

Recording is done accurately and can be continuous or manual, and the measurements are saved electronically. The saved measurements can then be accessed via a computer or directly from the tablet screen.

The rate at which measurements are recorded, called the sample rate, can be varied from as short a time as $\frac{1}{100\,000}$th of a second through to once an hour. The data capture rate selected will depend on what the operator needs. Note that the higher the sample rate, the more data will be recorded and the larger the file size.

Uses of electronic data acquisition

Given the number of different probes available, electronic data acquisition has many uses. Sensors and probes can monitor the temperature of ice-cream being transported from a factory to the supermarket. They are used to record the speed, engine conditions and brake force of trains, buses and trucks. An engine-control unit in a car will record data from parts of the engine, which the mechanic can access when servicing the car, or on a console on the steering wheel (Figure 1.7.15). The control unit records any problems with the car's engine and computer system. Built-in sensors and probes are also used for diagnostic testing of equipment in planes, commercial air-conditioners, office equipment such as photocopiers, and in vehicles to provide data on speed and engine operation.

FIGURE 1.7.15 Data acquisition is used throughout many industries to provide informative feedback to manufacturers during the assembly of vehicles, and in many devices (especially electronics) for quality control and assurance.

RISK ASSESSMENT

When planning for an experiment or investigation in either the laboratory or outside in the field, it is important for your safety and the safety of others that you consider the potential risks.

Everything you do has some risk involved. Risk assessments are performed to identify, assess and control hazards. A risk assessment should be performed for any situation that could cause harm to people, property or animals. Always identify the risks and control them to keep everyone safe. To identify risks, think about:

- the activity you will be carrying out
- where in the environment you will be working; for example, in a laboratory, school grounds, or a natural environment
- how you will use any equipment or chemicals that you will be handling, including sources of heat, radiation and electricity (Figure 1.7.16).
- the clothing you should wear, such as lab coat and goggles.

A hierarchy of risk controls is shown in Figure 1.7.17. It is organised from the most effective to least effective. The most commonly used risk control measure that addresses the majority of risks is personal protective equipment. The least common, but most protective, control measure is eliminating the risk from the scientific investigation.

FIGURE 1.7.16 When planning an investigation you need to identify, assess and control hazards.

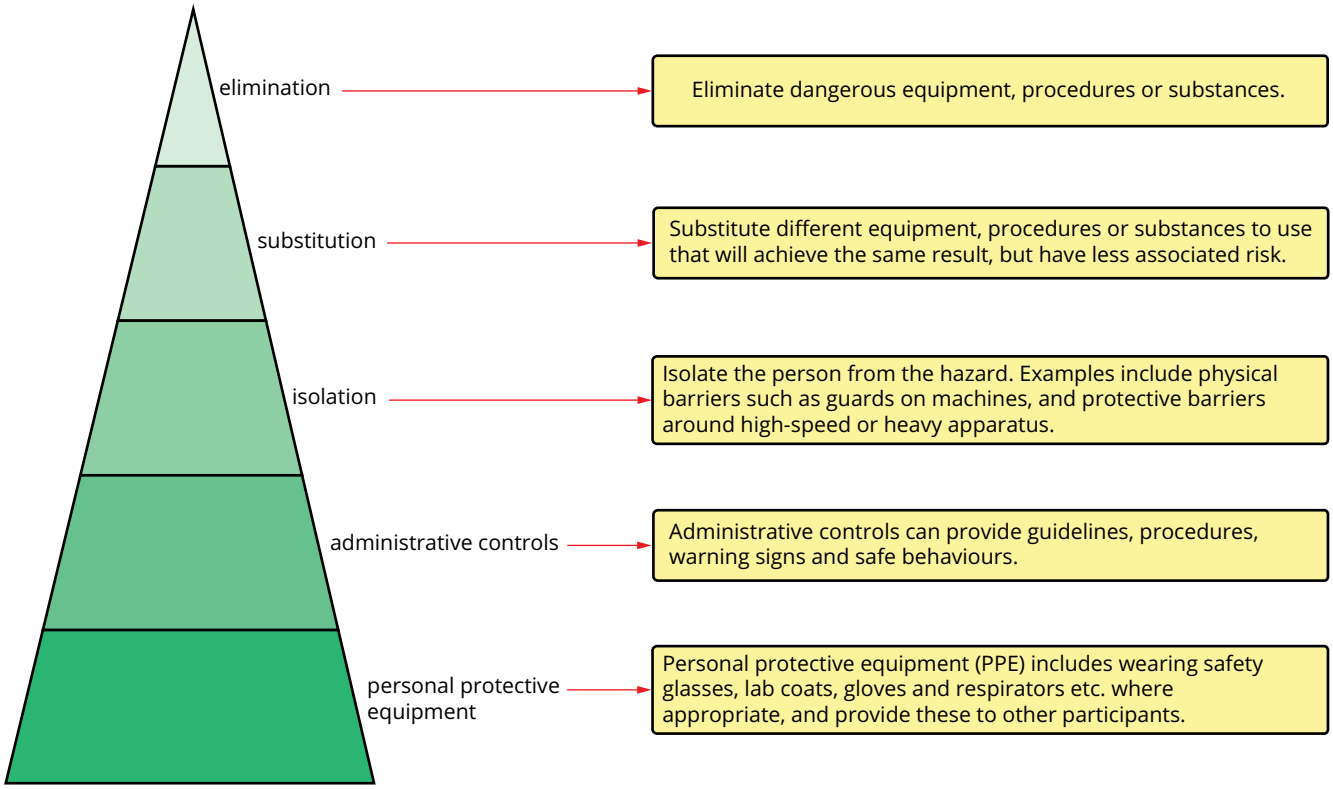


FIGURE 1.7.17 The hierarchy for risk control is shown in this pyramid, marked from bottom to top in order of increasing importance.

Personal protective equipment

Everyone who works in a laboratory wears items that help to keep them safe. This is called personal protective equipment (PPE) and includes:

- safety glasses
- shoes with covered tops
- disposable gloves when handling certain chemicals
- a disposable apron or a lab coat if there is risk of damage to clothing.

These are all shown in Figure 1.7.18.

FIGURE 1.7.18 Examples of PPE shown are protective eyewear, lab coats and gloves.

Chemical codes

The chemicals at school or at a hardware shop have a warning symbol on the label. These are chemical (HAZCHEM) codes. In 2017 the Globally Harmonised System of Classification and Labelling of Chemicals (GHS) was introduced in Australia for use in workplaces, including school laboratories. Some common pictogram codes and their meanings are shown in Table 1.7.3.

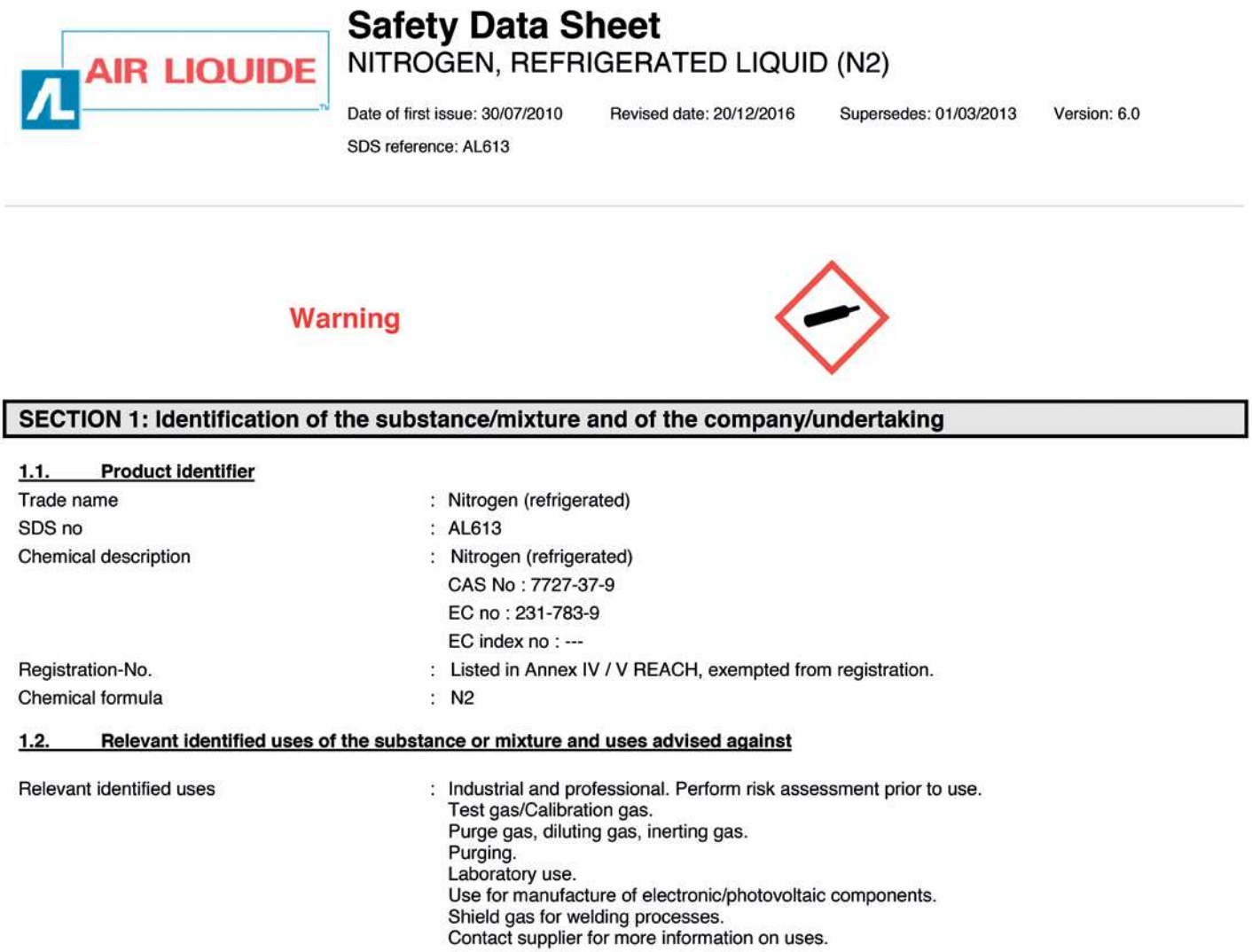
TABLE 1.7.3 Common HAZCHEM codes and their meanings

Symbol				
Meaning				
Corrosive: can dissolve or eat away at substances, including tissues such as your skin or airways	Poison: can cause injury or death if ingested, inhaled or absorbed	Irritant: causes discomfort, pain or itchiness	Flammable	Danger: The danger can include any biological harm; for example, cancer, allergy, breathing difficulties etc.

Safety data sheets

Each chemical substance has an accompanying document called a Safety Data Sheet (SDS) (Figure 1.7.19). An SDS contains important safety and first aid information about each chemical you commonly use in the laboratory. If the products of a reaction are toxic to the environment, you must pour your waste into a special container (not down the sink).

The SDS provides employers, workers and health and safety representatives with the necessary information to safely manage the risk of hazardous substance exposure.



AIR LIQUIDE

Safety Data Sheet

NITROGEN, REFRIGERATED LIQUID (N2)

Date of first issue: 30/07/2010 Revised date: 20/12/2016 Supersedes: 01/03/2013 Version: 6.0

SDS reference: AL613

Warning

SECTION 1: Identification of the substance/mixture and of the company/undertaking

1.1. Product identifier

Trade name	:	Nitrogen (refrigerated)
SDS no	:	AL613
Chemical description	:	Nitrogen (refrigerated) CAS No : 7727-37-9 EC no : 231-783-9 EC index no : ---
Registration-No.	:	Listed in Annex IV / V REACH, exempted from registration.
Chemical formula	:	N2

1.2. Relevant identified uses of the substance or mixture and uses advised against

Relevant identified uses	:	Industrial and professional. Perform risk assessment prior to use. Test gas/Calibration gas. Purge gas, diluting gas, inerting gas. Purging. Laboratory use. Use for manufacture of electronic/photovoltaic components. Shield gas for welding processes. Contact supplier for more information on uses.

FIGURE 1.7.19 An example of part of an SDS for liquid nitrogen depicting the pictogram for a compressed gas alerting the reader to any potential hazards when using the substance, including appropriate measures to reduce risk of harm.

Ethical considerations

When planning an investigation, researchers should always identify all possible ethical considerations and evaluate their necessity or ways that can reduce or mitigate them. Ethics is a set of moral principles by which your actions can be judged as right or wrong. Every society or group of people has its own principles or rules of conduct. Scientists have to obtain approval from an ethics committee and follow ethical guidelines when conducting research that involves animals including, and especially, humans. Ethical issues might include the following.

- Can this affect the wider society?
- Does one party benefit over another such as an individual, a group of individuals or a community?
- Is there a risk of harm (physical or mental) to people involved in the research?
- Does it prevent people from gaining their basic needs?
- Can this impact on future ethical decisions or issues?
- Does the research cause damage to the environment or other living things?

In reality, school physics investigations generally will have minor ethical issues, if any, but these should be considered in your planning.

Refining the methodology

As the planning of the methodology is not linear, refinement will occur several times, due to further background research, refinement of the research question or as understanding of the variables develops. Scientists will employ an experimental methodology that has been refined numerous times over several years.

Record all refinements in the journal. The following may help with refining the methodology:

- Record everything.
- Be prepared to make changes and refinements to the plan and methodology.
- Note any difficulties encountered and the ways they were overcome. What were the failures and successes? Every test carried out can contribute to the understanding of the investigation as a whole, no matter how much of a disaster it may first appear.

It is common for experimentation and testing not to occur according to plan. It is vital that comprehensive background research has been undertaken. Refinements are often made during experimentation to improve validity and reliability. This may be due to time constraints, instrumental limitations, resource limitations etc. Refinements also reduce error and uncertainty as the experimenter becomes aware of these problems.

Figure 1.7.20 shows a student journal demonstrating basic developments and refinements in their methodology.

If the expected data is not obtained, don't worry. As long as it can be critically and objectively evaluated, the limitations of the investigation identified and further investigations proposed, the work is worthwhile. Sometimes a different point of view, such as from a fellow student or a teacher, is all that is needed to find a solution. An evaluation and suggested improvement to the methodology or experiment is required in the scientific report. This is discussed further in Module 1.10.

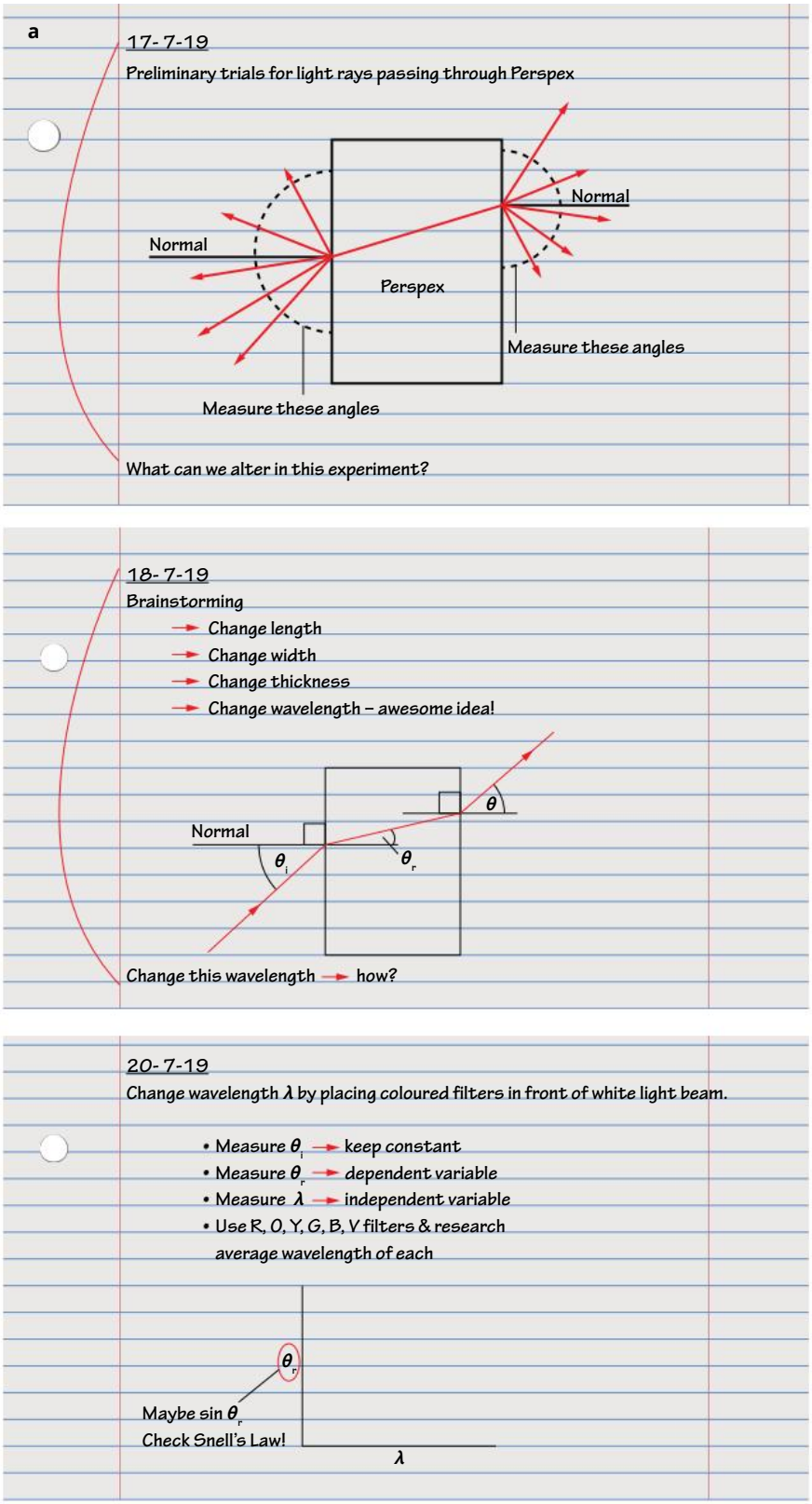


FIGURE 1.7.20 Demonstrating the alteration and refinement of a class practical into an experiment written in a student's journal. (a) The observations from the class practical. (b) The recordings of ideas and possible alterations of the class practical forming the student's development of an experiment. (c) Includes refinement of the student's idea for the experiment. The refinement was based on research.

1.7 Review

SUMMARY

- An independent variable is a variable that is controlled by the researcher.
- A dependent variable is a variable that may change in response to a change in the independent variable, and is measured or observed.
- Controlled variables are the variables that are kept constant during the investigation.
- Measured variables are the variables in an open system that cannot be controlled and therefore must be measured.
- Research questions should:
  - include measurable variables (the independent and dependent variable)
  - have a guiding word, such as *who, what, why* or *will*
  - be phrased so that a definitive answer can be developed
  - be able to link the guiding word to command verbs (such as *identify, describe, compare, contrast, distinguish, analyse, evaluate* or *create*) so that a task can be determined.
- A simple way to formulate a hypothesis is to link the independent and dependent variables using the following sentence structure:
  - If (independent variable) happens, then (dependent variable) will happen.
- A scientific journal is a document scientists use to record all their ideas, questions, background research and literature reviews, methodology drafts and revisions, results and refinements related to an experiment.
- Validity refers to whether an experiment or investigation is in fact testing the set research question or hypothesis.
- Data can either be qualitative or quantitative.
- Qualitative data is descriptive and unmeasurable and uses descriptions or adjectives to record observations.
- Qualitative data can be characterised as either:
  - nominal, when the order of data is not important
  - ordinal, when the ordering of data is important.
- Quantitative data is empirically measurable and uses instruments to record observations.
- Quantitative data can be characterised as either:
  - discrete, when data can only be recorded as particular numerical values
  - continuous, when data is not restricted to particular numerical values, but occurs within a given range.
- Reliability refers to the notion that if the experiment is repeated many times, the results obtained should be consistent.
- Reliability is improved by:
  - replication, having multiple samples within an experiment
  - repeat trials, repeating the experimental test.
- Risk assessments identify, assess and control hazards.
- HAZCHEM pictograms are warning images used to identify hazardous substances.

KEY QUESTIONS

Retrieval

1 **a** State the meaning of the term 'variable'.

b Copy and complete the table below with definitions of the types of variables.

Independent variable	Controlled variables	Dependent variable

Comprehension

2 Represent each of the three inferences below as a hypothesis that could be tested using a battery in an experiment.

a The battery lasts longer when it is cold.

b Current still flows when the battery is connected back to front.

c A particular battery will not work even though it has a voltage of 1.2 volts.

3 Develop a research question for each of the following observations:
   a Inflated balloons are much better at creating sparks than deflated balloons.
   b Olympic swimmers swim faster in deep water than in shallow water.
   c Satellites only appear at dusk or dawn.

4 Explain the difference between quantitative and qualitative data.

5 Identify which of the following pieces of information about a cup of coffee are qualitative, and which are quantitative. Place a tick in the appropriate column.

Information	Qualitative	Quantitative
cost $3.95		
robust aroma		
coffee temperature 82°C		
cup height 9 cm		
frothy appearance		
volume 180 mL		
strong taste		
white cup		

6 Identify the independent, dependent and controlled variables that would be needed to investigate each of the following hypotheses:
   a An increase in temperature will lead to an increase in the rate of evaporation of water.
   b If there is no light, there will be no current flowing through a photoresistor.
   c The longer the wavelength of light, the more it will bend through a piece of transparent glass.
   d Thick wires allow more current to flow through them than thinner wires.

7 In a practical investigation, the student changes the voltage by adding or subtracting batteries in a row in the circuit.
   a Explain how the voltage could be a discrete value.
   b Explain how the voltage could be continuous.

8 Explain the reasons for having an SDS for the chemicals used in the laboratory.

9 Describe the appropriate action to take if you spilled a chemical substance with the following label on yourself.

Analysis

10 Select the best hypothesis from the three options below. Give reasons for your choice.
   A Take-off angular momentum and inertia affect rotational velocity.
   B Body position during airborne motion affects its inertia.
   C A springboard diver's rotational velocity is slower when they hold a stretched-out position than when they are in a tuck position, if they take off with the same momentum.

1.8 Conducting and experimenting

BY THE END OF THIS MODULE, YOU SHOULD BE ABLE TO:

- determine relevant data that is needed to test a research question or hypothesis
- determine what is considered to be sufficient data to test a research question or hypothesis
- select appropriate equipment to collect relevant and sufficient data.

When you have defined the variables and planned the methodology, the experiment can be conducted. Experiments rarely run according to plan.

CONDUCTING THE EXPERIMENT

While conducting the experiment, variables must be controlled and conditions must be maintained, to ensure the measured or recorded raw data is valid and reliable. Others must be able to repeat your results under the same conditions, therefore all variables must be measured.

The precision of the instruments used to measure and record data is important. It determines the significant figures when analysing the data, and may affect the accuracy of the experimental results. The more precise the instrument, the more accurate the measurements and more reliable the data will be.

Possible considerations when conducting an experiment

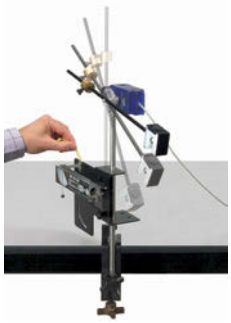
Depending on what the student experiment is testing, there are several aspects of the experiment that should be included in the planning. These include:

- equipment
- instruments
- safety precautions
- time (preparation, testing)
- complexity of testing
- sequential order of activities to complete testing.

Equipment

The choice of equipment and instrumentation will influence the reliability of the experiment. It is recommended, where possible, to use precision equipment rather than human means to conduct experiments, as shown in Table 1.8.1.

TABLE 1.8.1 Outlining examples of rudimentary versus improved experimental testing

Rudimentary set-up	Improved set-up
Measuring the period of a pendulum by stopwatch.	 Measuring the period of a pendulum by motion sensor.
Estimating the temperature of a liquid by hand.	Measurung the temperature using a digital thermometer (sensor) with known precision and uncertainty.

Safety precautions

Always employ safe procedures and use common sense. For example, all equipment and instruments should be used at the back of the bench so students walking by do not cause an accident. Place a sign on the lab bench warning other students and staff not to touch the equipment.

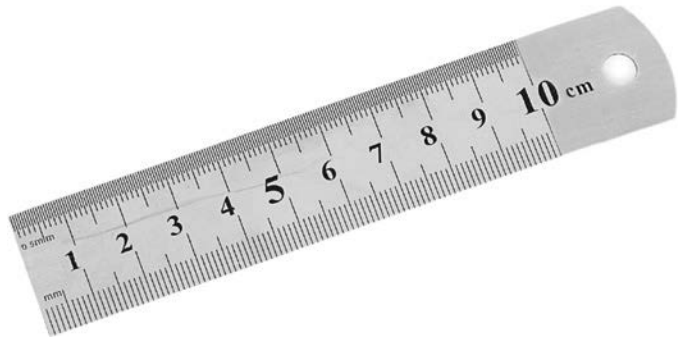
The school's and teacher's safety and risk assessment guidelines need to be adhered to. Completing the risk assessment may require completing a form or completing an online process.

When conducting the experiment, it is recommended that you use the most precise instruments available. With higher precision instruments there is less chance of error and lower uncertainty in the measurement. Table 1.8.2 demonstrates the benefits of greater precision instruments through lower uncertainty.

COLLECT SUFFICIENT AND RELEVANT DATA

The data that you collect must relate directly to the variables in your experiment. The data collected and measured must be relevant to the proposed relationship in the research question or hypothesis. Also it must be sufficient to provide accuracy and precision; otherwise, the analysis and interpretation of the data will not be reliable or valid in relation to the research question or hypothesis.

TABLE 1.8.2 The difference in precision between instruments

Lower precision instruments		
		
Glass thermometer with a precision of ±2.5°C	Measuring beaker with a precision of ±5 mL	A metal ruler with a precison of 1 mm
Higher precision instruments		
Digital infrared thermometer with a precision of ±0.1°C	Measuring cylinder with a precision of ±0.25 mL	A micrometer with a precision of 0.005 mm

Collecting sufficient data

The term 'sufficient' is defined by the syllabus as 'enough or adequate for the purpose'.

You need to collect enough data to substantiate whether or not a relationship exists between the variables. This includes collecting an appropriate number of replicates and an appropriate number of individual samples (also known as observational or collection points). It is also important to collect data around interesting points in your range, such as any parts of a graph where the curve reaches a maximum or minimum point, as shown in Figure 1.6.3 on page e51.

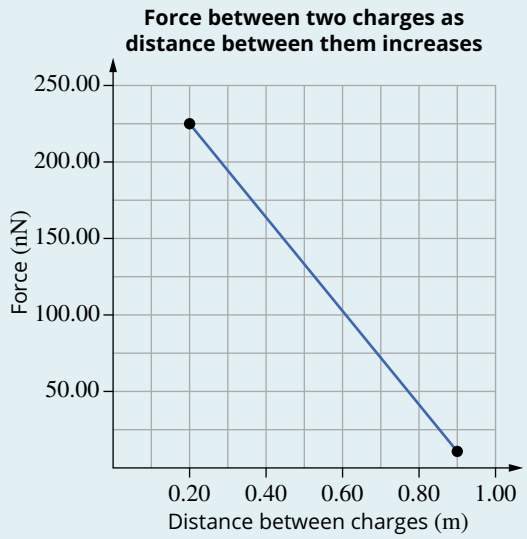
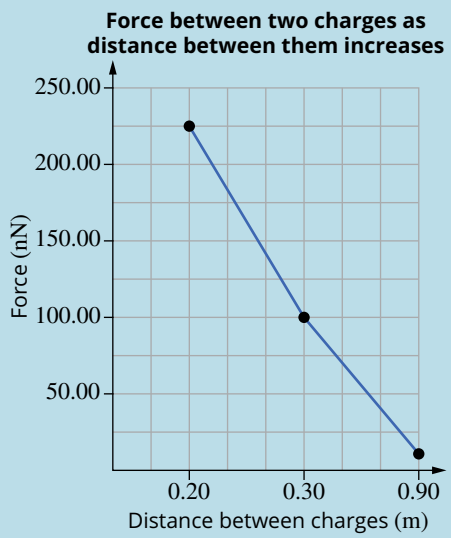
Together, the number of replicates and individual samples determine the sample size. This is vital, so a valid interpretation of the data can be achieved or determined.

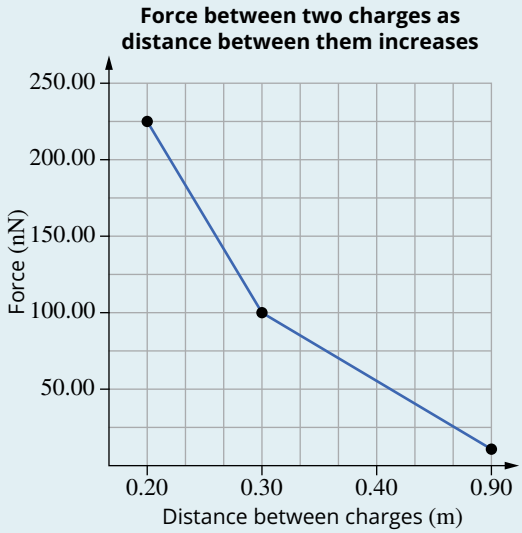
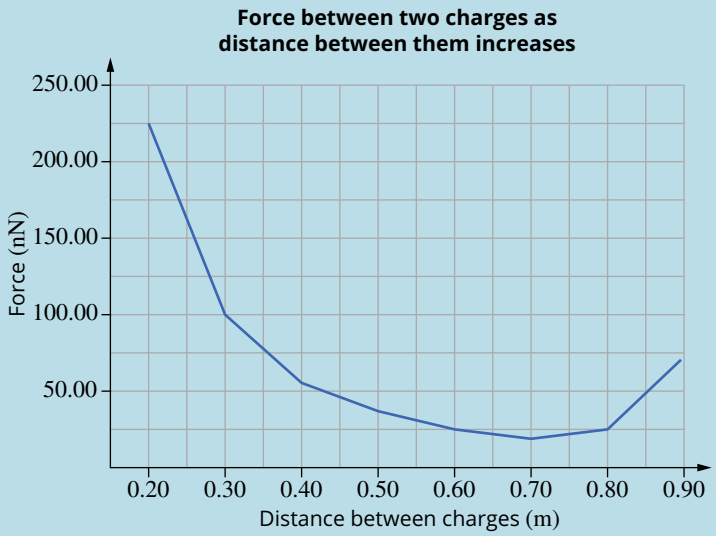
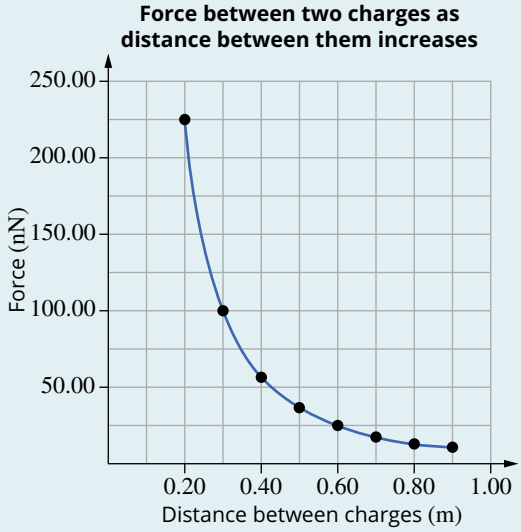
Table 1.8.3 outlines examples of sample size and their effect on the results of an experiment. The results are from an experiment into the effect of how distance between two charges affects the force between them.

Collecting relevant data

The variables to be measured or collected must be directly related to the proposed independent-dependent variable relationship. Additional variables can be measured or collected that are indirectly related to the hypothesised relationship, if the background research shows it could be beneficial in the analysis or interpretation of the relationship. If you do not have any background research relating a variable to the research question or hypothesis, then it is not relevant, and therefore is not to be measured or collected.

TABLE 1.8.3 Examples of sample size and their effect on the results of an experiment

Examples of analysed data	Effect of sample size on analysis
A line graph with two sample points 	With only two individual sample points, this graph suggests an inappropriate linear relationship for the force acting between two charges as the distance between them increases.
Line graph with three sample points and an uneven scale 	The scale on the horizontal axis is not evenly spread, which distorts the shape of the graph. These results suggest an incorrect relationship for the force acting between two charges as the distance between them increases.

Examples of analysed data	Effect of sample size on analysis
Line graph showing limited sample points and an uneven scale 	The chosen number of individual sample points is insufficient, because the true relationship is not fully displayed. The next example of displayed results provides more validity for the relationship.
Line graph based on data that had no replicates 	These results are due to only a single measurement for each individual sample point. In this example, the measurements for distances greater than 0.70 m are incorrect. These results suggest an incorrect relationship between the variables.
Scatter graph with appropriate number and distribution of sample points 	The number of individual sample points here best demonstrates the relationship between the variables. Note that a scatter plot has been used rather than a line graph.

1.8 Review

SUMMARY

- The choice of equipment and instruments will influence the reliability of the experiment.
- The precision of equipment and instruments is important for accuracy and reliability.
- The data collected and measured must be relevant to the proposed relationship in the research question or hypothesis.
- Equipment used during an experiment should enable you to collect and measure relevant data.

KEY QUESTIONS

Retrieval

1 Explain why it is important to choose appropriate equipment and instruments to conduct experiments.

Comprehension

2 Explain how the precision of equipment can impact scientific conclusions.

Analysis

3 A student recorded the data in the table below to test this hypothesis: Temperature affects the resistance of a piece of copper wire when placed into a circuit. Comment on whether or not sufficient and relevant data was collected.

Temperature (°C)	Current through copper wire (A)	Voltage across copper wire (V)	Resistance of copper wire (Ω)	Length of copper wire (cm)	Thickness of copper wire	Brand of copper wire
0	3	4	1.2	about 20	normal	ACME
2	4	4	1	about 20	normal	Sid's wire shop

1.9 Results

BY THE END OF THIS MODULE, YOU SHOULD BE ABLE TO:

- analyse raw data to produce processed data
- interpret data to draw valid conclusions.

All measurements and observations made during the experiment must be recorded in your journal. This is the raw data. Choosing not to record certain measurements or observations (raw data) is invalid, shows bias and is scientifically fraudulent. Unusual and unexpected measurements and observations may be due to valid relationships between variables that are unknown to the scientist. This cannot be determined until the raw data is processed, analysed and interpreted.

The results, after analysis, need to show whether or not a relationship exists between the variables in the research question. To achieve this, the results need to be presented appropriately. Being able to present results appropriately is dependent on appropriate measurement, observation and recordings (e.g. quantitative or qualitative). Make sure this is planned before the experiment is conducted.

The raw data needs to be analysed and then represented using tables, graphs, schematics or diagrams with correct mathematical and scientific conventions. Refer to Module 1.6 for specific guidance on producing quality and appropriate graphs. Module 1.10 outlines details regarding representing results.

IDENTIFYING ERRORS

Most practical investigations have errors, or uncertainties, associated with them, as shown in Figure 1.9.1.

ANALYSING

Analysing the raw data enables processing in numerous ways to search for relationships between variables, trends or patterns in the data, uncertainties and mistakes, outliers and results of significance. This will produce processed data.

Data can be presented in a number of ways, including tables, graphs, flow charts and diagrams. The best way to visualise the data depends on its nature. More information on these different formats is provided in Module 1.10.

In this module, you will learn how to discuss your investigation and draw evidence-based conclusions in relation to your research question. When analysing data, it is important not to select processes that demonstrate what the scientist wants to see. Bias will result in using analysis tools (e.g. statistics) inappropriately and will result in invalid conclusions and academic fraud. Quality scientific analysis processes the raw data as it is and is open to any result.

The syllabus criterion 'Analysis of evidence' stipulates the characteristics of the top performance level. In order to be awarded a mark of 5 or 6 for this criterion, you need to show a very thorough, thoughtful and comprehensive engagement with the task. For example, appropriately applying algorithms and representations of data through correct and relevant data processing is working at the highest performance level. However, adequate application and basic data processing is working in the next lower performance level. If the application is rudimentary and data is incorrect and irrelevant, the performance level is lower again.

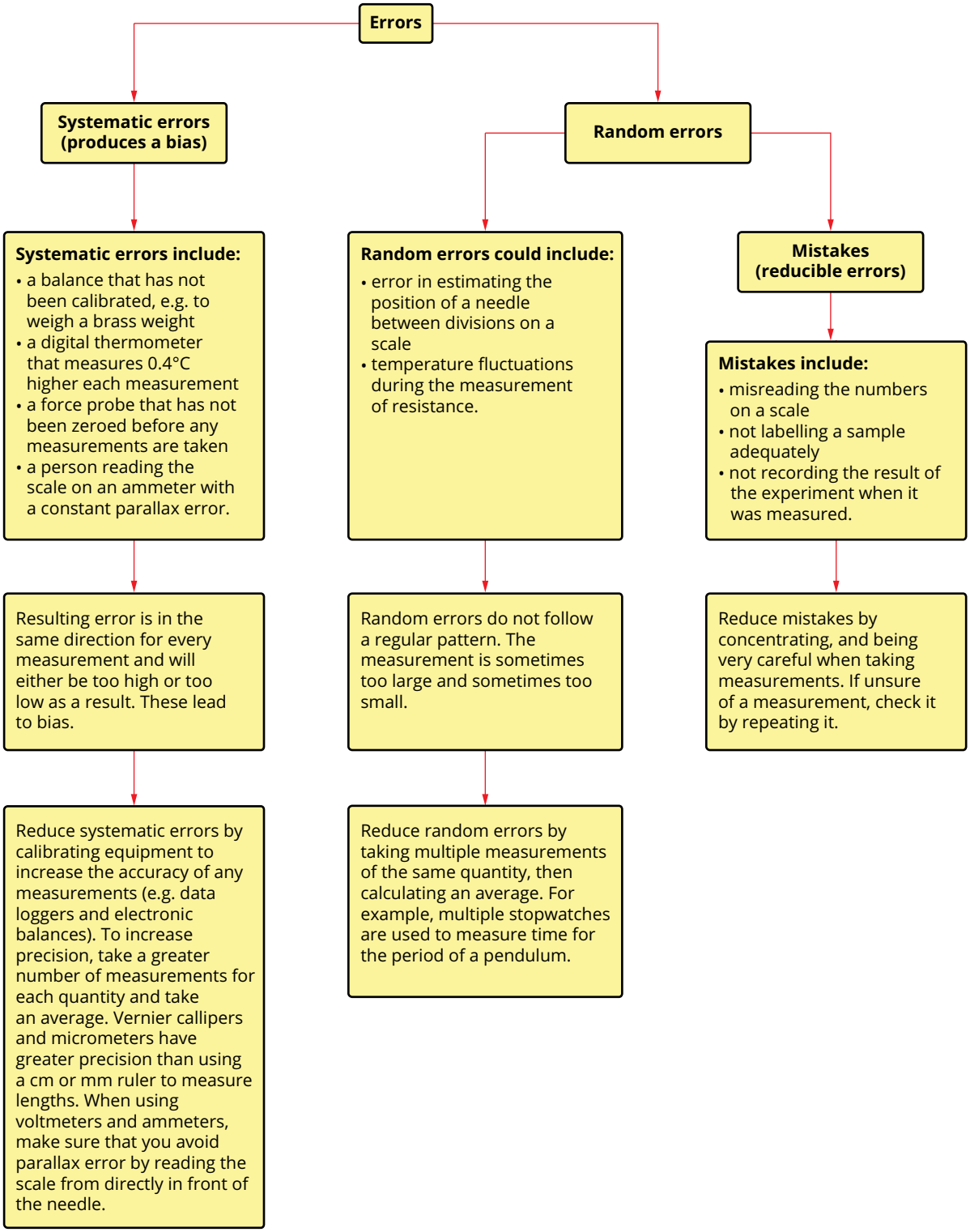


FIGURE 1.9.1 Types of errors that can be made in an experiment

Analysing precision

Understanding uncertainty and precision is vital in any analysis of data. In physics there is always variation in measurements or recordings. In your experiment, you should determine whether the variation is caused by systematic or random errors. In other words, how much variation is due to nature and how much is due to instrumentation?

The precision and uncertainty of the instruments must always be displayed as a range of data next to the results (e.g. measurement ± Δmeasurement). See Module 1.5 for more explanation. If calculations are performed with the results, then the appropriate calculations must be done with the uncertainties. When the total uncertainty is known, it can then be established whether variation in the data is due to the instrument or the variables being tested.

If the measurements between trials fall within the uncertainty range of the instrument (Table 1.9.1), then the variation in results could simply be due to the instrument. If the difference between the measured results is greater than the uncertainty range, then the variation in the results is not due to the instrument and must therefore be due to other variables.

TABLE 1.9.1 The measured charge on fully inflated 20 cm rubber balloons after being rubbed with wool in a consistent manner

Balloon	Measured charge (nC)
Balloon 1	206.3 ± 0.5
Balloon 2	205.9 ± 0.5
Balloon 3	206.8 ± 0.5
Balloon 4	208.2 ± 0.5
Balloon 5	199.5 ± 0.5
Balloon 6	199.8 ± 0.5
Mean	204 ± 4

Table 1.9.1 shows the mean charge on six different balloons rubbed with a piece of wool. The absolute uncertainty in the mean is calculated using the methods outlined in Module 1.5. There is a notable variation between the measured results. The charges on balloons 1 and 2 have a difference of 0.4 nC. The uncertainty in the measurements due to the precision of the instrument is ±0.5 nC, therefore the difference in charge between balloons 1 and 2 is within the uncertainty range of the instrumental precision. Therefore, this difference in charge may be due to the instrument and not physical reasons. Because this cannot be determined with certainty, it must be interpreted that there is no physical difference between balloons 1 and 2.

The difference in charge between balloons 3 and 4 is greater than the uncertainty range of the instrument, and therefore you can be certain it is due to other reasons besides the instrument. If the methodology controlled the extraneous variables appropriately and nothing unforeseen influenced the results, then you can interpret the difference between the charges on those balloons to be due to physical reasons related to the experiment.

It is important to understand the accuracy and precision of the instruments, as it affects the interpretation of the results. There are a few ways to analyse precision, including:

- **instrumental uncertainty**, which displays the precision of the instrument and explains instrumental variation in the measured results
- **range**, which outlines the difference between the smallest and largest measurements
- **central tendency** (e.g. mean), which outlines the potential variation in instrumental measurements due to the instrument's design or increments.

Analysing validity and theoretical relationships

The results and data must be processed to look for trends, patterns or differences. The processes for analysing data include statistical calculations to determine the true values, uncertainties, errors and significance of the measurements. When the quality of the data is understood, then the validity in relation to established theoretical concepts can be analysed.

Analysis can also find anomalies and outliers in data that are not valid measurements. During the experiment, your record of observations may provide a reason for any outlier in your data. This can then be used to suggest improvements in the methodology to remove such measurements.

INTERPRETING

When the results have been processed and analysed, you should offer explanations of what occurred and why it occurred. Processing and analysing data is the manipulation of numbers or observations to understand and ascertain true values, uncertainties, anomalies and relationships. Interpreting the results involves placing this understanding into words and providing an in-depth explanation of the meaning of the numbers in terms of the variables. Interpretation is writing an explanation of the results.

Interpretations should never provide an explanation beyond the constraints of the experimentation and methodology. Interpretations are not meant to provide all the answers or comprehensive explanations for everything related to an experiment. Interpretations are only valid and reliable if based on what was measured. It is important to note that science can never measure the true value of a phenomenon, so the interpretation is always an inference. The interpretation of results in the scientific report should always be concise.

It is important to interpret the measured results and not the planned or expected results.

- If the results follow expectations, then this research can be used to interpret the theoretical reasons for the measured results. However, ensure the interpretation stays within the limits of the uncertainties and instrumental precision.
- When the results do not follow expectations, interpret them as such. The results still need to be related to theory, and so further research may be required to explain the results. This is where recording observations in the journal during the experiment becomes invaluable. When the results do not occur as expected, the observation provides a clue or a basis for what concepts or relationships need to be further researched. Further research will provide the theory to offer plausibility (infer a reason) for the results. If the results are not as expected, it is important that statistical analysis is used to establish that the results did not follow expectations, rather than just stating because it 'looks' like it.

When the interpretation is complete in your journal, the scientific report can be written, summarising all the scientific work and method used for the experiment.

1.9 Review

SUMMARY

- Raw data includes the measurements and observations made during an experiment.
- Processed data is derived from processing and manipulating raw data.
- Processed data enables trends, patterns and differences to be identified.
- If the measurements between samples or tests fall within the uncertainty range of the instrument, then the variation in results could simply be due to the instrument.
- Interpretations of data attempt to explain the observed results.

KEY QUESTIONS

Retrieval

1 Recall the two types of data.

2 Define 'systematic error'.

3 Define 'random errors'.

Comprehension

4 Explain the difference between processing data and interpreting data.

Analysis

5 A group of students want to test the shielding strength of copper by comparing the strength of Earth's magnetic field inside and outside of the box. Their hypothesis is as follows:
A copper box offers some shielding to Earth's magnetic field, so the value of Earth's magnetic field inside the box should be lower than the value outside the box.

Their results are shown below. Deduce if the results support the hypothesis. In your answer, comment on the two means and the range of uncertainties.

Trial number	Earth's magnetic field outside copper box (μT)	Earth's magnetic field inside copper box (μT)
1	51 ± 5	50 ± 5
2	52 ± 5	51 ± 5
3	49 ± 5	54 ± 5
4	54 ± 5	49 ± 5
5	48 ± 5	49 ± 5
6	50 ± 5	49 ± 5
Mean	51 ± 5	50 ± 5

1.10 Communicating and writing a scientific report

BY THE END OF THIS MODULE, YOU SHOULD BE ABLE TO:

- dentify and explain the sections of a scientific report
- write a scientific report.

To write a scientific report, you need to follow some general conventions. Even though there are many ways to present a report, the report must follow a scientific genre and meet the requirements of the syllabus. This section will provide a guide to writing an appropriate scientific report.

> **i** Your journal should contain all the information required to complete the scientific report for the student experiment. After all, it is a report, and reports summarise research and information gathered on a topic. The scientific report does not require much time to complete when reporting from a comprehensive journal.

SCIENTIFIC WRITING AND LITERACY

The scientific language and terms used by scientists have specific meanings and may differ from the understanding of the term in common language. This allows a common understanding of words, in all languages, to convey specific scientific meaning.

Table 1.10.1 provides some examples of the differences in the understanding of words in common language and in scientific language.

TABLE 1.10.1 A comparison of common and scientific language

Term	Common language meaning	Scientific language meaning	Difference in meaning
Sample	A representative part or a single item from a larger whole or group especially when presented for inspection or shown as evidence of quality	The specifically chosen physical representative of a phenomenon, that was tested, measured or observed during experimentation or an investigation	Very similar: the scientific term is specific to a controlled or measured phenomenon. The quality is not known until after analysis, though inspection is carried out through testing. In common language it can be used generically, whereas in scientific language it is specific to the independent variable.
Results	The outcomes, consequences or effects	The recorded evidence of the sample during experimentation or observation; it includes raw and processed data	Very similar: the scientific term requires measurement or explicit recording of the observed consequence or effect arising from the independent variable.
Significance	Something that is conveyed as a meaning often obscurely or indirectly; the quality of conveying or implying; the quality of being important	Important; of consequence; expressing a meaning; indicative; includes all that is important; sufficiently great or important to be worthy of attention; noteworthy; having a particular meaning; indicative of something	Similar: the scientific term refers to the quality of being important. To establish importance, statistical analysis has to have been conducted to achieve the meaning, or indicate sufficient difference, or worth, and to indicate a particular meaning.
Correlation	The state or relation of being correlated; specifically a relation existing between phenomena or things or between mathematical or statistical variables that tend to vary, be associated or occur together in a way not expected on the basis of chance alone	A relationship existing between phenomena on the foundation of statistical or processed analysis	Almost identical: the scientific term refers to when data processing or statistical analysis has been applied to the common term. As such, the strength of the correlation can be predicted or assumed.

Ensure that your report is written using agreed scientific language and conventions. Your report should be fluent and concise. Carefully plan all parts of the report:

- introduction
- summary of altered methodology
- results
- analysis and interpretation
- evaluation and conclusion
- suggested improvements.

Writing fluently and concisely

The report should be brief and comprehensive, so only use the words required to communicate your information. A report that is concise avoids repetition and remains within the required word count or length. Use scientific language so you can communicate details and knowledge in fewer words. Table 1.10.2 demonstrates communication of the same concept in a few different ways. Fluent and concise wording should cut the word count of the report and improve the quality of the writing.

TABLE 1.10.2 Communicating concepts in various ways

Concept	Communication	Commentary of communication
Outlining the basic structure of an atom	An atom is made up of protons, neutrons and electrons.	This is fluent and concise, however lacks scientific terms or language to convey in-depth understanding.
	Atoms are tiny little objects made up of numerous parts that form the basis of matter. Atoms are made up of electrons, neutrons and protons. The electrons are found away from the centre of the atom. The centre of the atom contains the protons and neutrons.	This is fluent but not concise. There is repetition (e.g. 'tiny' and 'little' have the same meaning, and 'made up' is stated twice). It also uses many words without using scientific terms to provide detail and understanding. This may be useful language in the journal when learning about a topic, but not in the scientific report.
	Atoms are particles comprised of three subatomic particles: the proton, electron and neutron. The centre of an atom is the nucleus and contains the protons and neutrons, with the electrons occupying space external to the nucleus.	This is fluent and concise. Much in-depth understanding is communicated through scientific terms, which enable information to be conveyed in fewer words.

Writing in a scientific genre

The genres or styles of scientific communication include a scientific report, a literature review, an empirical essay and a poster presentation. This section will focus on a scientific report, which is a document that communicates a summary of information, focusing on the main points of interest. It uses headings, sections, tables and graphs to present information. A scientific report follows scientific conventions, including format and language.

Reporting

Headings are an essential feature of a scientific report. International conventions for scientific report writing are specific to the journal publication, so there is no single convention for scientific report writing. Table 1.10.3 lists headings that are commonly used in scientific reports, and describes the information that would be provided under each heading. Sections can be broken down further into subsections, as shown. As can be seen, some subheadings are suitable for more than one section; however, each scientific report will only use each heading and subheading once. It is best to ask you teacher about which headings are preferred, and how to align your scientific report and its headings to the syllabus.

TABLE 1.10.3 Scientific report sections and appropriate titles and information

Scientific report section title	Common title alternatives	Expected information within the section
Title	–	A specific statement that outlines the expected relationship between independent and dependent variable, or a question asking about the relationship between the independent and dependent variable.
Abstract	–	Summarises the entire experiment/investigation in a single paragraph outlining the main information for each section of the background information, method, results, analysis and conclusion. The summary for each section is usually 1–3 sentences per section, usually less rather than more.
Introduction	• Background information • Background research • Literature review	Provides the information already known or inferred from previous experimentation and scientific literature specific to the research question or hypothesis. Explains the current scientific knowledge about the relationship between the independent and dependent variable and any other variables that may alter the relationship.
Method • Sampling technique • Preparation • Experiment	• Procedure	Outlines the exact details for other scientists to repeat the experiment, including specific details about instruments, equipment models and precision, techniques employed and all information required for others to obtain the same results. It is not common to differentiate the materials (equipment and instruments used) from the procedure that uses them.
Results • Raw data • Analysis • Statistical analysis • Interpretation	• Data analysis	The type of data presented is unique to specific journal publications; however, in general, all the data, observations and results need to be presented to explain the interpretation and conclusion. The results must show all the required information to answer the research question or hypothesis.
Conclusion • Analysis • Interpretation • Discussion • Evaluation	• Interpretation • Discussion • Evaluation • Sources of error • Suggestion for improvements/ modifications	Provides an explanation of the results including quality of experimentation (accuracy, precision, validity and reliability of the methodology) and relates the results to current scientific understanding (theory). The strength of the relationship between the experimental evidence (data, uncertainties, observations or results) is to be stated. No new data is to be included in this section.
References	–	A list of all sources used in the scientific report.

Language of reports

The experiment report is written for a scientific audience, so it is important to ensure that the report uses appropriate scientific language and conventions. This contrasts with English writing used in everyday situations.

Experiment reports should be written using:

- past tense—the experiment was conducted in the past, so the report should be in the past tense
- third person, passive voice and impersonal verbs (Table 1.10.4)
- scientific language—the terms used are specific to concepts, models and theories
- objective, unbiased language—avoid subjective and emotional or persuasive writing (Table 1.10.5)
- concise language—avoid unnecessary repetition and express ideas. Scientific language allows more details, knowledge and understanding to be communicated in fewer words. Use shorter sentences that are less wordy (Table 1.10.6).

TABLE 1.10.4 Examples of first-person and third-person narrative

First person	Third person
I firstly put a 150 g brass weight onto the trolley and then moved it to the starting position.	First, a 150 g brass weight was loaded onto the trolley, and then the trolley was moved to the starting position.
After the trolley was released, I found that …	After the trolley was released, the results showed …
My colleagues and I found …	Researchers found …

TABLE 1.10.5 Persuasive writing versus scientific writing styles

Persuasive writing examples	Scientific writing equivalent examples
Use of biased and subjective language • The results are extremely bad, atrocious, wonderful etc. • This is terrible because…	**Use of unbiased and objective language** • The results showed… • The implications of these results suggest… • The results imply…
Use of exaggeration • The object weighed a colossal amount, like an elephant. • Safety crisis…	**Use of non-emotive language** • The object weighed 256 kg. • Safety issue…
Use of everyday or colloquial language • The experiment didn't work because we were clueless. • The results don't… • The researchers had a sneaking suspicion…	**Use of formal language** • Further research is needed to fully determine why the results of the experiment were not as expected. • The results do not… • The researchers predicted/ hypothesised/theorised…

TABLE 1.10.6 Examples of wordy and concise language

Verbose language	Concise language
Due to the fact that…	Because…
Smith undertook an investigation into…	Smith investigated…
It is possible that the cause could be…	The cause may be…
End result…	Result…
In the event that…	If…
Shorter in length…	Shorter…

To produce a fluent report, the scientific language must be used without error, so that the reader understands the meaning of the information easily. The report must remain within the required word count or length. If you are fluent and concise, it will significantly influence the word count and the quality of writing within the specified word limit.

Language constructs

The experiment report is to be written using paragraphs, with each paragraph explaining only one idea. Developing paragraphs is essential when writing fluently and concisely. Each paragraph should explain only one topic. The first sentence (topic sentence) of the paragraph introduces the topic. Following sentences provide the details of the idea. The final sentence concludes the idea. Each sentence within a paragraph should contain only one subject (perhaps two if necessary), and each sentence should flow on to the next, slowly building the details of the explanation. The report should be brief and comprehensive, so you should only use the words required to communicate, and use language that conveys detailed understanding.

Presenting scientific ideas

An efficient way of presenting complex data and explaining scientific concepts is through photographs, graphs, tables and scientific models such as flow charts and diagrams. Ensure you include:

- a descriptive title
- labels, captions or descriptions
- numbering, e.g. Figure 1, Figure 2… or Table 1, Table 2…
- a source, if the work is not your own or is adapted from work that is not your own.

Using tables and graphs

In general, tables provide more detailed data than graphs. However, it is easier to observe trends and patterns in graphs, making them a very useful tool for presenting evidence. Pie charts illustrate percentages well, while scatterplots illustrate relationships between variables. Bar charts are best used for qualitative data and discrete quantitative data. Scatterplots are best used for continuous quantitative data.

Editing your report

Editing your report is an important part of the process. After editing your report, save the new draft with a different file name and always back up your files in another location. Pretend you are reading your report for the first time when editing. Once you have completed a draft, it is always good practice to read your work a day or two after you have completed it. When reading your own work, do not read it as you intended. Instead, carefully read your work, following the punctuation, grammar and spelling as it appears on the page. This is more easily achieved if you read the report aloud. When editing, look for content that:

- is ambiguous or unclear
- is repetitive
- is awkwardly phrased
- is too lengthy
- is not relevant to your research question
- is poorly structured
- lacks evidence
- lacks a reference (if it is another researcher's work)
- contains spelling mistakes.

Acknowledging sources

All the quotations, documents, publications and ideas used in your investigation need to be listed in the references and acknowledgments. In order to avoid plagiarism and to ensure creators are properly credited for their work, this must be completed accurately. References and acknowledgements also give credibility to your study and allow the audience to locate information sources for further study.

Plagiarism is using other people's work without acknowledging them as the author or creator. To avoid plagiarism, include a reference every time you report the work of others. Place the reference at the end of a sentence or following a diagram. If you use a direct quotation from a source, enclose it in quotation marks. This will ensure you give credit to the original author and it will enable the reader to find the original source.

Referencing

A number of different referencing styles can be followed, such as Harvard or APA (American Psychological Association). The sources of information must be acknowledged using a referencing style that is suitable for the purpose of the investigation. Check the preferred referencing style or convention of your teacher for in-text referencing and a complete reference list.

The student experiment does not require a bibliography; a reference list is sufficient. A bibliography is a list of all the sources used during the research to develop understanding (including information in the journal) even if the information was not used directly or explicitly in the scientific report. A reference list only lists the sources used and cited (or in-text referenced) in the scientific report.

The sources must be listed at the end of the report in alphabetical order (by lead author's last name or organisation name). Compile your references in a separate document as you conduct the student experiment. This will save you time later. APA style is the most commonly used referencing style.

In-text citations

Each time you write about the findings of other people or organisations, you need to provide an in-text citation and provide full details of the source in a reference list. In the APA style, in-text citations include the first author's last name and date in brackets (author, date).

The following examples show the use of in-text citation and the reference list entry.

In-text citations show two options for inclusion in the sentence.
A single atom of the rare-earth metal holmium has been made into the world's smallest, stable magnet. This was then used to make an atomic hard drive, in which each holmium atom stored one bit of information (Natterer et al., 2017).
Natterer et al. (2017) reported that a single atom of the rare-earth metal holmium was made into the world's smallest, stable magnet. This was then used to make an atomic hard drive in which each holmium atom stored one bit of information.
Reference list the example above would be:
Natterer, F., Yang, K., Paul, W., Willke, P., Choi, T., Greber, T., Heinrich, A., & Lutz, C. (2017), Reading and writing single-atom magnets. *Nature*, 543, 226–228.

ADDRESSING THE SYLLABUS INSTRUMENT-SPECIFIC MARKING GUIDE (ISMG)

It is imperative that your final scientific report addresses all the characteristics in the performance level descriptors of the student experiment ISMG. Before you begin the scientific report, you should plan the sections and titles and then assign the ISMG characteristics to each section. As outlined on pages e68–9 there is no single convention for the scientific report, and the student experiment ISMG characteristics will fit into any scientific report convention. You will just need to decide where. It would best to discuss this with your teacher and develop a plan.

Word limits or word count guides can be assigned to each section. Apply a larger word count to the sections requiring explanations, such as introduction, discussion/conclusion and perhaps the analysis (depending on the convention chosen). Consider how many words will be required for each section, noting the maximum allowable limit set by the ISMG for the entire scientific report. This word allocation will act as a guide, but is flexible. By outlining a word guide, you can attempt to avoid repetitiveness and encourage use of scientific language using fewer words. Make sure the word limit outlined in the ISMG is not exceeded.

When you edit your completed report, assess whether it includes all the evidence in the four criteria (Research and planning, Analysis of evidence, Interpretation and evaluation, Communication) that make up the ISMG (IA2). These are the words that follow 'demonstrated by ...'

1.10 Review

SUMMARY

- A scientific report has the following features:
  - title—a specific statement that outlines the expected relationship between the independent and the dependent variables
  - abstract—a single-paragraph summary of the entire experiment/investigation
  - introduction—an explanation of the current scientific knowledge about the relationship between the independent and dependent variable and any other variables that may alter the relationship
  - method—an outline of the exact details of the experiment, including specific details about instruments, equipment models and precision, techniques employed and all information require for others to obtain the same results
  - results—the relevant data, observations and results relating to the experiment
  - conclusion—an explanation of the results, including quality of experimentation and uncertainties, which is related to current scientific understanding. The strength of the relationship between the experimental evidence is stated. Do not introduce any new data in this section
  - references—a list of all sources used in the scientific report.
- The scientific report must address the requirements of the syllabus.

KEY QUESTIONS

Retrieval

1 Describe the information that is included in the following sections of a scientific report.
- **a** method
- **b** conclusion

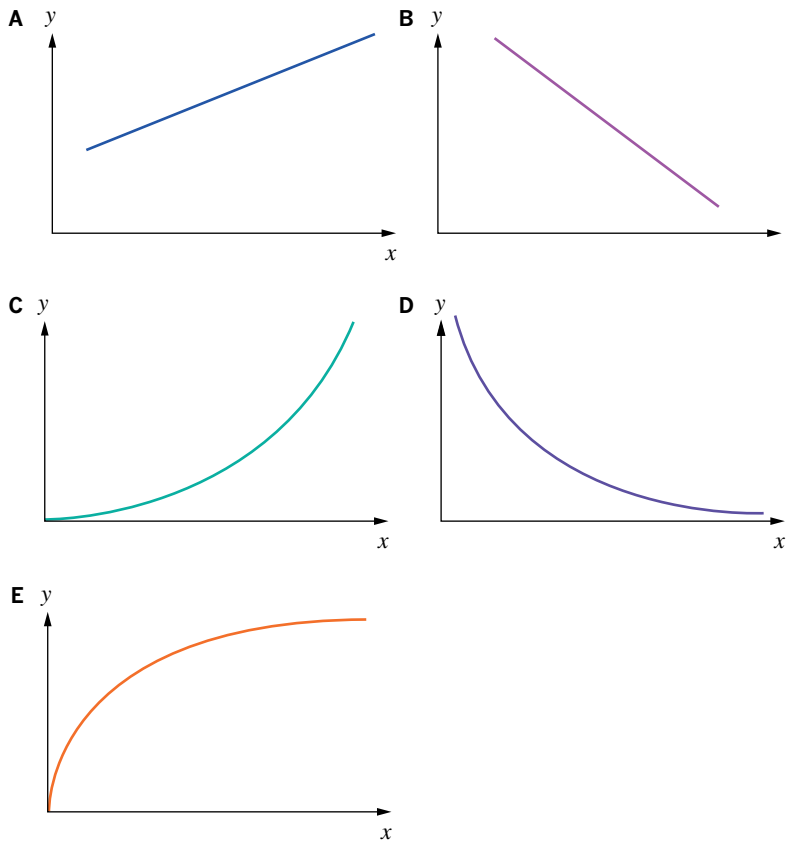
2 Recall in which section of a scientific report you would find processed data.

Comprehension

3 Explain the difference between a bibliography and a reference list.

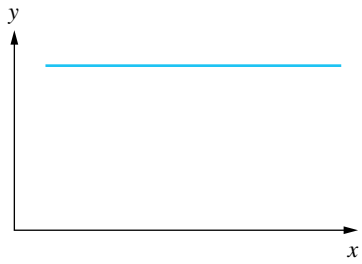
Analysis

4 Use the graphs A–E to answer the following questions:
- **a** Identify the graph(s) that show that the dependent variable increases at a constant rate.
- **b** Identify the graph(s) that show that the dependent variable increases at an increasing rate.
- **c** Identify the graph(s) that show that the dependent variable increases at a decreasing rate.
- **d** Identify the graph(s) that describes the following observation.
  You are measuring the volume of air in a vertically held syringe. A number of books are placed on top of the syringe and you observe the volume of the air decrease at a decreasing rate.



1.10 Review *continued*

e Describe the relationship between the dependent variable and the independent variable in the graph below.



5 Outline what might cause a sample size to be limited in an investigation.

6 Consider this investigation hypothesis:
An increase in the current passing through a single resistor in an electrical circuit will cause an increase in the voltage drop across the resistor.
Improve the following response to the hypothesis by making it more concise:
When the current was 0.03 A, the voltage drop was 0.93 V, and when the current was 0.05 A, the voltage drop was 1.81 V.

PART C RESEARCH INVESTIGATION

The QCAA requires students to complete a research investigation in Unit 4 Physics. In preparation for Unit 4, teachers may choose to assign a similar assessment task in Unit 1, as suggested by the QCAA in their assessment guidance.

The research investigation assessment task requires students to investigate a claim, by drawing on secondary evidence from scientific texts. Students use research conventions to analyse and interpret the evidence to reach a justifiable conclusion about the claim. The research requires students to locate and use information beyond the scope of their knowledge and data they have been given.

The research investigation requires students to gather secondary evidence on a research question. Students must work individually to develop and investigate their research question based on a number of possible claims the teacher provides.

Evidence must be obtained by researching scientifically credible sources, such as scientific journals, books, websites of governments, universities, independent research bodies or science and technology manufacturers.

The research investigation constitutes 20% of the total assessment in Unit 4 Physics.

A summary of the objectives and marking for the research investigation (Unit 4) are shown in the following table.

Research investigation may be presented in:

- written form (e.g. scientific report), 1500–2000 words, or
- multimodal presentation form (e.g. poster presentation), 9–11 minutes.

Criteria	Assessment objectives	Demonstrated by	Marks
Research and planning	• Apply understanding. • Perform an investigation.	• a considered rationale showing how the research question was developed from the claim • a research question that is specific and relevant • collected sources that are sufficient and relevant	6
Analysis and interpretation	• Analyse the evidence sourced during the research. • Interpret the research evidence.	• collection of sufficient and relevant sources • detailed and careful coverage of relevant trends, patterns and relationships • detailed and careful coverage of the evidence's limitations • justified scientific arguments based on evidence	6
Conclusion and evaluation	• Interpret the evidence from the research. • Evaluate the processes, claims and conclusions within the research.	• a conclusion that is justified and addresses the research question • insightful examination of the evidence's quality • extension of investigation findings that are credible • consideration of possible improvements and extensions to the investigation that are relevant to the claim	6
Communication	• Present the research findings, including arguments and conclusions.	• scientific language and representations that are concise and fluent • suitable use of genre conventions • appropriate referencing conventions to acknowledge sources	2
Total			20

The scientific inquiry is not a linear process. Scientists will not necessarily complete these steps in the stated order and some steps may need to be repeated or altered in order to more accurately address the research question.

INSTRUMENT-SPECIFIC MARKING GUIDE

Student responses are assessed against an ISMG. In developing your research investigation and planning your response, it is important to always have in mind the assessment objectives, and in particular the characteristics that are described in the performance level descriptors.

The major features of the ISMG are outlined below and shown for the research and planning criterion. Just as for the student experiment, the ISMG is organised in:

- four criteria, though these differ for the research investigation—research and planning, analysis and interpretation, conclusion and evaluation, and communication
- performance levels against which the qualities of the response are assessed
- performance level mark, which may be a single mark or 2-mark range
- performance level descriptor.

In the modules that follow, you will find a guide to an investigation report.

Criterion: Research and planning

Objectives of assessment task

2 apply understanding of... to develop research questions
5 investigate... through research

Key features that distinguish between marking levels:	Marks
• Applying an understanding of the subject matter in an informed way that demonstrates development of the research question from the claim • Applying an understanding of the subject matter in an informed way, that demonstrates careful consideration of the rationale for the question • Development of a research question that is specific and relevant from effective and efficient investigations • Using sufficient resources that are relevant in and effective and efficient investigation	5–6
• Applying an understanding of the subject matter in an adequate way that demonstrates links from the claim to the research question • Applying an understanding of the subject matter in an adequate way that demonstrates a reasonable rationale for the question • Development of a research question that is relevant from an effective investigation • Using resources that are relevant to an effective investigation	3–4
• Applying an understanding of the subject matter in a rudimentary way that demonstrates a weak rationale between the research question and the claim • Development of an inappropriate research question from an ineffective investigation • Using irrelevant and insufficient resources in an ineffective investigation	1–2
• Descriptors not addressed	0

Performance level

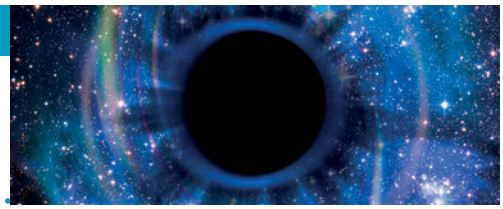
Performance mark: the performance indicator describes requirements to achieve marks.

Examples of performance characteristics

1.11 Developing the research question from a claim

BY THE END OF THIS MODULE, YOU SHOULD BE ABLE TO:

- analyse a claim to identify scientific concepts, variables and measureable terms within the claim
- develop a research question or hypothesis from a claim.



The research question should specifically address one of the concepts associated with the claim. It should clearly state the relevant variables. All the research conducted for the research investigation will be directly related to the research question. Therefore the process begins with the claim and then develops, based on the concepts addressed by the claim.

UNDERSTANDING THE CLAIM

The syllabus defines a claim as 'an assertion made without any accompanying evidence to support it'. The assertion or claim can be a sentence, a statement within a sentence, the title of an article, a quote or anything published in any form. Your research question will focus your investigation, necessitating evidence to be gathered so that the claim can be evaluated. An example of a claim is shown in the title of an article in Figure 1.11.1.

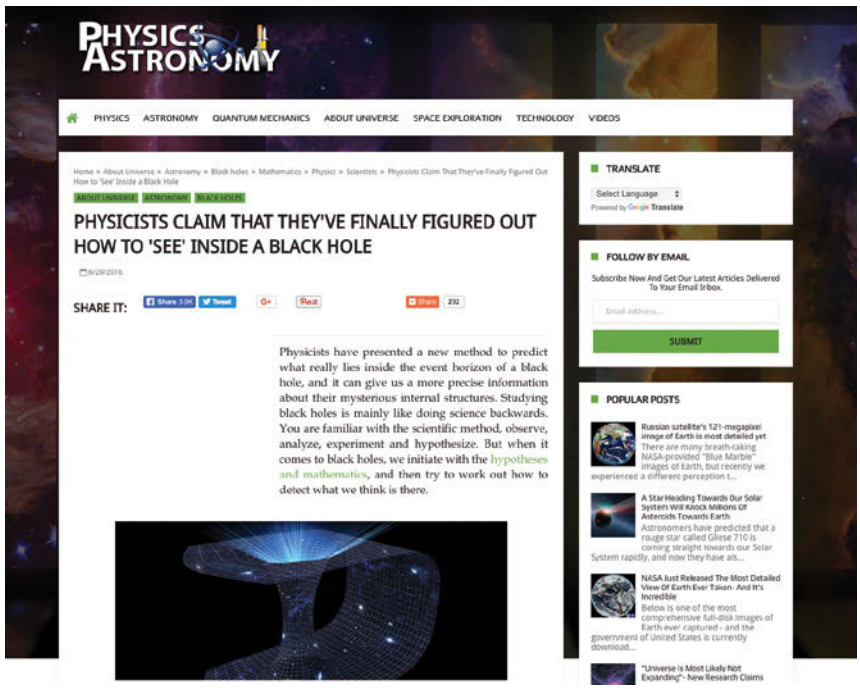


FIGURE 1.11.1 Article with a claim in the title

So how is a research question formed from a claim that is not supported by evidence? The claim itself has to be analysed and understood. Within the claim, identify one or more of:

- known scientific concepts
- variables
- measurable quantities
- ideas related to concepts
- quantities that are claimed to influence another.

You should record all the information you collect during the investigation in a journal, including the process of developing a research question from a claim. This will be used in your research investigation report to address ISMG characteristics about developing a research question from a claim. Write down all the elements found in the claim and try to categorise them using the above list. Each element within the claim may suit more than one category. Table 1.11.1 outlines an example of analysing and categorising elements of a claim.

TABLE 1.11.1 Two examples of analysing and classifying elements of a claim

Example 1

Claim	It is well known that panes of stained glass in old European churches are thicker at the bottom because glass is a slow-moving liquid that flows downwards over centuries.
Source and context of claim	An article from the *New York Times* in July 2008 referred to the unclear nature of glass and whether it was is a solid or a liquid.
Elements in the claim	• Glass is thicker at the bottom than at the top • Viscosity • Melting point • Entropy

Classifying elements of the claim

Glass
- known concepts: solid or a liquid
- uses entropy to determine when it should melt
- structure of glass not well understood

Viscosity
- measureable known concept
- related to thickness and resistance to motion

Melting point
- can be measured for a simple solid
- not constant for glass

Entropy
- a measure of the randomness of the glass
- causes fluctuations in many measurable quantities
- could explain the unusual nature of glass

Example 2

Claim	Cold fusion could provide a limitless supply of energy to the world.
Source and context of claim	Journal article from an established science journal states that nuclear fusion can be created by room temperature sources.
Elements in the claim	• Nuclear fusion • Energy production • Heat source and temperature required • Electrolytic cell

Classifying elements of the claim

Nuclear fusion
- known scientific concept
- not achieved yet on Earth
- source of energy created when smaller nuclei collide and join to make a heavier nucleus
- needs small nuclei such as hydrogen or helium

Energy production
- produces vast amounts of energy per kilogram of matter via Einstein's equation $E = mc^2$

Heat source
- fusion requires tens to hundreds of millions of kelvin to start and sustain
- natural fusion occurs in the cores of stars
- very limited success on Earth with the use of magnetic bottles to contain the material

Electrolytic cell
- a known method of producing electricity via a chemical reaction
- not known to produce a nuclear reaction but does produce a chemical reaction

If you unpack the claim into elements such as related terms and concepts, variables and measureable quantities, you can formulate questions.

FORMING A QUESTION

A research question needs to be formed from the claim because the variables stated in the claim may not be measurable or directly observable, and therefore they may not be scientific.

After extrapolating and expanding the claim further into possible scientific elements, each of these elements can be used to form a question (Table 1.11.2). It is best to formulate a number of questions related to the claim and write them all down in the journal. Each question must enable a response that will evaluate the validity or the reliability of the claim.

When phrasing the research question you will need an understanding of the dependent and independent variables and the relationship between the variables. The claim must identify the dependent variable and may also specify the independent variable. If the independent variable is not in the claim, it will be elsewhere in the material about the claim.

Some guidelines to help form a question include:

1 finding the dependent variable in the claim, or refining it by rephrasing it into something measurable
2 choosing an element of the claim to become the independent variable, or identifying it in the material
3 phrasing a question to ask if the independent variable will influence, cause or correlate with the dependent variable
4 writing a few different questions. Usually the questions improve as you write more, which allows the formulation of a more developed research question.

Read through Table 1.11.2 to see examples of questions formed from the elements of the claims from Table 1.11.1.

TABLE 1.11.2 Two examples of formulated questions from the claims in Table 1.11.1

Example 1	
Claim	It is well known that panes of stained glass in old European churches are thicker at the bottom because glass is a slow-moving liquid that flows downwards over centuries.
Elements of the claim	**Viscosity** • known concept • measureable, related to thickness and resistance to motion
Formulated questions	**a** Can the viscosity of glass be measured? **b** How does gravity affect the viscosity of a liquid? **c** Is there a relationship between the thickness variation of a pane of glass and its age?
Example 2	
Claim	Cold fusion could provide a limitless supply of energy to the world.
Elements of the claim	**Electrolytic cell** • It is a known method of producing electricity via a chemical reaction.
Formulated questions	**a** Does the rate of energy production from an electrolytic cell depend on its temperature? **b** How much mass is lost during an electrolytic cell's operation?

REFINING THE RESEARCH QUESTION

It is possible that one of the questions you write in your journal, from the elements in the claim, will become your research question. As you conduct research into the concepts underpinning the independent and dependent variables, new information will refine the question.

The process to developing a research question is often cyclical, as shown in Figure 1.11.2.

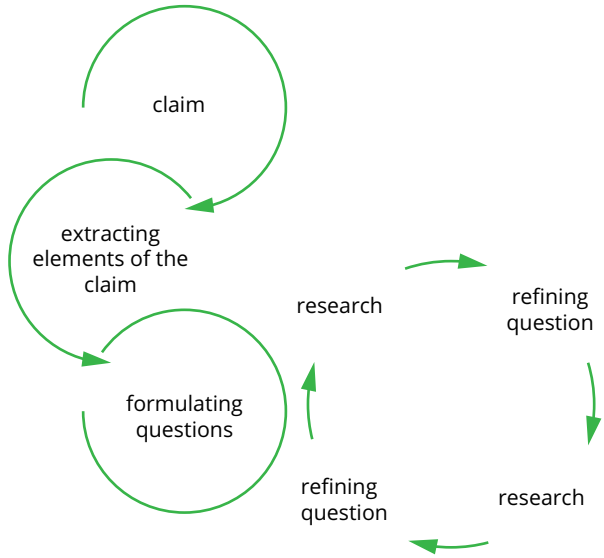


FIGURE 1.11.2 A chart of a common process for developing a research question. This cycle can be repeated as many times as necessary until a scientist is satisfied with the investigation question.

The research question and the development of the research question from the claim using research, scientific concepts, knowledge and understanding, is related to ISMG characteristics:

- a carefully and deliberately constructed rationale identifying an easy to understand development of the claim from the research question
- a research question that is clear and, applicable and pertinent to the methodology
- the selection of adequate, applicable and pertinent resources.

It is important to record your development of conceptual understanding and the knowledge you gain about the relationships between variables. The research investigation requires evidence of the development from the claim to the research question, as stated in the ISMG.

During the research, continue to record your findings in the journal and make note of any ideas that may arise related to the questions. As your knowledge and understanding about the variables develops, refine the question to be more specific.

The goal is to develop the research question to a point where exact data or evidence can be found regarding the variables in the question. It will develop into a research question when evidence from research can answer the question. Table 1.11.3 compares formulated research questions that were refined.

TABLE 1.11.3 Development of the original formulated questions into research questions

Example 1			
Claim	It is well known that panes of stained glass in old European churches are thicker at the bottom because glass is a slow-moving liquid that flows downward over centuries.		
Formulated questions	**a** Can the viscosity of glass be measured?	**b** How does gravity affect the viscosity of a liquid?	**c** Is there a relationship between the thickness variation of a pane of glass and its age?
Refined research question	**a** Is the viscosity of glass measurable using equipment found in a high school physics laboratory?	**b** What is the relationship between the acceleration due to Earth's gravitational field and the viscosity of a liquid?	**c** Does the thickness variation of a plane of glass increase with the age of the glass?

Example 2		
Claim	Cold fusion could provide a limitless supply of energy to the world.	
Formulated questions	**a** Does the rate of energy production from an electrolytic cell depend on its temperature?	**b** How much mass is lost during an electrolytic cell's operation?
Refined research question	**a** Does the temperature of an electrolytic cell increase the rate of energy production?	**b** What is the relationship between the duration of energy production from an electrolytic cell to the total mass lost by the cell?

In your research investigation report, the research you recorded in your journal will be used to write the considered rationale for the research question, displaying its clear development from the claim. This will be achieved by using the research in your journal to outline its step-by-step development, justifying the steps using scientific concepts, knowledge and understanding, as shown in Figure 1.11.2.

The syllabus defines specific (required by the research investigation ISMG) as 'clearly defined or identified; precise and clear in making statements or issuing instructions; explicit' and relevant as 'bearing upon or connected with the matter in hand; to purpose; applicable and pertinent; having a direct bearing on'. Therefore, a specific research question must explicitly identify the dependent and independent variables. The research question must be connected to the considered rationale and the topic of study.

1.11 Review

SUMMARY

- A claim is an assertion made without any accompanying evidence to support it.
- Research questions and hypotheses can be developed from claims by identifying the underlying scientific concepts and variables of a claim.

KEY QUESTIONS

Retrieval

1 Define 'claim'.

2 Identify what a research question should explicitly state.

Comprehension

3 Explain why the research question should be refined.

Analysis

4 Outline the relationship between research and understanding, and the research question that is relevant to the ISMG.

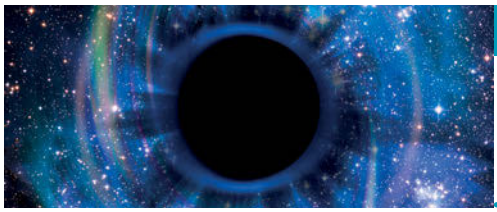
5 Formulate a research question and then a hypothesis for the following claims.

a Aluminium foil stops gamma radiation.

b Magnetic fields have medicinal benefits.

c High-voltage power lines emit dangerous radiation.

1.12 Finding and choosing suitable resources



BY THE END OF THIS MODULE, YOU SHOULD BE ABLE TO:

- distinguish between primary and secondary sources
- locate a range of primary and secondary sources
- determine the validity and reliability of a source.

When gathering scientific evidence for the research investigation, use reputable publications including:

- scientific journals—research papers and scientific reviews
- scientific articles written by organisations that apply scientific research to their industry
- commercial articles such as those in science magazines, newspapers and some websites.

The research investigation must include a reference list of cited resources. The resources used should be sufficient and relevant. The syllabus defines sufficient as 'enough or adequate for the purpose', and relevant as 'bearing upon or connected with the matter in hand; to the purpose; pertinent; applicable and pertinent; has direct bearing on'. Figure 1.12.1 points out the features of sources deemed 'sufficient' and 'relevant'.

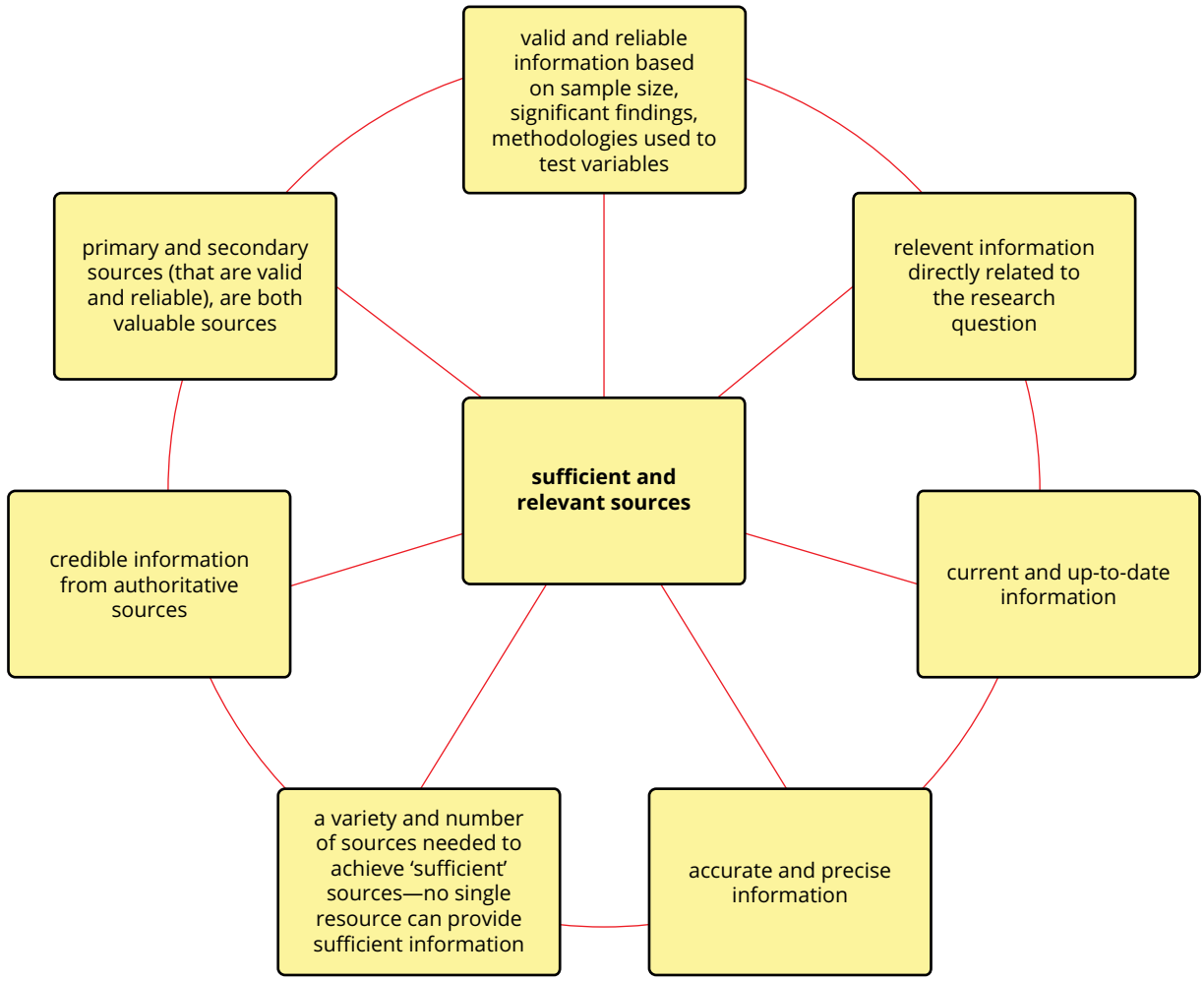


FIGURE 1.12.1 Features of sources suitable for the research investigation

SOURCING INFORMATION

Consider whether the information you use is from a primary or secondary source.

Primary and secondary sources

Primary sources of information are written by the observer or witness of an event or the scientist who conducted the research. The original observer has only processed the information, therefore it is the least biased of all available sources of information. However, even primary sources may be biased, as the observer or researcher had to make choices related to the observation, control of variables, use of instruments and choices for processing data.

Secondary sources of information are not eye-witness accounts but interpretations of events by other people. As second-hand information, accuracy and reliability may be reduced, and events may be interpreted through the writer's perception and bias. You should aim to use a wide range of data sources when using secondary data, to cross-check for accuracy, reliability and validity of information.

When searching for information and evidence, follow these guidelines:

1 Determine if it is a primary or secondary resource.
2 Confirm it is valid:
   - Is the information specifically related to the claim?
   - Is the evidence and information relevant to the variables in the research question?
3 Assess its reliability:
   - Is it current information?
   - Is it up-to-date in its understanding of relationships?
   - Is the evidence equivalent to that from other sources?
   - Does the author have credible qualifications and expertise?
   - Is the methodology valid and were the variables controlled or measured?

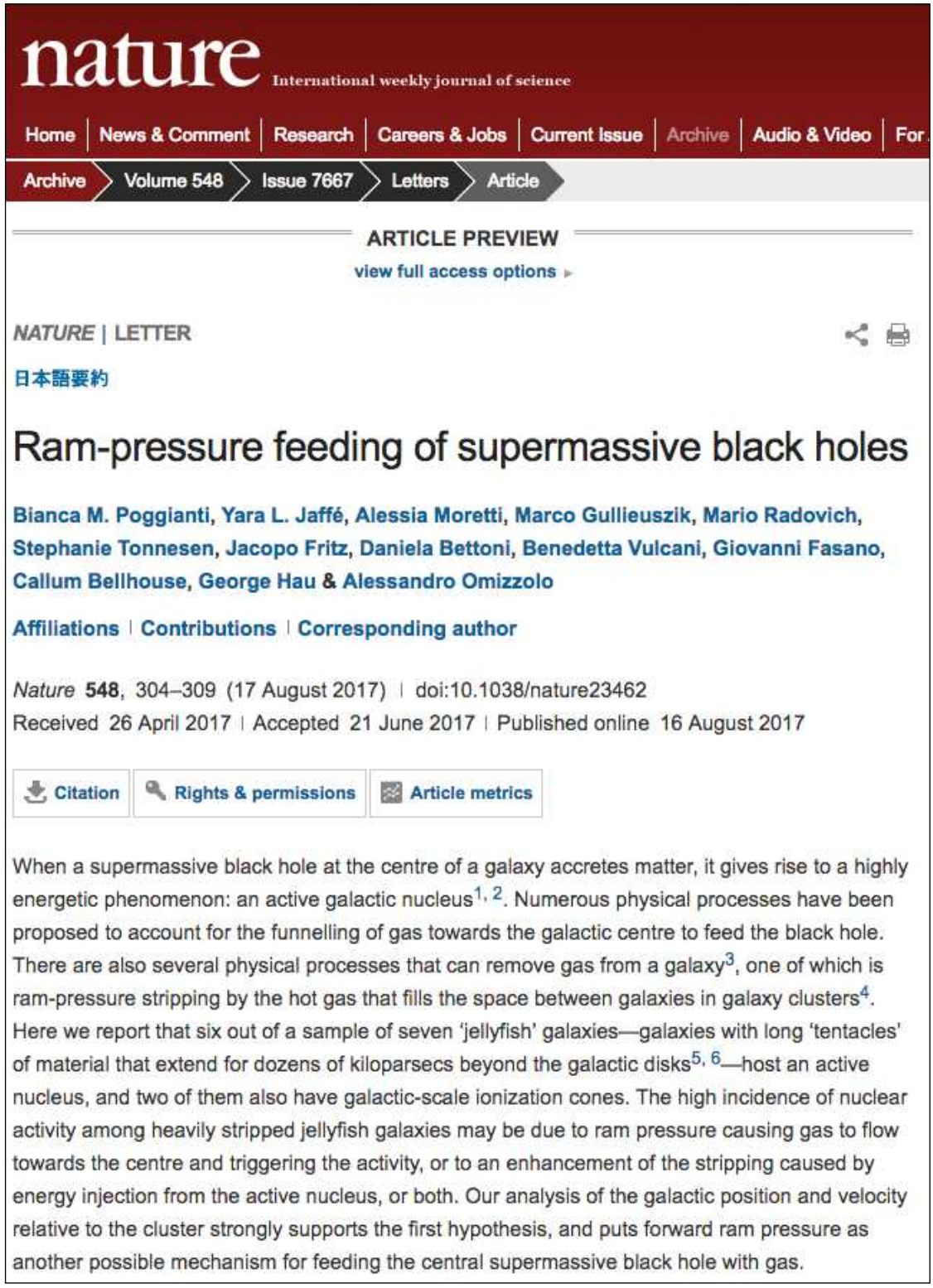
Table 1.12.1 summarises the characteristics of primary and secondary sources. Sometimes the same type of resource may be classified as both a primary and a secondary source, depending on when and by whom it was written. For example, a scientist's journal article on a how a gamma ray laser can be used to measure tiny cracks in metals is a primary source, while a general magazine article about gamma rays written by a journalist and referring to the scientific study is a secondary source.

TABLE 1.12.1 Summary of primary and secondary sources

	Primary sources	Secondary sources
Characteristics	• first-hand records of events or experiences • written at the time the event happened • original documents	• interpretations of primary sources • written by people who did not see or experience the event • use information from original documents but rework it
Examples	• results of experiments • scientific journal/magazine articles • reports of scientific discoveries • photographs, specimens, maps and artefacts • interviews with experts • websites (if they meet the criteria above)	• textbooks • biographies • newspaper articles • magazine articles • radio and television documentaries • websites that interpret the scientific work of others • podcasts

Articles in scientific journals

Peer-reviewed scientific journals are excellent sources of information. Journals are a collection of scientific reports written by the scientists who conducted the research. The reports and articles found in scientific journals are published primary sources, meaning they are the results of the experiments (Figure 1.12.2).



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NATURE | LETTER

日本語要約

Ram-pressure feeding of supermassive black holes

Bianca M. Poggianti, Yara L. Jaffé, Alessia Moretti, Marco Gullieuszik, Mario Radovich, Stephanie Tonnesen, Jacopo Fritz, Daniela Bettoni, Benedetta Vulcani, Giovanni Fasano, Callum Bellhouse, George Hau & Alessandro Omizzolo

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When a supermassive black hole at the centre of a galaxy accretes matter, it gives rise to a highly energetic phenomenon: an active galactic nucleus[1, 2]. Numerous physical processes have been proposed to account for the funnelling of gas towards the galactic centre to feed the black hole. There are also several physical processes that can remove gas from a galaxy[3], one of which is ram-pressure stripping by the hot gas that fills the space between galaxies in galaxy clusters[4]. Here we report that six out of a sample of seven 'jellyfish' galaxies—galaxies with long 'tentacles' of material that extend for dozens of kiloparsecs beyond the galactic disks[5, 6]—host an active nucleus, and two of them also have galactic-scale ionization cones. The high incidence of nuclear activity among heavily stripped jellyfish galaxies may be due to ram pressure causing gas to flow towards the centre and triggering the activity, or to an enhancement of the stripping caused by energy injection from the active nucleus, or both. Our analysis of the galactic position and velocity relative to the cluster strongly supports the first hypothesis, and puts forward ram pressure as another possible mechanism for feeding the central supermassive black hole with gas.

FIGURE 1.12.2 An extract of an article in a scientific journal of a research report written by scientists. The article follows a strict structure: a pertinent title; names of authors; an abstract; and the report, which uses the convention of introduction, method, results, analysis, conclusion and a reference list.

Access to scientific journals can be restricted, as many journals require subscriptions or membership at a financial cost, although some are free. Figure 1.12.3 provides ideas for accessing scientific journals. NASA ADS is another service that allows access to physics and astronomy abstracts.

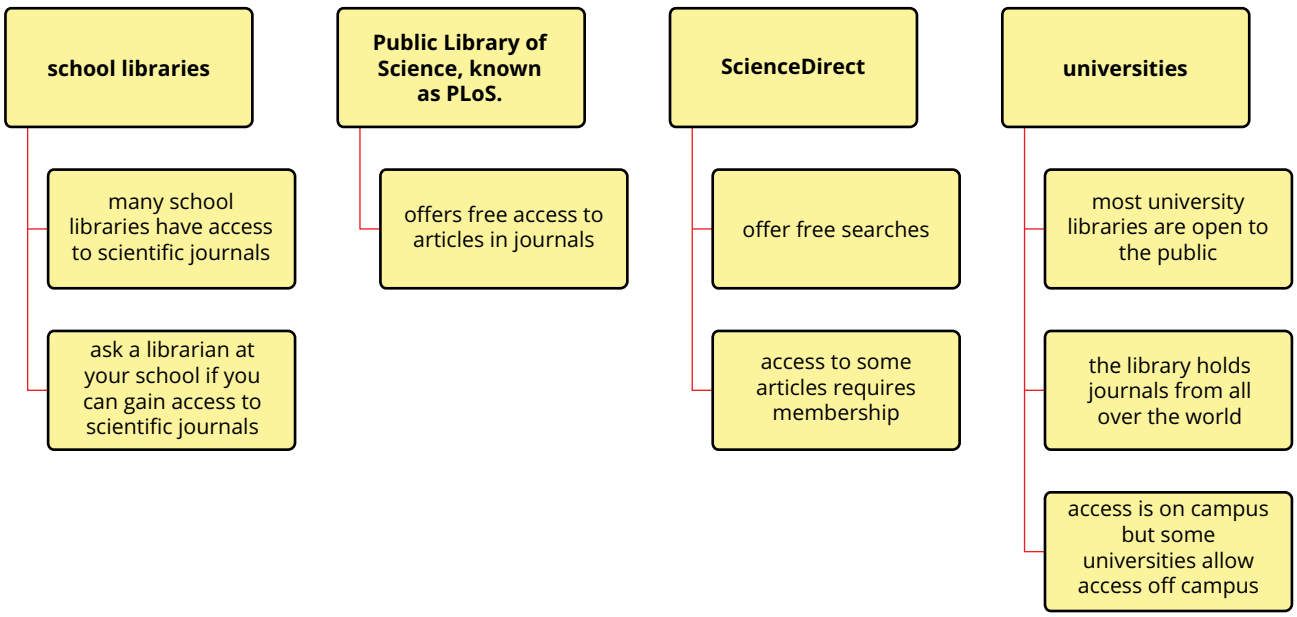


FIGURE 1.12.3 Suggestions and information on accessing scientific journal articles

Scientific articles are excellent sources of information, but they also have their drawbacks as sources for the research investigation. Table 1.12.2 outlines some advantages and disadvantages of sourcing and using articles in scientific journals for the research investigation.

TABLE 1.12.2 Advantages and disadvantages of scientific articles

Advantages	Disadvantages
• written by experts • authoritative information (peer-reviewed) • most current information • logical, organised layout • content is relevant to the topic • contain an abstract that summarises all information in the article (if you don't find the information in the abstract, the article is not relevant) • primary source	• information is complex and challenging to understand, with complex language and advanced processing and analysis of data • require an understanding of scientific literacy, language and numeracy • may be time-consuming to read and analyse • do not have recently published articles about well-established concepts • may be difficult to locate

Books and physical publications

Secondary sources such as good science magazines and books are valuable sources of secondary information.

The first source you should use is your textbook. The language and concepts are presented specifically for high school students. In addition, the textbook addresses the syllabus objectives. Non-fiction books and magazines will probably be commonly used resources for the research investigation. Common commercial science magazines you might find in your school library include *New Scientist*, *Cosmos*, *Scientific American* and *The Helix* (Figure 1.12.4).

FIGURE 1.12.4 You might find this science magazine in your school library.

Table 1.12.3 outlines some advantages and disadvantages of non-fiction books as sources for your research.

TABLE 1.12.3 Advantages and disadvantages of book resources

Advantages	Disadvantages
• may be written by experts • potentially authoritative information • logical, organised layout • content is relevant to the topic • contain table of contents and index to help find relevant information • easily located in libraries • written in language that is understandable	• may not have been published recently • usable by only one person at a time • may have more bias than primary sources

Searching online

Online sources include online scientific organisations such as CSIRO, AIP (Australian Institute of Physics), IOP (Institute of Physics), NASA, and other university publications and presses. Many government and privately funded science organisations publish material along with non-for-profit scientific organisations. Websites may direct you to magazines and scientific journals, such as those described above, the news, podcasts, blogs and videos (institutional, company and personal).

Information located on the internet requires very careful scrutiny. The openness and ease of publishing on the internet means information may not be valid and reliable. Use the guidelines above to help you evaluate sources. Table 1.12.4. outlines advantages and disadvantages of locating and using information online.

When searching for relevant information you need appropriate search terms to enter into a search engine. These tips can help your search.

- Break your search statement into concepts and key words.
- Find synonyms, other related terms and concepts that apply to the topic.
- Create concepts of 1–3 words to enter into the search engine.
- Try different combinations of terms.
- Don't settle for the first sites on the list or your first attempt and look beyond the first page of results.
- Look through the results for sites from science organisations and research institutions (e.g. CSIRO, NASA, .gov, .org), universities (.edu) and science journals and magazines.

TABLE 1.12.4 Advantages and disadvantages of online resources

Advantages	Disadvantages
• quick and easy to access • allow access to hard-to-find information • allow access to the whole world; millions of websites • information is potentially more up-to-date • may be interactive and use animations to enhance understanding • may not be reliable, valid or credible	• can easily side-track with non-relevant information • a lot of 'junk' sites and potentially more biased material • need to discern search engine results to find most useful sites • cannot always tell how up-to-date information is • can be hard to tell who has responsibility for authorship • information may not be well ordered • some journal articles are not free

Overview of resources

Your textbook should be your first source of reliable information. Other information should be consistent with this. Articles published in journals and magazines often present findings of new research, which may or may not be confirmed later, so be careful not to treat such sources of information as established fact. Scientific journals are peer-reviewed (critically reviewed by other specialist scientists), which gives them more credibility than other sources.

SKILLBUILDER

Evaluating sources for validity and reliability

Determining the validity and reliability of a source can be a challenging task. For some sources it is easy to find details about the author, evidence and concurrency, while others only contain content and do not offer any other details. Another difficulty is that when learning about a new topic or concept you are all novice learners; so it can be challenging to tell if a source is valid or not.

These tables outline examples of evaluating a resource step-by-step, for a claim about the ability of sound waves to levitate polystyrene foam particles.

SOURCE EVALUATED: Three-dimensional mid-air acoustic manipulation by ultrasonic phased arrays
Scientific research article http://journals.plos.org/plosone/article?id=10.1371/journal.pone.0097590#s3

Criteria		Decision	Support/justification
Primary or secondary	Is this an eye-witness account or a second-hand source?	Primary	Research article published in PLoS Research results published in article
Validity	Does it contain information that is specifically related to the claim?	Yes	Outlines information directly related to levitation of small polystyrene spheres by sound waves
	Is the evidence and information pertinent to the variables in the research question?	Yes	Information, experiment and results are specific to acceleration and maximum time of suspension of the spheres.
Reliability	Is it current/recent information?	Yes	Published July 2014
	Is it up-to-date in its understanding of relationships?	Yes	Information outlines history of sound wave levitation from as far back as 1975 to recent resources up to 2012.
	Is the evidence equivalent to other sources?	Mostly	Some results are new and previously untested, therefore provides new knowledge never before seen. As a result there are only eight references.
	Check credibility and consider the author's qualifications and expertise.		Authors are Japanese researchers at Japanese universities.
	Try to find the sample size.	Unknown	Not easily found
	Try to establish what variables were controlled or measured.	Known	• Frequency of sound (increments of only 1 Hz) • Acceleration of the spheres • Distance travelled by the spheres before they fell • Time elapsed before the spheres fell

A judgement could be made about this source such as:
The information and evidence was published by experts in a peer-reviewed journal article that is current and with variables of experimentation known and directly related to the claim and research question. The results are new but are not yet substantiated, therefore affecting the reliability of the evidence. This resource is both valid and reliable.

continued over page

Skillbuilder *continued*

The judgement of this second source could be as follows: No evidence is provided about the source of information, author (their expertise) or dates of claims; however, the information is current and directly related to the claim and research question. The source is valid but may not be reliable.

SOURCE EVALUATED: Scientists levitate small animals
https://www.livescience.com/1165-scientists-levitate-small-animals.html

Criteria		Decision	Support/justification
Primary or secondary	Is this an eye-witness account or a second-hand source?	Secondary	General information with photos
Validity	Does it contain information that is specifically related to the claim?	Mostly	Effect of levitation on insects
	Is the evidence and information pertinent to the variables in the research question?	Yes	Levitation and weight
Reliability	Is it current/recent information?	Mostly	November 2006
	Is it up-to-date in its understanding of relationships?	Unknown	Resources not listed, however corroborates with other sources
	Is the evidence equivalent to other sources?	Mostly	Equivalent to other sources
	Check credibility and consider the author's qualifications and expertise.	Yes	Author is a science journalist
	Try to find the sample size.	Unknown	Not published
	Try to establish what variables were controlled or measured.	Unknown	Not published

Test the skill

In researching about the claim 'Objects that can travel faster than light', the article, 'These four cosmic phenomena travel faster than light', at https://www.sciencealert.com/these-4-cosmic-phenomena-travel-faster-than-the-speed-of-light, was found. Evaluate this source in relation to its usefulness in investigating the claim. Use the table to make a judgement of the validity and reliability of the source.

SOURCE EVALUATED: These four cosmic phenomena travel faster than light
https://www.sciencealert.com/these-4-cosmic-phenomena-travel-faster-than-the-speed-of-light

Criteria		Decision	Support/justification
Primary or secondary	Is this an eye-witness account or a second-hand source?		
Validity	Does it contain information that is specifically related to the claim?		
	Is the evidence and information pertinent to the variables in the research question?		
Reliability	Is it current/recent information?		
	Is it up-to-date in its understanding of relationships?		
	Is the evidence equivalent to other sources?		
	Check credibility and consider the author's qualifications and expertise.		
	Try to find the sample size.		
	Try to establish what variables were controlled or measured.		

Solution: Source is valid and reliable.

1.12 Review

SUMMARY

- Scientific evidence for the research investigation can be sourced from numerous publications including scientific journals, scientific articles and commercial articles.
- A primary source is written by the observer/witness of an event, or the scientist who conducted the research.
- A secondary source is a document that refers to or analyses a primary source.

KEY QUESTIONS

Retrieval

1 Decide whether each of the following is a primary or a secondary source.

a a newspaper article about global warming

b an experiment to investigate chemical changes when mixing combinations of chemicals

c an interview with a forensic scientist about using science to track criminals

d a website with information about interplanetary travel by humans

Comprehension

2 Explain the difference between a primary and a secondary resource.

Analysis

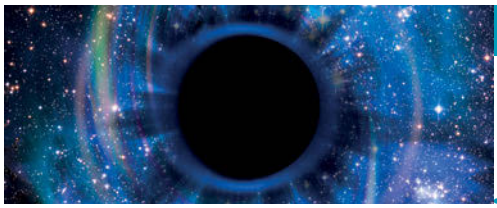
3 You are learning about orbits of planets in other solar systems, and are searching for facts about how the mass of the central star affects the shape of an orbit. From the list below, identify which one would be the best resource to use. Explain your answer.

A the book *Exoplanets: Diamond Worlds, Super Earths, Pulsar Planets, and the New Search for Life beyond Our Solar System*, first published in 2017 for the general public

B an article in the prestigious journal *Astronomy and Astrophysics*, published in June 2017

C the website Exoplanet.eu, accessed on 6 June 2017

1.13 Research: taking and organising notes



BY THE END OF THIS MODULE, YOU SHOULD BE ABLE TO:

- use your scientific journal to take and organise notes, and to refine experimental procedures
- paraphrase information found in primary and secondary sources.

As previously mentioned, a journal should be maintained in which you record all the ideas, research and developments of the research investigation. Once all the work is complete, the information in the journal should form the basis of your response. There is no need to produce new work as it is already completed in the journal.

Scientists organise their journal notes with the following general features:

- date of journal entries
- journal entries for:
  - ideas, observations, proposals and questions
  - research background information for ideas, observations, proposals and questions
  - refinements
  - personal explanations of information, concepts, ideas, observations, proposals and questions (this often includes diagrams)
  - results, data and evidence
- origin of information (recording sources).

RECORDING DATE OF JOURNAL ENTRIES

Always place the date at the start of each day you record in your journal. This is done by professionals worldwide to catalogue and file information. When trying to find previously completed work, most people search their memory as to 'when' they completed the work. They think 'I'm sure I did the research of Y after I found the information on X last week'. So the date of your research will become a simple yet effective filing system.

Many professionals use more than one cataloguing system when they are recording information in their journals, usually recording the date of entries and providing a title for their entries. The titles are often related to their own work and objectives (categories) rather than the title of the source. The title of the source is recorded when the origin is recorded. The most common cataloguing techniques are dates, titles and sources.

RECORDING JOURNAL ENTRIES

Each journal entry should follow a cataloguing system; most typically this is the date and a title. A reference point or cataloguing system helps you to find information when you are searching for it later.

Ideas, observations, proposals and questions

You may be surprised how often simple ideas, observations, proposals and questions influence, direct and help your research days or weeks later. Your ideas, observations, proposals and questions could be related to:

- the variables or concepts involved in your investigation
- new terms you were exposed to and do not understand
- data or evidence you do not currently comprehend but is important to a part of the investigation
- statistics about significance in the analysis of some information
- ideas and proposals about possible future research and questions.

Record all of these in your journal. Later they may:

- save you time by:
  - ensuring you do not research the same idea twice
  - helping you to link ideas from one day or week to the next when you return to your work
  - suggesting guidance and pathways for research and queries that are related
- provide links between concepts in the future that are currently unknown
- provide answers (or partial answers) to future issues, conceptual blocks and questions
- develop understanding of unrelated concepts that become pertinent later.

The content and recordings in your journal will not be in a logical conceptual order, as are your class notes or a textbook. This is because you are researching unfamiliar knowledge and you won't know how it all fits together until the research is complete. The journal will contain all you need to complete the report later.

Before you add an entry to your journal make sure you have recorded the date and provided your own title for the entry. As you take notes from different sources, always record the source information. such as the title, web address, author and page. Figure 1.13.1 is an example of a journal entry.

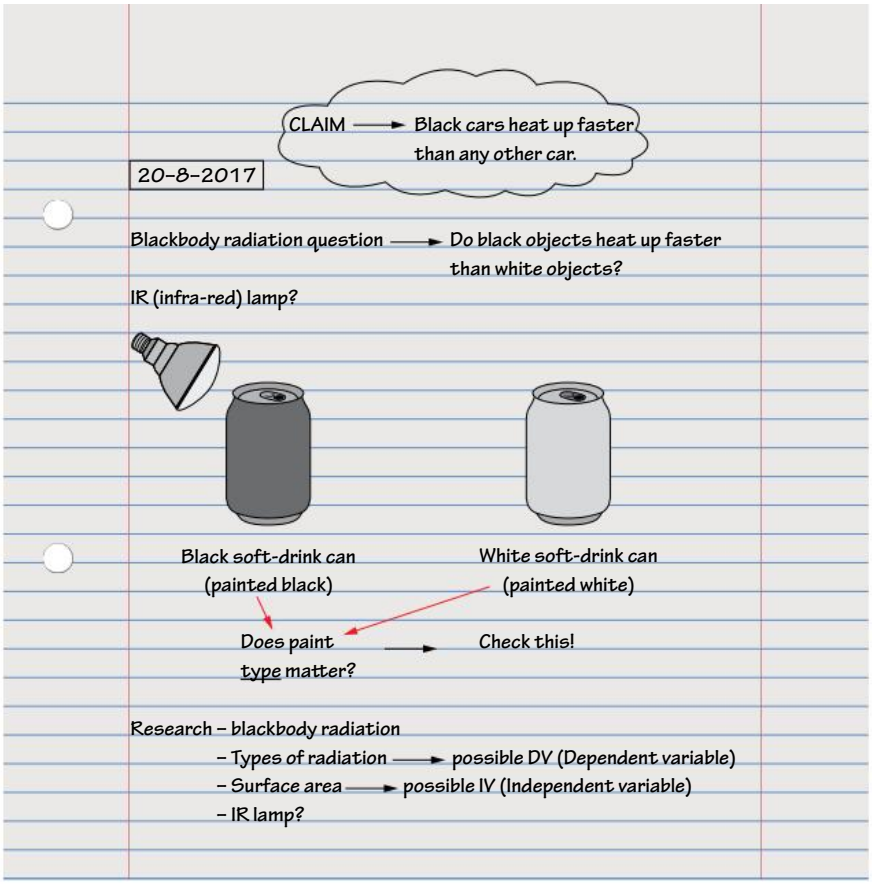


FIGURE 1.13.1 A journal entry with the journal entry date, titles and information. There will be numerous journal entries on any given date, and most likely with their own titles. The same titles will appear on different entry dates as research continues on that topic.

Research background information

Information taken from a source should be rewritten or summarised in your own words in the journal. Avoid copying information verbatim so you are not tempted to plagiarise when you write up the research investigation.

It can be difficult sometimes to rewrite sources into your own words, especially if it is already expressed well and concisely. Before you write and record the research information, read the material and grasp its understanding. Without referring back to the source, write notes in your journal, in your own words. Use multiple sources and a dictionary as references for information. The notes in your journals should be detailed with extended explanations that you will fully comprehend when you refer back to them at a future date.

Worked example 1.13.1

RE-WORDING INFORMATION FROM SOURCES

A resource for information states that:

'It can be expected that the days will be warm and the nights will be cool over the next three days due the high-pressure system moving across the region.'

Rewrite this information into your own words.

Thinking	Working
Swap the order of information, so that the reason (high-pressure system) comes before the object (the warm days and cool nights).	Due to the high-pressure system moving across the region, the days will be warm while the nights will be cool.
Change numerous words such adjectives, verbs, adverbs and nouns.	It has been predicted that during the daytime it will be warm while the evenings will be cool for about 3 days, as a high-pressure system travels over the region.
Gather more data so you can elaborate on the information to explicitly outline explanations.	The weather forecast expects (made a prediction based on computer simulations) that the temperature during the day will be warm (22–25°C) and the evenings will be cool (below 12°C) due to a high-pressure system (weak high-pressure system), which dissipates clouds and allows direct sunshine to warm Earth's surface; however, in the evenings this system brings cool air from higher altitudes that is no longer warmed by the Sun.

➤ Try yourself 1.13.1

RE-WORDING INFORMATION FROM SOURCES

A resource for information states that:

'It can be expected that days will be cooler and there will be more rain over the next three days due the low-pressure system moving across the region.'

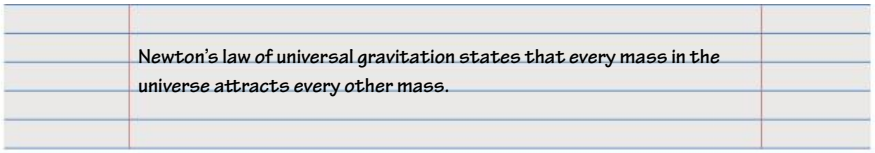
Rewrite this information into your own words.

Personal explanations and interpretation

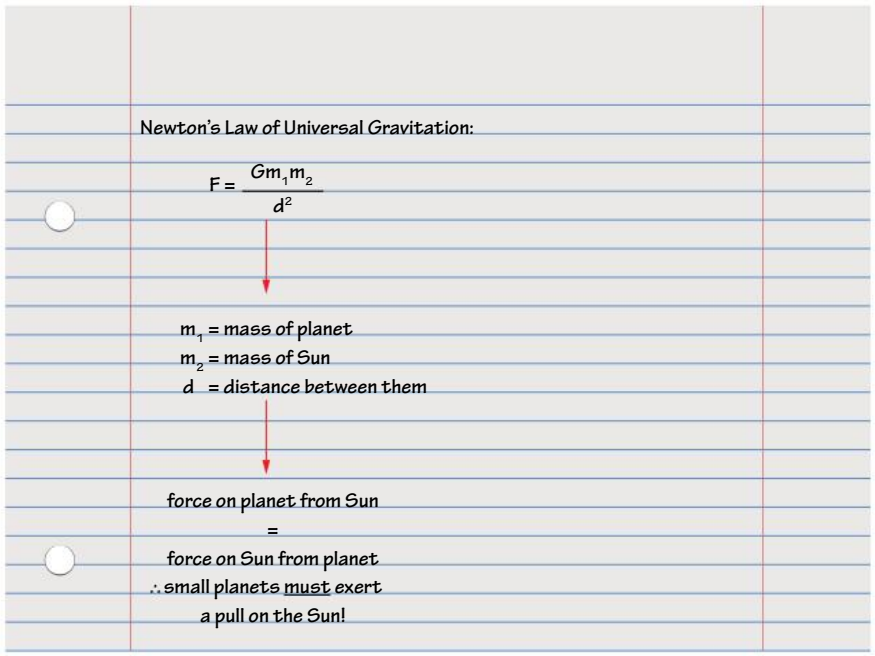
The journal is a valuable tool that is personal to you. As such, it should be written and displayed in formats that you understand and that make meaning of information to produce the research investigation report. It can include writing, drawings and schematics (e.g. flow charts).

Sometimes, one form of recording information provides more details than others, and details are not just facts, it can be the order of events, their location or their physical orientation. Therefore, use a variety of ways to record or present the information to encapsulate more comprehensive details. Figure 1.13.2 presents the same information in a few different ways.

a



b



c

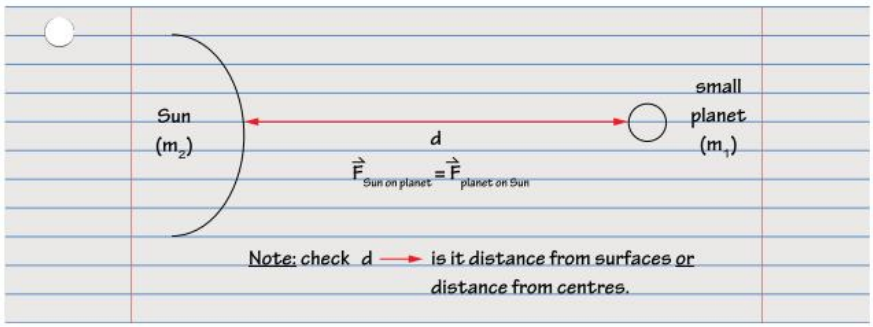


FIGURE 1.13.2 (a) Sample page from a journal explaining Newton's law of universal gravitation in the claim that small planets exert a pull on the Sun. (b) Sample page from a journal explaining Newton's law of universal gravitation in a flow chart as a schematic to unpack the above claim. (c) Sample page from a journal explaining Newton's law of universal gravitation in a diagram.

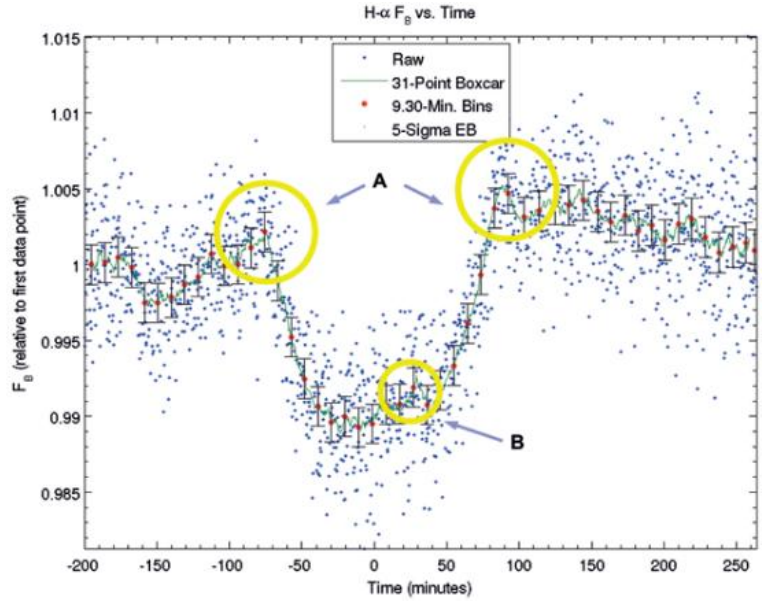
RESULTS, DATA AND EVIDENCE

When you find scientific results in a resource, it is important to record the values or reproduce them in the journal. Your notes about the results, data or evidence should include:

- specific details and your own interpretation of significant values
- the trend or pattern
- the comparison or difference between one set of values and another
- the statistics used to establish significance and also the author's interpretation
- notes written in your own words.

Figure 1.13.3 shows examples of research evidence and how they can be reinterpreted for a journal entry. Figure 1.13.3a is the original evidence the student found through research and Figure 1.13.3b is the student's notes and interpretation of the evidence.

a



b

21-8-17

This is the light curve -> F_B (flux or intensity) of the star DS16402 over 7½ hours, in hydrogen-alpha or 656 nm wavelength.

The features are : a big dip from −80 minutes to +50 minutes

: the brightness (?) appears to be larger after the planet had passed than before it passed (marked as "A")

: There is a smaller dip at about −150 minutes -> not sure why or if it is important.

http://user.astro.columbia.edu/~astrobio/Transit_detection.html

Statistics and Analysis

Red dots = averaged data over 9½ minutes with error bars ✓

Blue dots = raw data ✓ (no error bars?)

Box car = ?

22-8-2017

Box car = A method of smoothing data recorded over a time interval. e.g. over 31 samples in this example

http://sunnytek.net/admin/xiazaifiles/2010114103920522.pdf

FIGURE 1.13.3 (a) Examples of representing evidence using graphs and statistics. This data is of the light curve of distant star as an exoplanet passes in front of it. Statistical information is given in the legend, and three anomalies are highlighted in the yellow circles. (b) An example of a student record of their interpretation of the evidence found in the resource.

When making journal entries it is important for your understanding and analysis of statistical method (e.g. R^2 value), that you express information in your own words. You will most likely have to conduct further research to understand the statistics, their meaning and the author's interpretation of the results, as you will come across new statistical calculations you haven't seen previously.

Recording the origin of information

As you conduct your investigation and research, it is important to write down the source of the information. This will enable you to return to the source later to continue researching, collect further information or re-check details. You will also be required to produce a reference list in the report, and it will save time if you have already recorded the source of the information. You could use a table as shown.

Books	Online
• Author(s) • Title • Date of publication • Publisher • Place of publication • Page/s	• Author(s) or organisation • Title • Date website was written or updated • Date website was accessed • Website address (URL)

1.13 Review

SUMMARY

- There is no single method for taking and organising notes.
- A scientific journal enables scientists to record and organise their notes.
- Scientists continually revise and refine their experiments based on previous experimentation and results.

KEY QUESTIONS

Retrieval

1 List at least four things you should write down in your scientific journal.

Comprehension

2 State how to record information from a source in your journal.

3 Explain the benefit of keeping a scientific journal.

Analysis

4 Paraphrase the following:

a A group of scientists were using different metals to determine their ability at shielding beta particles coming from a radioactive source in a nuclear reactor. There was no statistically significant difference between the metals and their shielding ability.

b A researcher found that by increasing the amount of semiconductor material mixed with conducting material, the resistance of the mixture was drastically reduced. Further experimentation also showed that as the temperature of the mixture was reduced the resistance was even further decreased.

c A study found that the mass attached to a freely swinging pendulum bob had little to no effect on the period of the pendulum's motion. The researchers also found that the pull-back distance had little effect on the period of the pendulum.

1.14 Writing a report for the research investigation

BY THE END OF THIS MODULE, YOU SHOULD BE ABLE TO:

- write a report for your research investigation
- write a literature review for your research investigation.

Different genres can be used to report a research investigation. As a written report, the genres include a literature review, empirical essay and annotated bibliography. The report must be 1500–2000 words. Alternatively, a poster can be used as a multimodal presentation of 9–11 minutes. Even though there are many ways to present your report, it must follow a scientific genre and meet the requirements of the syllabus.

Writing a research investigation report requires scientific communication and will need to follow scientific genre conventions. An explanation of these requirements has been provided in Module 1.10. A report will communicate information in a logical sequence (introduction, body and conclusion) and may contain subheadings. Many of the characteristics of the student experiment are closely related to the research investigation. The focus of the student experiment is on interpreting data collected during a scientific investigation, whereas the focus of the research investigation is to explore a claim.

Characteristics of the genres for presenting the research investigation are summarised in Table 1.14.1. This module will focus on the literature review.

TABLE 1.14.1 Summary of features of presentation genres, for the research investigation

Science presentation genre	Brief description	Features
Literature review	A report that evaluates information found in a publication, related to the selected topic. The report gives a theoretical base for the claim (question), and analyses and interprets information/data related to the claim. The objective is to point out strengths and weaknesses of the claim.	• Abstract • Introduction to topic providing context • Discussion of information/ data • Analysis of data/information • Evaluation of information/ data • Conclusion related back to claim • Presented as paragraphs that flow on in a logical development of ideas • Uses subheadings
Empirical essay	Very similar to a literature review.	
Annotated bibliography	Notes, comments and explanations about article/s. An evaluation of a claim after investigating how other sources treat the claim.	
Poster	An oral presentation accompanies the poster. Poster presents ideas concisely and clearly. These ideas are elaborated on in the oral presentation.	• Includes all the above • Visual, oral and text presentation • Use of font size, colour, dot points, subheadings, logical flow of information to effectively deliver information

LITERATURE REVIEW

A literature review usually includes an introduction, body and conclusion. It critically analyses information and convinces the reader of the significance or importance of the topic being investigated. This is achieved by presenting the information in a logical sequence that guides the reader through the material to understand its significance. The research question provides the foundational direction and guidance of the literature review.

Qualities found in a literature review

Not all qualities and elements of a full literature review will be appropriate for the research investigation. The literature review will be limited to the word count and ISMG characteristics in the syllabus. Depending on the research question and the topic being investigated, your literature review may:

- determine the current understanding on the topic
- provide an overview of key concepts (relevant to the research question)
- identify important relationships between variables (specific to variables that influence the independent or dependent variables stated in the research question)
- identify strengths and weaknesses of evidence in the information used for the above points
- identify any gaps in the research
- identify any conflicting evidence.

One of the key qualities of a literature review is that it is a critical analysis of the evidence to communicate a true understanding of the 'big picture' about a topic. It does not just summarise information. Science is about models, theories, laws and principles, and their continual development. The literature review should critically analyse evidence, the strengths and weaknesses as well as the gaps and conflicts, to convince the reader about the current state of a large jigsaw puzzle of conceptual relationships.

A literature review should:

- critically analyse the evidence—establish what it means and account for the statistical processing of data used (be sure to analyse the methodologies, samples, results and data processing and analysis)
- discriminate between relevant and irrelevant sources and content—only use the relevant in the literature review
- logically inform and convince the reader—plan the introduction, body and conclusion.

There is no hard-and-fast rule about the number of articles you should consult for the research investigation. The term 'sufficient' is defined by the QCAA Physics syllabus as 'enough or adequate for the purpose'. The purpose of the research investigation is to evaluate the claim. Therefore, if the number of articles enables you to draw a justified conclusion about the research question and explore both sides of the argument, then the number of sources is sufficient. Relevant research is that which is connected to the rationale and unit under study.

A thorough analysis requires complete attention to every detail. Therefore the research should include analysis and synthesis from different sources. It should identify patterns, trends and relationships that are related to the investigation. Also it should be explicitly connected to the research question as well as clarify where the sources agree and disagree.

The analysis should identify all the limitations of the research, because this may have a bearing on how valid the information (primary or secondary) is to the research question. It is important that when you analyse data and its limitations you do not do it in a way that only demonstrates what you want to show. Such bias will result in an inappropriate and erroneous conclusion that is invalid. Quality scientific analysis is open to any result.

Justified scientific arguments are those that are supported by sound reasons or evidence. Therefore, you must apply your scientific understanding and conceptual knowledge to the evidence that you have examined. You should consider the following factors.

- State whether a pattern, trend or relationship was observed between the independent and dependent variables.
- Describe the pattern mathematically and specify under what conditions it was observed.
- Note and explain any deviations in the data or information.
- Identify any limitations and uncertainties in the data or information researched. Why and how do these limitations affect the validity to the research question or conclusion?

Your analysis of information may also include an evaluation of the methodology used by the authors to obtain their data or information.

Conclusion and evaluation

In the conclusion, the discussion should include an understanding of the features of the evidence that limit its usefulness. For example, did the sampled population reflect the population referred to in the research question? Is the data from measured samples or from estimated models? Did the studies occur under different conditions or categorise the independent variables differently so that comparison was impossible?

The above questions require a justified discussion that evaluates the reliability and validity of the evidence. Therefore, it is important to discuss the limitations of each source. You can do this by:

- evaluating the method of evidence collection
- identifying issues that could affect validity, accuracy, precision and reliability of evidence
- stating sources of systematic and random errors
- recommending improvements to the evidence to improve validity.

In the discussion, you should recommend improvements to the investigation that are linked to the evidence and would address the limitations and gaps in knowledge that you have identified during the research investigation. Your suggestions must be connected to the claim and allow further investigation.

Communication

This section will provide a guide to writing an appropriate scientific report and some of the general conventions that need to be followed for a literature review.

Once a plan for the literature review has been developed, word limit guides can be assigned to each section. The notes in your research journal will give you a good idea of which sections will require more words for explanations than others. The journal will also help you make decisions on which figures, data and evidence to include, and how many words may be required to elaborate on the evidence. Distribute the total word count across all sections you plan to include in the literature review.

The word guide is not binding. As you complete your review you can alter the word guide and distribution of the word count if you feel it is necessary. However, make sure the limit outlined in the syllabus is never exceeded.

Planning the research investigation report will help address the syllabus ISMG. Figure 1.14.1 illustrates how planning can to be done to ensure the syllabus ISMG is addressed.

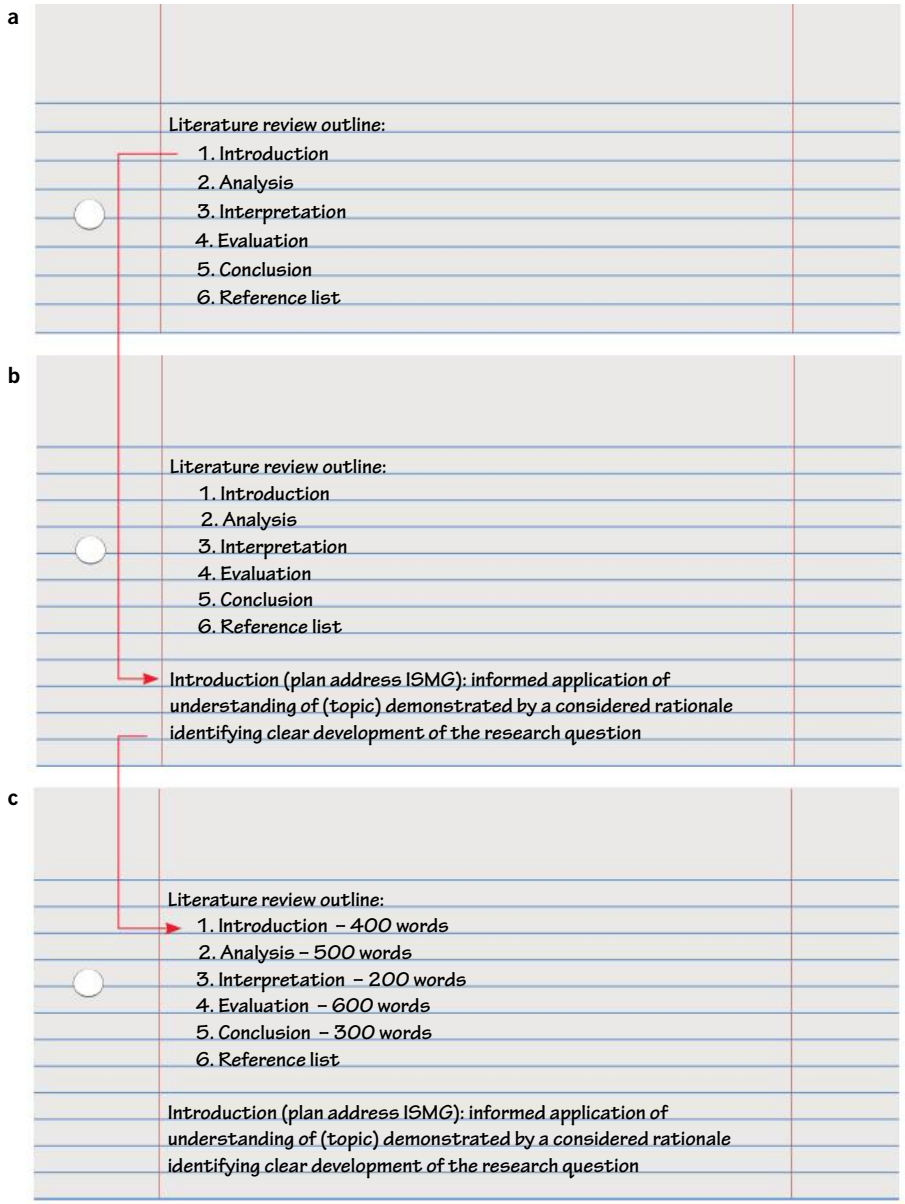


FIGURE 1.14.1 Planning the literature review (a) A planned outline of the research investigation report to ensure the ISMG is addressed. (b) Assigning the ISMG descriptors to the sections in the planned outline. (c) Shows the word count guide planned.

Structure of a written report

Although the use of headings in scientific reports is essential to guide and direct scientists to particular information, there is no single correct convention for a scientific report. A typical structure includes an introduction, body, conclusion and reference list.

Edit the report after you have completed it. Editing is an important part of the process. After editing your report, save new drafts with different file names and always back up your files in another location. Pretend you are reading your report for the first time when editing. When reading your own work, do not read it as what you intended to write, but what you have actually written. Reading the report out aloud will help you to read it more critically. When editing, look for content that is:

- ambiguous or unclear
- repetitive
- awkwardly phrased
- too lengthy
- not relevant to your research question
- poorly structured
- lacking evidence
- lacking a reference (if it is another researcher's work).

1.14 Review

SUMMARY

- There are several genres that can be used to report a research investigation, such as a literature review, empirical essay, poster presentation and annotated bibliography.
- A literature review critically analyses information and convinces the reader of the significance or importance of the topic being investigated.

KEY QUESTIONS

Retrieval

1 Recall the convention for the flow of information through a literature review.

2 State the convention for the literature review genre.

Comprehension

3 Explain the purpose of a literature review.

Analysis

4 Outline how you would achieve an analysis of the methodologies, sample size and results in a literature review.

UNIT 1

Thermal, nuclear and electrical physics

Topic 1 • Heating processes

Topic 2 • Ionising radiation and nuclear reactions

Topic 3 • Electrical circuits

Unit 1 objectives

Students will:

- describe and explain heating processes, ionising radiation and nuclear reactions, and electrical circuits
- apply understanding of heating processes, ionising radiation and nuclear reactions, and electrical circuits
- analyse evidence about heating processes, ionising radiation and nuclear reactions, and electrical circuits
- interpret evidence about heating processes, ionising radiation and nuclear reactions, and electrical circuits
- investigate phenomena associated with heating processes, ionising radiation and nuclear reactions, and electrical circuits
- evaluate processes, claims and conclusions about heating processes, ionising radiation and nuclear reactions, and electrical circuits
- communicate understandings, findings, arguments and conclusions about heating processes, ionising radiation and nuclear reactions, and electrical circuits.

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CHAPTER

02 Heating processes

Thermal energy is part of our everyday experience. Humans can thrive in Earth's climatic extremes, from the outback deserts to ski slopes in winter. Due to increasing levels of carbon dioxide in the atmosphere, the Earth is getting warmer. The last two decades of the 20th century were the warmest for more than 400 years. In 2016, the Earth was the warmest since records began in 1890. These higher temperatures increase the severity of bushfires and increase the rate of evaporation from pastures, which dries the land and reduces the level of food production.

WS 1.1.1

Temperature is a measure of the motion of particles. Different substances will absorb different amounts of heat to raise their temperature or to change state from solid to liquid to gas, depending on their atomic structure. Heat energy can be transmitted through materials in different ways, depending on the material's properties. Energy is conserved in the universe, but in each energy transfer, energy can be 'lost' to less useful forms. The efficiency of energy transfers is considered in this chapter.

Topic 1 • Heating processes

KINETIC PARTICLE MODEL AND HEAT FLOW

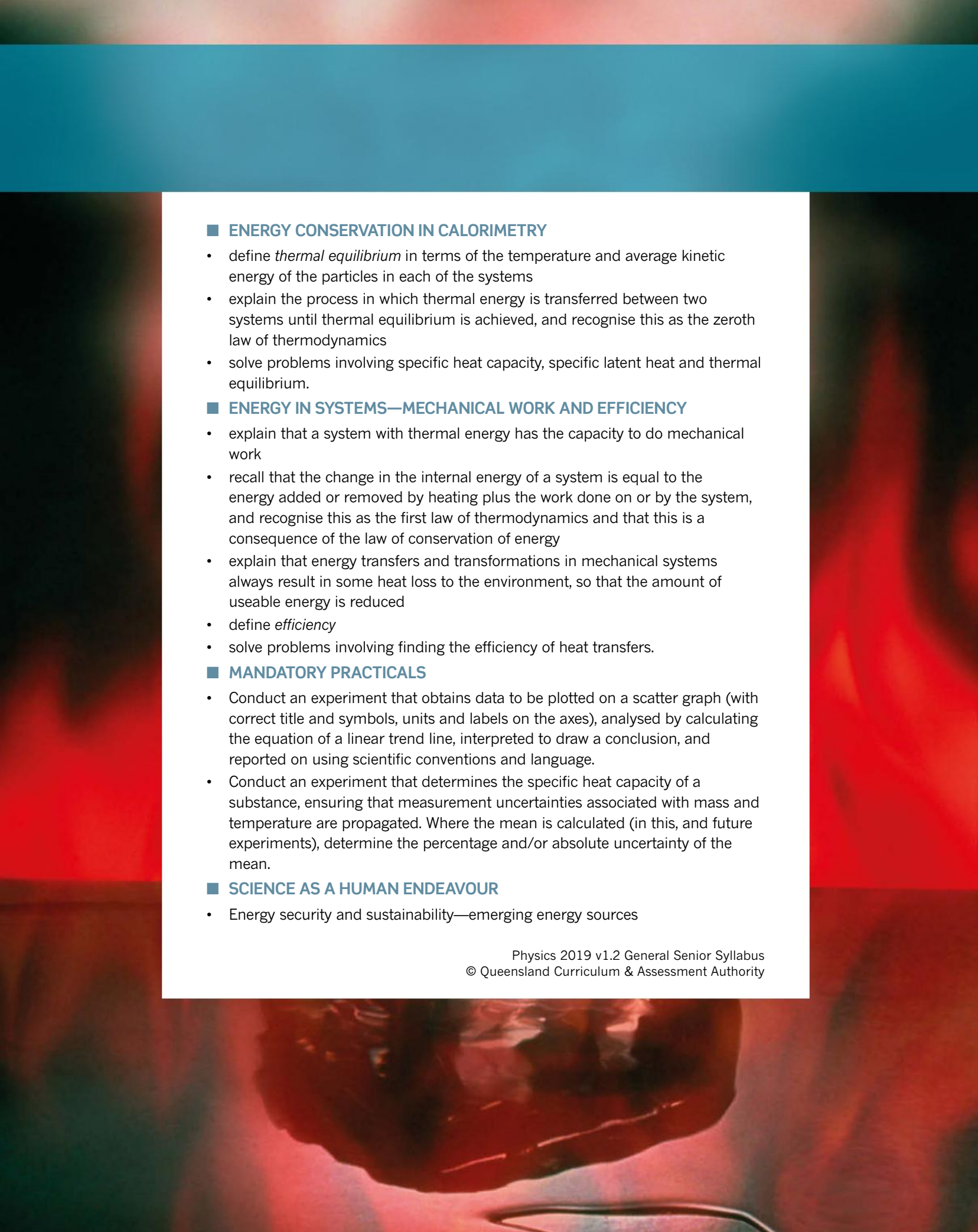
- describe the kinetic particle model of matter
- define and distinguish between thermal energy, temperature, kinetic energy, heat and internal energy
- explain heat transfers in terms of conduction, convection and radiation.

TEMPERATURE AND SPECIFIC HEAT CAPACITY

- use $T_K = T_C + 273$ to convert temperature measurements between Celsius and Kelvin
- use digital and other measuring devices to collect data, ensuring measurements are recorded using the correct symbol, SI unit, number of significant figures and associated measurement uncertainty (absolute and percentage); all experimental measurements should be recorded in this way
- explain that a change in temperature is due to the addition or removal of energy from a system (without phase change)
- define *specific heat capacity* and the concept of proportionality
- interpret tabulated and graphical data of heat added to a substance and its subsequent temperature change (without phase change)
- solve problems involving specific heat capacity.

PHASE CHANGES AND SPECIFIC LATENT HEAT

- explain why the temperature of the system remains the same during the process of state change; explain it in terms of the internal energy of a system and the kinetic particle model of matter
- define *specific latent heat*
- solve problems involving specific latent heat.



ENERGY CONSERVATION IN CALORIMETRY

- define *thermal equilibrium* in terms of the temperature and average kinetic energy of the particles in each of the systems
- explain the process in which thermal energy is transferred between two systems until thermal equilibrium is achieved, and recognise this as the zeroth law of thermodynamics
- solve problems involving specific heat capacity, specific latent heat and thermal equilibrium.

ENERGY IN SYSTEMS—MECHANICAL WORK AND EFFICIENCY

- explain that a system with thermal energy has the capacity to do mechanical work
- recall that the change in the internal energy of a system is equal to the energy added or removed by heating plus the work done on or by the system, and recognise this as the first law of thermodynamics and that this is a consequence of the law of conservation of energy
- explain that energy transfers and transformations in mechanical systems always result in some heat loss to the environment, so that the amount of useable energy is reduced
- define *efficiency*
- solve problems involving finding the efficiency of heat transfers.

MANDATORY PRACTICALS

- Conduct an experiment that obtains data to be plotted on a scatter graph (with correct title and symbols, units and labels on the axes), analysed by calculating the equation of a linear trend line, interpreted to draw a conclusion, and reported on using scientific conventions and language.
- Conduct an experiment that determines the specific heat capacity of a substance, ensuring that measurement uncertainties associated with mass and temperature are propagated. Where the mean is calculated (in this, and future experiments), determine the percentage and/or absolute uncertainty of the mean.

SCIENCE AS A HUMAN ENDEAVOUR

- Energy security and sustainability—emerging energy sources

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2.1 The kinetic particle model

BY THE END OF THIS MODULE, YOU SHOULD BE ABLE TO:

- describe the kinetic particle model of matter
- apply the kinetic particle model to solids, liquids and gases
- understand potential and kinetic energy
- understand heat, temperature and thermal energy
- recognise the internal energy of a substance is a combination of its potential and kinetic energy.

In the 16th century, Sir Francis Bacon, an English essayist and philosopher, proposed a radical idea: that heat is motion. He went on to write that heat is the rapid vibration of tiny particles within every substance. At the time, his ideas were dismissed because the nature of particles wasn't fully understood. An opposing theory at the time was that heat was related to the movement of a fluid called 'caloric' that filled the spaces within a substance.

Today, it is understood that all matter is made up of small particles (atoms or molecules). Using this knowledge, it is possible to look more closely at what happens during heating processes. This section starts by looking at the kinetic particle model, which describes the behaviour of the particles in a substance.

KINETIC PARTICLE MODEL OF MATTER

A **model** is a representation that describes or explains the workings within an object, system or idea. Models can be used to simplify complex structures or systems. Scientists use models to understand and analyse complex systems, and to make predictions about these systems.

The behaviour of particles in a substance is complex, so a model is used to describe it.

Some philosophers in the 17th century believed that heat was a fluid that filled the spaces between the particles of a substance and flowed from one substance to another. This is known as the 'caloric' theory. When caloric flowed from one substance into another, the first object cooled down and the second object heated up. Many attempts were made to detect caloric, but none were successful. It was assumed that caloric had no mass, odour, taste or colour. Scientists now know that caloric simply doesn't exist.

Much of our understanding of the behaviour of matter today depends on a model called the **kinetic particle model** (also known as kinetic theory).

The kinetic particle model of matter states that the small particles (atoms or molecules) that make up all matter have kinetic energy. This means that all particles are in constant motion, even in extremely cold solids. It was thought centuries ago that if a material was continually made cooler, there would be a point at which the particles would eventually stop moving. This coldest possible **temperature** is called **absolute zero** and will be discussed later in Module 2.2.

These are the assumptions of the kinetic particle model:

- All matter is made up of many very small particles (atoms or molecules).
- The particles are in constant motion.
- No kinetic energy is lost or gained overall during collisions between particles.
- There are forces of attraction and repulsion between the particles in a material.
- The distances between particles in a gas are large compared with the size of the particles.

The kinetic theory applies to all states (or phases) of matter: solids, liquids, gases and plasmas.

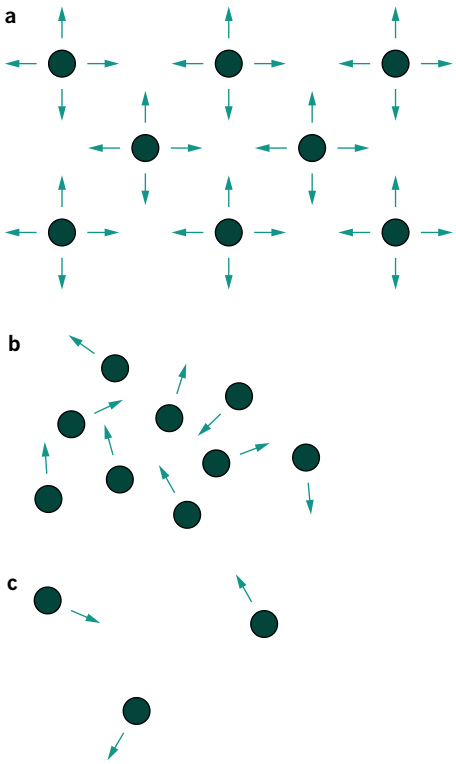

FIGURE 2.1.1 (a) Molecules in a solid have low kinetic energy and vibrate around average positions within a regular arrangement. (b) The molecules in a liquid have more kinetic energy than those in a solid. They move more freely and will take the shape of the container. (c) Gas molecules are free to move in any direction.

Solids

In a solid, the matter holds its fixed shape because the particles exert forces on each other. There are also repulsive forces, without which the attractive forces would cause the solid to collapse. In a solid, the attractive and repulsive forces hold these particles in more or less fixed positions, usually in a regular arrangement or lattice, as shown in Figure 2.1.1a. The particles in a solid are not completely still; they vibrate around average positions. The forces on individual particles are sometimes predominantly attractive and sometimes repulsive, depending on their exact position relative to neighbouring particles.

Liquids

In a liquid, the particles exert a balance of forces of attraction and repulsion. Compared with a solid, the particles in a liquid have more freedom to move around each other and will therefore take the shape of the container. Particles collide but remain attracted to each other, so the liquid remains within a fixed volume but with no fixed shape (Figure 2.1.1b). In general, a liquid takes up a slightly greater volume than the same amount of matter would in the solid state. One exception is water, which is less dense as a solid (ice).

Gases

In a gas, particles are in constant, random motion, colliding with each other and the walls of the container. The particles move rapidly in every direction, quickly filling the volume of any container and occasionally colliding with each other (Figure 2.1.1c). A gas has no fixed volume. The particle speeds are high enough that, when the particles collide, the attractive forces are not strong enough to keep the particles close together. The repulsive forces cause the particles to separate and move off in other directions.

Plasmas

Plasma exists when matter is heated to very high temperatures and electrons are freed (ionisation). A gas that is ionised and has an equal number of positive and negative charges is called plasma. The interior of stars consists of plasma. In fact, most of the matter in the universe is plasma (Figure 2.1.2).

FIGURE 2.1.2 99.9% of the visible universe is made up of plasma.

WS 1.1.2

ENERGY

Energy is a very important concept in the study of the physical world, and is a focus in all areas of scientific study. Later chapters investigate energy in more detail.

Work is defined as being done when a force is applied to an object and moves it.

Energy is a measure of an object's ability to do work. Work is done when energy is transformed. For example, raising an object's temperature or moving or lifting an object is referred to as doing work. Work is measured in joules. The symbol for joules is J. Figure 2.1.3 shows the amount of energy available from some energy sources.

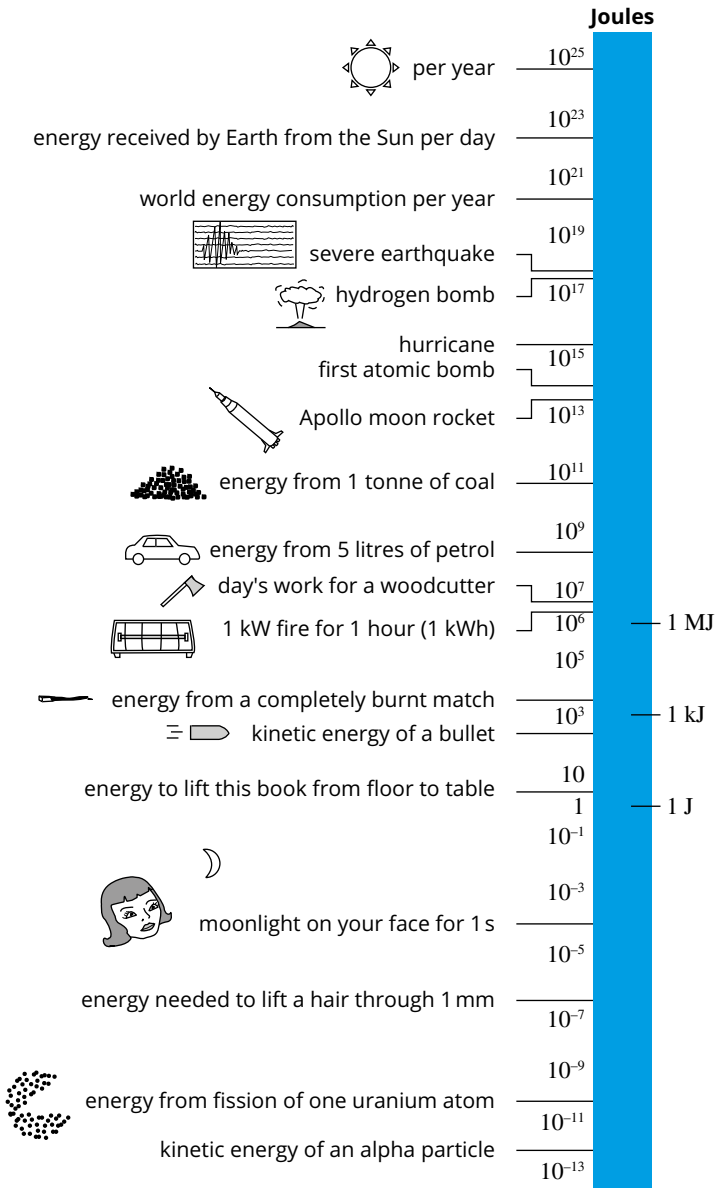

FIGURE 2.1.3 The comparative amounts of energy available from several sources

Potential energy

Potential energy is stored energy. Examples of potential energy include gravitational, nuclear, spring and chemical energy. A compressed spring has potential (stored) energy. Chemical potential energy is associated with the bonds between the particles of a substance. An increase in the potential energy of particles in a substance results in movement of the particles from their equilibrium positions.

Kinetic energy

Kinetic energy is the energy of movement. It is equal to the amount of work needed to bring an object from rest to its present speed or to return it to rest.

Internal energy and heat

The kinetic particle model can be used to explain the idea of heat as a transfer of energy. **Heat** (measured in joules) is the transfer of **thermal energy** from a hotter to a colder body. Thermal energy is the energy a substance has because of its temperature. Heating is observed by the change in temperature, the change of state or the expansion of a substance.

- Heating is a process that always transfers thermal energy from a hotter substance to a colder substance.
- Heat is measured in joules (J).
- Temperature is related to the average kinetic energy of the particles in the substance. The faster the particles move, the higher the temperature of the substance.

When a solid substance is 'heated', the particles within the material gain kinetic energy (move faster) and/or potential energy (move away from their equilibrium positions).

The term 'heat' refers to energy that is being transferred (moved), so it is incorrect to talk about heat contained in a substance. The term **internal energy** refers to the total kinetic and potential energy of the particles within a substance. Heating (the transfer of thermal energy) changes the internal energy of a substance by affecting the kinetic energy and/or potential energy of the particles within the substance. Individual particles in a substance move back and forth in an ordered manner, due to their kinetic energy, and this behaviour can be modelled. In contrast, the internal energy of a system is associated with the chaotic motion of the particles and relates to the behaviour of a large number of particles that all have their own kinetic and potential energy.

According to the kinetic particle model, an increase in the total internal energy of the particles in a substance will result in an increase in temperature if there is a net gain in kinetic energy. Hot air balloons are an example of this process in action. The air in a hot air balloon is heated by a gas burner to a maximum of 120°C. The nitrogen (78%) and oxygen (21%) molecules in the air in the balloon gain energy and so move faster. The air in the balloon becomes less dense than the surrounding air, causing the balloon to float, as shown in Figure 2.1.4.

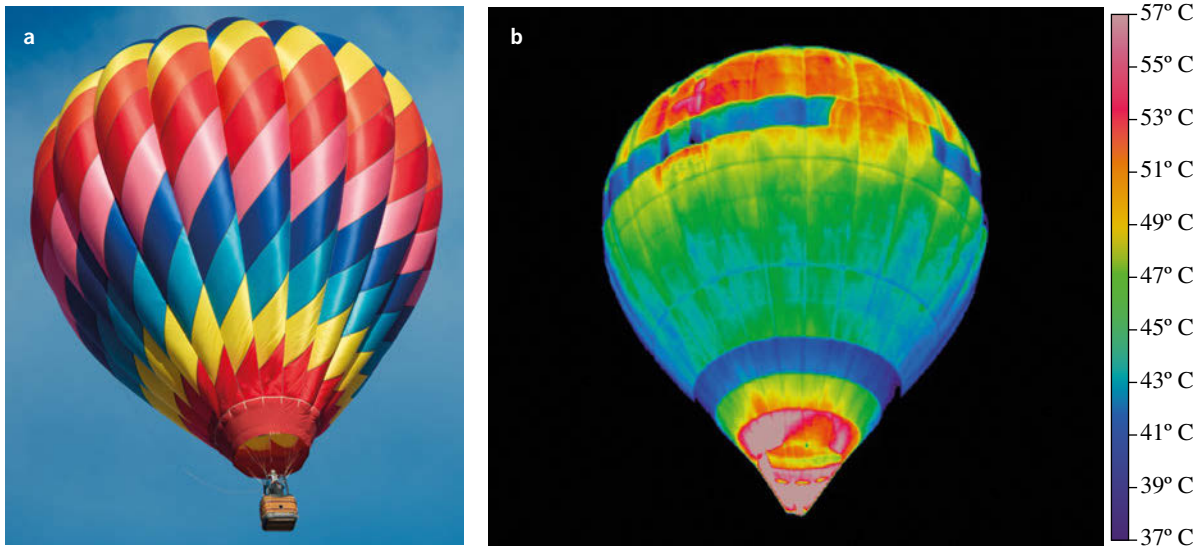

FIGURE 2.1.4 (a) Nitrogen and oxygen molecules gain energy when the air is heated, lowering the density of the air and causing the hot air balloon to rise off the ground. (b) A thermal image shows the temperature of the air inside the balloon.

Sometimes heating results only in the change of state or expansion of an object (phase change), and not a change in temperature. In these cases, the total internal energy of the particles has increased, but only the potential energy has increased; kinetic energy has not changed.

For example, particles in a solid being heated will continue to be mostly held in place, due to the relatively strong interparticle forces. For the substance to change state from solid to liquid, it must receive enough energy to separate the particles from each other and disrupt the regular arrangement of the solid. During this 'phase change' process, the energy is used to overcome the strong interparticle forces, but does not change the overall speed of the particles. In this situation, the temperature does not change. This will be discussed in more detail in Module 2.5.

Kinetic energy and temperature

As the temperature of a substance increases, the kinetic energy and therefore the speed of the particles also increases. At a particular temperature, the particles in a substance will have a range of kinetic energies. Although most of the particles have similar energies, there are always some particles with a high energy or a low energy. This range of energies is shown on a graph called a **Maxwell–Boltzmann distribution**. Figure 2.1.5 shows how the range of energies is represented in a Maxwell–Boltzmann distribution.

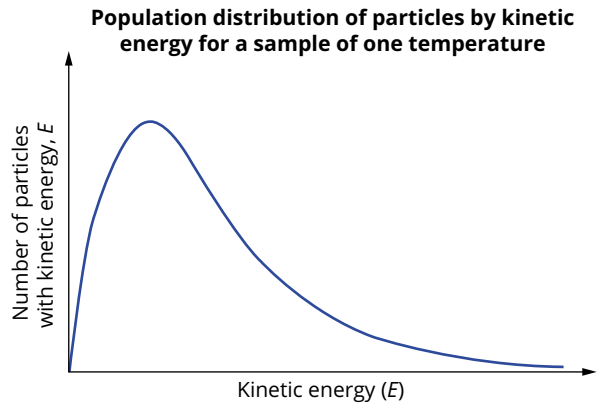

FIGURE 2.1.5 The Maxwell–Boltzmann distribution shows the range of kinetic energies of particles in a sample at a particular temperature. The peak of the graph corresponds to the energy of the greatest number of particles.

As the temperature of a system increases, the average kinetic energy of the particles increases and therefore the average velocity of the particles also increases. Figure 2.1.6 shows the distribution of kinetic energies for a gas at three different temperatures. Notice that the area under the curve, which is equal to the total number of particles in the sample, stays constant when the temperature is changed. As the temperature increases, the increasing average kinetic energy of the particles can be seen by the movement to the right of the peak in the Maxwell–Boltzmann distribution.

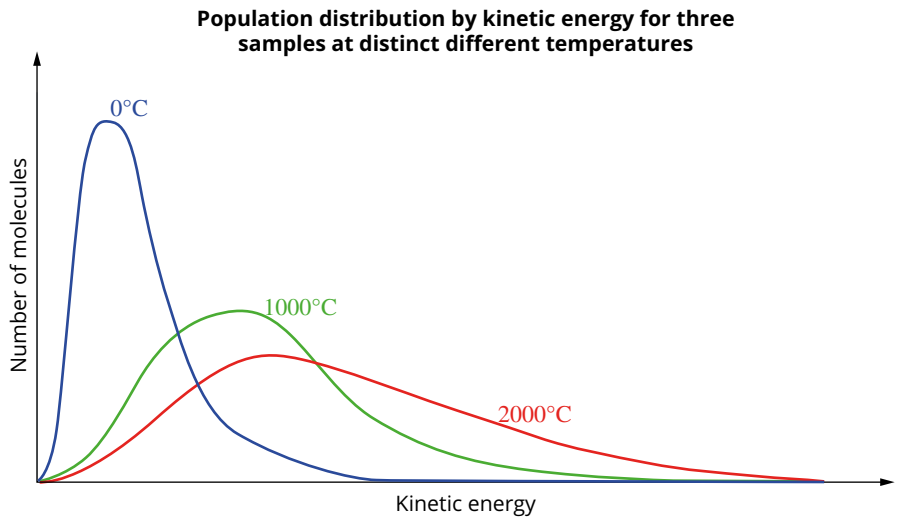

FIGURE 2.1.6 The Maxwell–Boltzmann kinetic energy distribution for a range of temperatures

2.1 Review

SUMMARY

- The kinetic particle theory proposes that all matter is made of atoms or molecules (particles) that are in constant motion.
- In solids, attractive and repulsive forces hold the particles in more or less fixed positions, usually in a regular arrangement or lattice. These particles are not completely still; they vibrate about average positions.
- In liquids, there is still a balance of attractive and repulsive forces between particles but the particles have more freedom to move around. Liquids maintain a fixed volume.
- In gases, the particle speeds are high enough that, when particles collide, the attractive forces are not strong enough to keep them close together. The repulsive forces cause the particles to move off in other directions.
- Internal energy refers to the total kinetic and potential energy of the particles within a substance.
- Temperature is related to the average kinetic energy of the particles in a substance.
- Heating is a process that always transfers thermal energy from a hotter substance to a colder substance.

KEY QUESTIONS

Retrieval

1 State the assumptions of the kinetic particle model.

2 Identify the state of matter that has the most internal energy.

3 Describe the two forms of internal energy.

Comprehension

4 Explain how you measure the change of the average kinetic energy of the molecules within a substance.

5 Describe which way the heat will flow when you put some hot coffee into a cold mug.

6 A substance is heated from solid to liquid to gas. Identify the first phase in which its molecules can move away from each other.

7 Explain how a hot air balloon can rise.

8 Use the kinetic particle model to explain why it is hard to compress a solid.

Analysis

9 Determine why the exact kinetic energy of each molecule in a substance will not be measured, if the temperature is measured.

10 Use the kinetic theory of matter to differentiate between water ice, liquid water and water vapour.

2.2 Temperature

BY THE END OF THIS MODULE, YOU SHOULD BE ABLE TO:

- understand the difference between absolute and arbitrary scales
- convert temperature measurements between Celsius and Kelvin
- explain how a change in temperature is due to an addition or removal of energy from a system.

MEASURING TEMPERATURE

Before thermometers were invented, temperatures were described using vague terms such as hot, cold and lukewarm. In about 1593, Italian inventor Galileo Galilei made one of the first thermometers. His 'thermoscope' was not particularly accurate as it did not take into account changes in air pressure, but it did suggest some basic principles for determining a suitable scale of measurement. His work suggested that there be two fixed points: the hottest day of summer and the coldest day of winter. A scale like this is referred to as an arbitrary scale, because the fixed points are randomly chosen.

How to measure temperature

To measure temperature you use properties of materials that change with temperature. Many thermometers, including mercury and alcohol thermometers (Figure 2.2.1), are based on thermal expansion. Thermal expansion is the expansion of a substance as it increases in temperature. The mercury (or alcohol) expands as it gets warmer, filling more of the thermometer, producing a higher temperature reading.

TEMPERATURE SCALES

Two of the better-known arbitrary temperature scales are the Fahrenheit and Celsius scales. Gabriel Fahrenheit of Germany invented the first mercury thermometer in 1714. The Fahrenheit scale is often used in the USA to measure temperature, but the Celsius scale is used in most countries of the world.

Absolute scales are different from arbitrary scales. For a scale to be regarded as 'absolute', it should have no negative values. The fixed points must be reproducible and have zero as the lowest value.

Kelvin temperature scale

When developing the absolute temperature scale, the triple point of water provides one reliable fixed point. The triple point is the point at which the combination of temperature and air pressure allows all three states of water to coexist. The triple point of water is only slightly above the standard freezing point (0.01°C) and provides a unique and repeatable temperature with which to adjust the Celsius scale.

The absolute or **Kelvin** temperature scale is based on absolute zero and the triple point of water. Figure 2.2.2 shows a comparison of the Kelvin and Celsius scales.

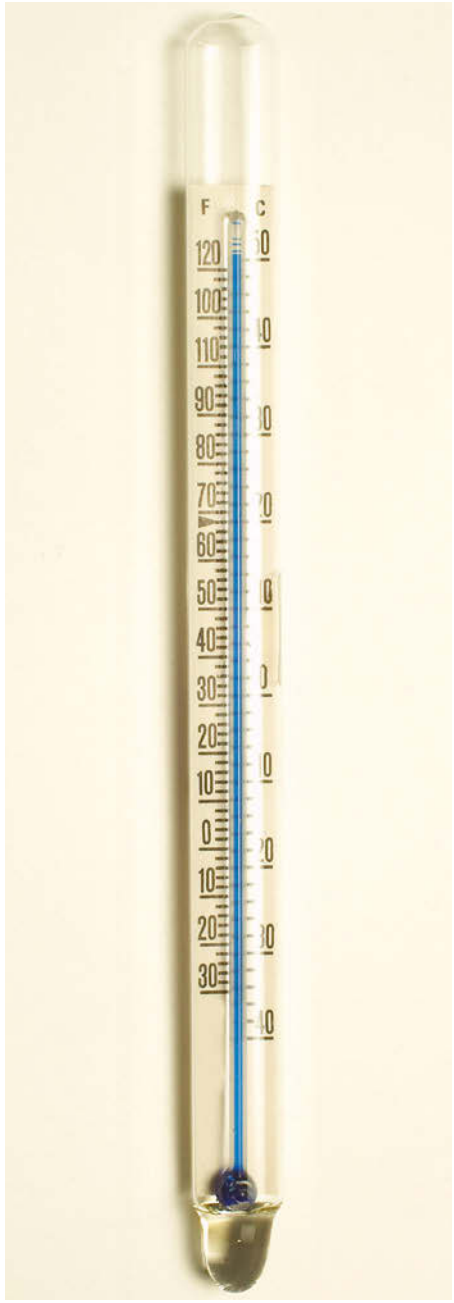

FIGURE 2.2.1 An alcohol thermometer contains alcohol (red or blue, as shown here) instead of mercury (silver).

- The freezing point of water (0°C) is equivalent to 273.15 K (kelvin). This is often approximated to 273 K.
- The size of each unit, (1°C) or 1 K, is the same.
- The word 'degree' and the degree symbol are not used with the Kelvin scale.
- To convert a temperature from degrees Celsius to kelvin: add 273.
- To convert a temperature from kelvin to degrees Celsius: subtract 273.
- 0°C is the freezing point of water at standard atmospheric pressure.
- 100°C is the boiling point of water at standard atmospheric pressure.

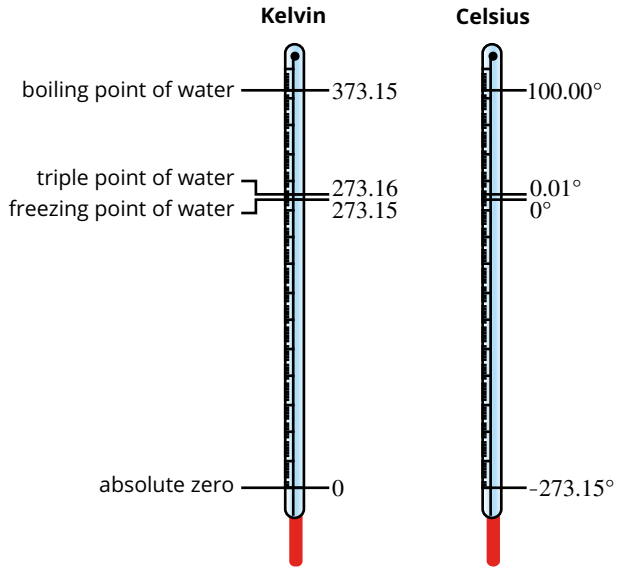

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FIGURE 2.2.2 Comparison of the Kelvin and Celsius scales. Note that there are no negative values on the Kelvin scale.

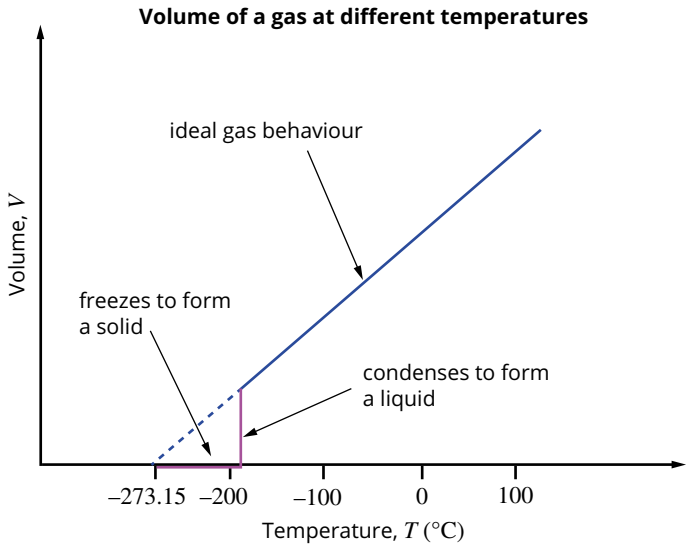

FIGURE 2.2.3 The volume of a gas decreases as the gas cools. This relationship is linear. Extrapolating (extending) the line for any substance to where the volume is zero gives a theoretical value of absolute zero.

Absolute zero

Experiments indicate that there is a limit to how cold things can get. The kinetic theory suggests that when a given quantity of gas is cooled, its volume decreases. The volume can be plotted against temperature and results in a straight-line graph, as shown in Figure 2.2.3. These experiments were conducted for many different gases and they all result in the same temperature when the graph is extrapolated to zero volume. For every ideal gas, zero volume is at –273.15°C.

Changing temperature

The temperature of a substance is a measure of the average kinetic energy of the molecules it contains. To increase the temperature of an object, you need to increase the average kinetic energy of its molecules. When an object is heated, extra energy is added to the molecules of the object, increasing their kinetic energy.

To cool an object, the average kinetic energy needs to decrease. One way to remove kinetic energy from an object is to put in contact with a colder object. The heat will flow from the hotter object to the colder object, cooling the hotter object as it shares its thermal energy. The flow of heat will be explored in Module 2.3.

2.2 Review

SUMMARY

- Temperatures can be measured in degrees Celsius (°C) or kelvin (K).
- Absolute zero is called simply 'zero kelvin' (0 K) and it is equal to –273.15°C.
- The size of each unit, 1°C or 1 K, is the same.
- To convert from degrees Celsius to kelvin: add 273; to convert from kelvin to degrees Celsius: subtract 273.
- To heat an object, add energy. To cool an object, remove energy.

KEY QUESTIONS

Retrieval

1 Describe how a mercury thermometer measures temperature.

2 Explain the concept of absolute zero temperature and the Kelvin scale.

Comprehension

3 Covert the following temperatures:

a 30.0°C into K

b 375 K into °C

4 A tank of pure helium is cooled to its freezing point of –272.2°C. Describe the energy of the helium particles at this temperature.

Analysis

5 Sort the following temperatures from coldest to hottest:

freezing point of water
100.0 K
absolute zero
–180°C
10.0 K

6 Tank A is filled with hydrogen gas at 0.0°C and another tank, B, is filled with hydrogen gas at 300.0 K. Contrast the average kinetic energy of the hydrogen particles in each tank.

7 Calculate the temperature of an object that has twice as much thermal energy as an object that is 15°C.

8 Explain how absolute zero temperature was determined. You may need some internet research to help with this.

2.3 Heat flow

BY THE END OF THIS MODULE, YOU SHOULD BE ABLE TO:

- understand conduction, convection and radiation
- explain heat transfers in terms of conduction, convection and radiation
- recognise that the properties of different materials will make good conductors or insulators.

If two objects at different temperatures are in thermal contact (that is, they can exchange energy via heat processes), then thermal energy will transfer from the hotter object to the cooler object. Figure 2.3.1 shows how, by preventing the chick's thermal contact with the cold ice, this adult is able to protect the vulnerable penguin offspring.

There are three possible means by which heat can be transferred:

- conduction
- convection
- radiation.

CONDUCTION

FIGURE 2.3.1 Emperor penguin chicks avoid heat loss through conduction by sitting on the adult's feet. In this way they avoid contact with the ice.

Conduction is the process by which heat is transferred without the net movement of particles (atoms or molecules) from one area to another. Particles in one object vibrate less, particles in the other object vibrate more, but no particles move from from one object to the other. Conduction can occur within a material or between materials that are in thermal contact. For example, if one end of a steel rod is placed in a fire, heat will travel along the rod so that the far end of the rod will also heat up. If a person holds an ice cube, then heat will travel from their hand to the ice.

All materials will conduct heat to some extent, but this process is most significant in solids. Conduction is important in liquids and plays a lesser role in the movement of energy in gases.

Conductors and insulators

Materials that conduct heat readily are referred to as good thermal **conductors**. Materials that are poor thermal conductors are referred to as **insulators**. An example of a good conductor and a good insulator can be seen in Figure 2.3.2.

In secondary physics, the terms 'conductor' and 'insulator' are used in the context of both electricity and heating processes. What makes a material a good conductor of heat doesn't necessarily make it a good conductor of electricity. The two types of conduction are related but it's important not to confuse the two processes. A material's ability to conduct heat depends on how conduction occurs within the material.

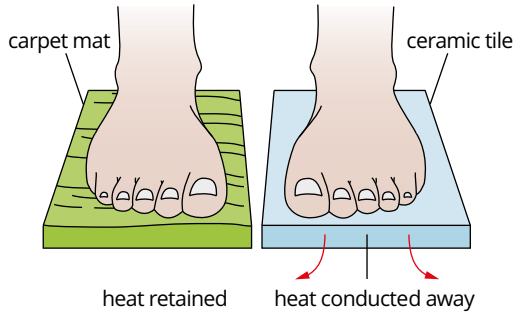

FIGURE 2.3.2 Ceramic floor tiles are good conductors of heat because they conduct heat away from the foot, so the tiles feel cold to your feet. The carpet mat is a thermal insulator because thermal energy from the foot is not transferred away as quickly, so the carpet doesn't feel as cold to your feet.

Conduction can happen in two ways:

- **by energy transfer through molecular or atomic collisions**
- **by energy transfer by free electrons.**

Thermal transfer by collision

The kinetic particle model explains that particles in a solid substance are constantly vibrating within the material structure and so interact with neighbouring particles. If one part of the material is heated, then the particles in that region will vibrate more rapidly. Interactions with neighbouring particles will pass on this kinetic energy throughout the system via the bonds between the particles (Figure 2.3.3).

Heat transfer by collision is a slow process because the mass of the particles is relatively large and the vibrational velocities are fairly low. This method of conduction is used for heat transfer in poor conductors of heat (thermal insulators) such as glass, wood and paper.

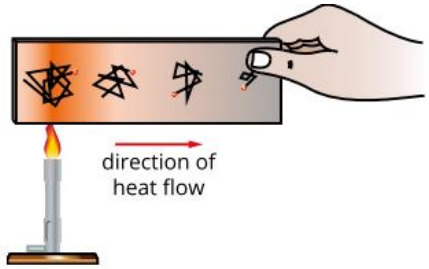

FIGURE 2.3.3 Thermal energy is passed on by collisions between adjacent particles.

Thermal transfer by free electrons

Some materials, particularly metals, have electrons that are not directly involved in any one particular chemical bond. Therefore, these electrons are free to move throughout the lattice of positive ions. These free electrons are able to carry heat through the material.

For example, if a metal is heated, then not only will the positive ions within the metal gain extra energy but so will these free electrons. As the electron's mass is considerably less than that of the positive ions, even a small energy gain will result in a very large gain in velocity. Consequently, these free electrons provide a means by which heat can be quickly transferred throughout the whole of the material. It is therefore no surprise that metals, which are good electrical conductors because of these free electrons, are also good thermal conductors.

Thermal conductivity

Thermal conductivity describes the ability of a material to conduct heat. It is temperature dependent and is measured in watts per metre kelvin ($W\,m^{-1}\,K^{-1}$). Table 2.3.1 highlights the difference in conductivity between metals and other substances.

TABLE 2.3.1 Thermal conductivities of some common materials

Material	Conductivity ($W\,m^{-1}\,K^{-1}$)
silver	420
copper	380
aluminium	240
steel	60
ice	2.2
brick, glass	≈ 1
concrete	≈ 1 (depending on composition)
water	0.6
human tissue	0.2
wood	0.15
polystyrene	0.08
paper	0.06
fibreglass	0.04
air	0.025

Factors that affect thermal conductivity

The rate at which heat is transferred is measured in joules per second ($J\,s^{-1}$), or watts (W). The rate at which heat will be transferred through a system is dependent on:

- the nature of the material. The larger a material's thermal conductivity, the more rapidly it will conduct heat energy.
- the temperature difference. A greater temperature difference between the two objects will result in a faster rate of energy transfer.

- the thickness of the material. Thicker materials require a greater number of collisions between particles or movement of electrons to transfer energy from one side to the other.
- the surface area. Increasing the surface area relative to the volume of a system increases the number of particles involved in the transfer process, increasing the rate of conduction.

CONVECTION

Convection is the transfer of thermal energy within a fluid (liquid or a gas) by the movement of hot areas from one place to another. Unlike other forms of heat transfer, such as conduction and radiation, convection involves the mass movement of particles within a system over a considerable distance.

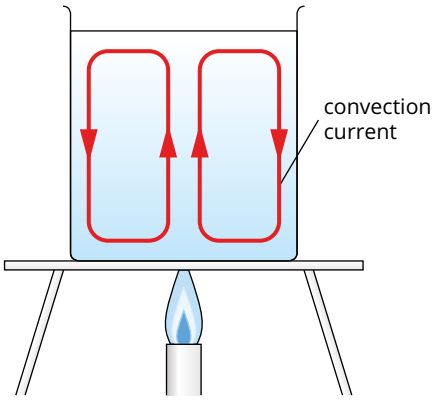

FIGURE 2.3.4 When a liquid or gas is heated, it becomes hotter and less dense so will rise. The colder, denser fluid will fall. As this fluid heats up, it in turn will rise, creating a convection current.

Heating by convection

Although liquids and gases are generally not good conductors of thermal energy, heat can be transferred quite quickly through liquids and gases by convection. Unlike other forms of thermal energy transfer, convection involves the mass movement of particles within a system over a distance.

As a fluid is heated, its particles gain kinetic energy and push apart due to the increased vibration of the particles. This causes the density of the heated fluid to decrease and the heated fluid rises. Colder fluid, with slower moving particles, is more dense and heavier and therefore falls, moving in to take the place of the warmer fluid. A convection current forms when there is warm fluid rising and cool fluid falling. This action can be seen in Figure 2.3.4. Upwellings in oceans, wind and weather patterns are at least partially due to convection on a very large scale.

Factors that affect thermal convection

It is difficult to quantify the thermal energy transferred via convection but some estimates can be made. The rate at which convection will occur is affected by:

- the temperature difference between the heat source and the convective fluid
- the surface area exposed to the convective fluid.

In a container, the effectiveness of convection to transfer heat depends on the placement of the source of heat. For example, the heating element in a kettle is always found near the bottom of the kettle. From this position, convection currents form throughout the water to heat it more effectively (Figure 2.3.5a). If the heating element is placed near the top of the kettle, convection currents form only near the top. This is because the hotter water is less dense than the cooler water below and will remain near the top. Convection currents will not form throughout the water (Figure 2.3.5b).

To visualise convection currents, set up a glass tank with one side under a hotplate and the other side under a bucket of ice. Fill the tank with water and add a couple of drops of food colouring. The convection patterns in the water will be highlighted and make a great photo.

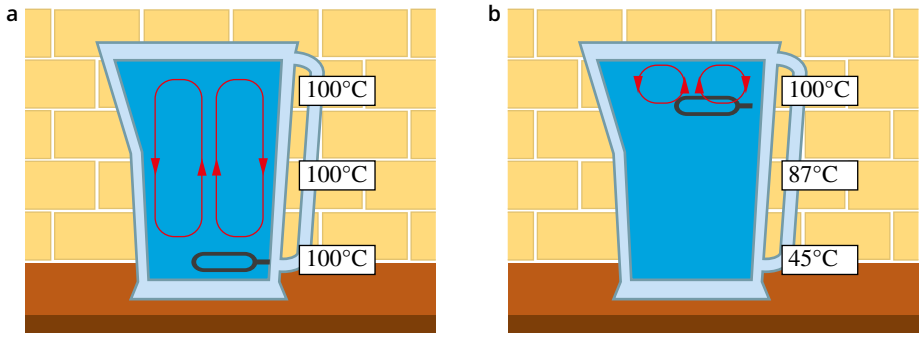

FIGURE 2.3.5 (a) By placing the heating element at the bottom of a kettle, the water near the bottom is heated and rises, forming convection currents throughout the entire depth of the water. (b) If the heating element is placed near the top of the kettle, the convection currents form near the top and heat transfer is slower.

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Applications of convection

There are two main causes of convection:

- forced convection, in which heat transfer is caused by an external source. An example is ducted heating in which air is heated and then blown into a room. Applications of forced convention are considered when designing heating and cooling systems.
- natural convection, in which heat transfer is induced by different temperature gradients of fluids in nature. Ocean currents are an example of natural convection.

A dramatic example of natural convection is the thunderhead clouds of summer storms (Figure 2.3.6), which form when hot, humid air from natural convection currents is carried rapidly upwards into the cooler upper atmosphere.

FIGURE 2.3.6 The thunderheads of summer storms are a very visible indication of natural convection in action.

Paragliders fly by sitting in a harness suspended beneath a fabric wing (Figure 2.3.7). They gain altitude by catching thermals. Thermals are columns of rising hot air created by dark regions on the ground that have been heated up by the Sun. Roads, rock faces and ploughed fields are good at creating thermals.

In 2007, Polish paraglider Ewa Wisnierska was practising in NSW for a competition when she was caught in an intense thermal updraught during a storm. She reached an altitude of almost 10 km. Fortunately, she lost altitude and landed about 60 km from where she started, where her crew found and rescued her. Ewa is now a paragliding instructor in Germany.

FIGURE 2.3.7 Paragliders can gain altitude by finding a thermal. Thermals are areas of rising hot air created by hot regions on the ground.

RADIATION

Both convection and conduction involve the transfer of heat through matter. Life on Earth depends upon the transfer of energy from the Sun through the near-vacuum of space. If heat could only be transferred by the action of particles, then the Sun's energy would never reach Earth. Radiation is a means of transfer of heat without the movement of matter.

Electromagnetic radiation

In this context, **radiation** is a shortened form of electromagnetic radiation, which includes visible, ultraviolet and infrared light. Together with other forms of light, these make up the **electromagnetic spectrum**.

Heat is transferred from one place to another without the movement of particles by electromagnetic radiation (light). Electromagnetic radiation travels at the speed of light. When electromagnetic radiation hits an object, it will be partially reflected, partially transmitted and partially absorbed. The absorbed radiation transfers thermal energy to the absorbing object and causes a rise in temperature. When you hold a marshmallow by an open fire, you are using a combination of radiation and convection to toast the marshmallow (Figure 2.3.8).

FIGURE 2.3.8 Heat transfer from the flame to the marshmallow is an example of radiation.

Electromagnetic radiation is emitted by all objects that are at a temperature above absolute zero (0 K or –273°C). The **wavelength** and **frequency** of the emitted radiation depend on the internal energy of the object. The higher the temperature of the object, the higher the frequency and the shorter the wavelength of the radiation emitted. The total radiant energy emitted increases as the temperature of the system increases. This can be seen in Figure 2.3.9.

A human body emits radiation in the infrared range of wavelengths, whereas hotter objects emit radiation of a higher frequency and shorter wavelength. Hotter objects can emit radiation in the range of visible, ultraviolet and shorter wavelengths of the electromagnetic spectrum. For example, as a red-hot fire poker heats up further, it becomes yellow-hot.

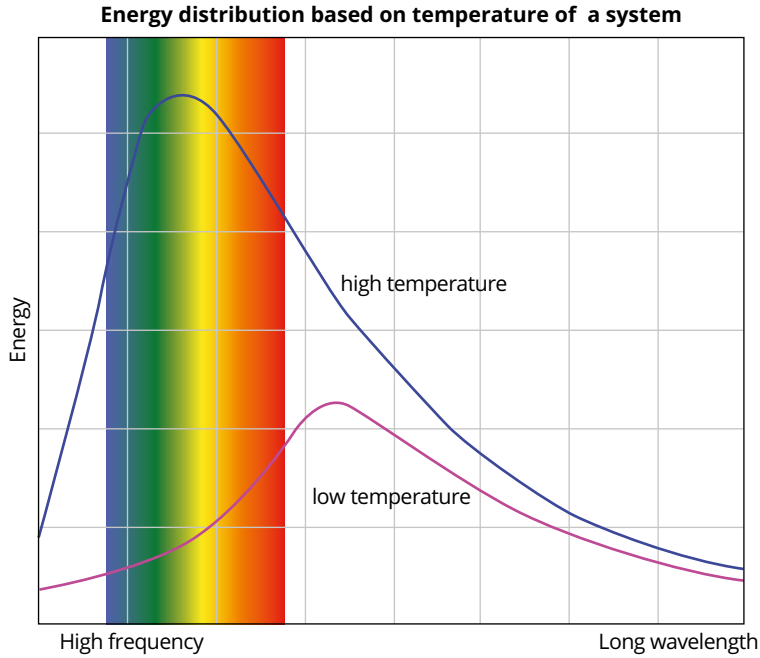


FIGURE 2.3.9 A system emits radiation over a range of frequencies. At a low temperature, it will emit small amounts of radiation of longer wavelengths. As the temperature of the system increases, more short-wavelength radiation is emitted and the total radiant energy emitted increases.

Absorption and emission of radiant energy

All objects both absorb and emit thermal energy by radiation. If an object absorbs more thermal energy than it emits, its temperature will increase. If an object emits more energy than it absorbs, its temperature will decrease. If no temperature change occurs, the object and its surroundings are in thermal equilibrium.

All objects emit some radiation, but they will not all emit or absorb at the same rate. A number of factors affect both the rate of **emission** and the rate of **absorption**.

- Surface area: The larger the exposed surface area, the higher the rate of radiant transfer.
- Temperature: The greater the difference between the temperature of the absorbing or emitting surface and the temperature of its surroundings, the greater the rate of energy transfer by radiation.
- Wavelength of the **incident** radiation: Matte black surfaces are almost perfect absorbers of radiant energy at all wavelengths. Highly reflective surfaces are good reflectors of all wavelengths. An example of how reflective surfaces can be exploited is shown in Figure 2.3.10. For all other surfaces, the absorption of particular wavelengths of radiant energy will be affected by the wavelength of that energy. For example, white surfaces absorb visible wavelengths of radiant energy poorly, but they will absorb infrared radiation just as well as black surfaces do.
- Surface colour and texture: The characteristics of the surface itself determine how readily that particular surface will emit or absorb radiant energy. Matte black surfaces will absorb and emit radiant energy faster than shiny, white surfaces. This means that a roughened, dark surface will heat up faster than a shiny, light surface. Matte black objects will also cool down faster because they will radiate energy just as efficiently as they absorb it. Car radiators are painted black to increase the emission by radiation of the thermal energy that is collected from the car engine.

FIGURE 2.3.10 The silvered surface of an emergency blanket reflects thermal energy back to the body, and retains the radiant energy, which would normally be lost. This simple method works as excellent thermal insulation.

Using thermal processes for heating and cooling homes

As the population grows and homes get bigger, more energy is consumed. A 2008 Australian government study estimated that the energy used in our homes would rise by 56% between 1990 and 2020. Around 40% of energy used in the home is for heating and cooling.

Rising energy costs, dwindling resources and environmental concerns have caused many countries to try to reduce the amount of fossil fuels used to provide energy for our homes, schools and industry. It's becoming more and more common to see solar panels on the roofs of homes. Australia is at the forefront of exciting research into solar cells, including new flexible-solar-cell technology, and is exploring the large-scale use of solar power with, for example, the 15 MW Sunshine Coast Solar Farm, to harness the Sun's energy to produce electricity. However, understanding the thermal processes described in this chapter has enabled architects to develop simple, efficient and cost-effective ways to heat and cool buildings without electricity.

Passive heating of a building through passive solar design is one way to reduce the overall energy being consumed within the building. Buildings that are designed with passive solar heating and cooling in mind take advantage of natural climate to maintain a comfortable temperature indoors. Figure 2.3.11 describes some of the principles of a passive solar house.

Insulation prevents heat loss by conduction in winter and gain of heat by conduction in summer. Solid brick walls and concrete slab floors provide large amounts of thermal mass, which take longer to heat up on hot days and to cool down on cold nights. Positioning large windows on the northern side of a house allows generous amounts of solar energy to warm the interior in winter. Overhanging eaves and deciduous trees provide shade in summer.

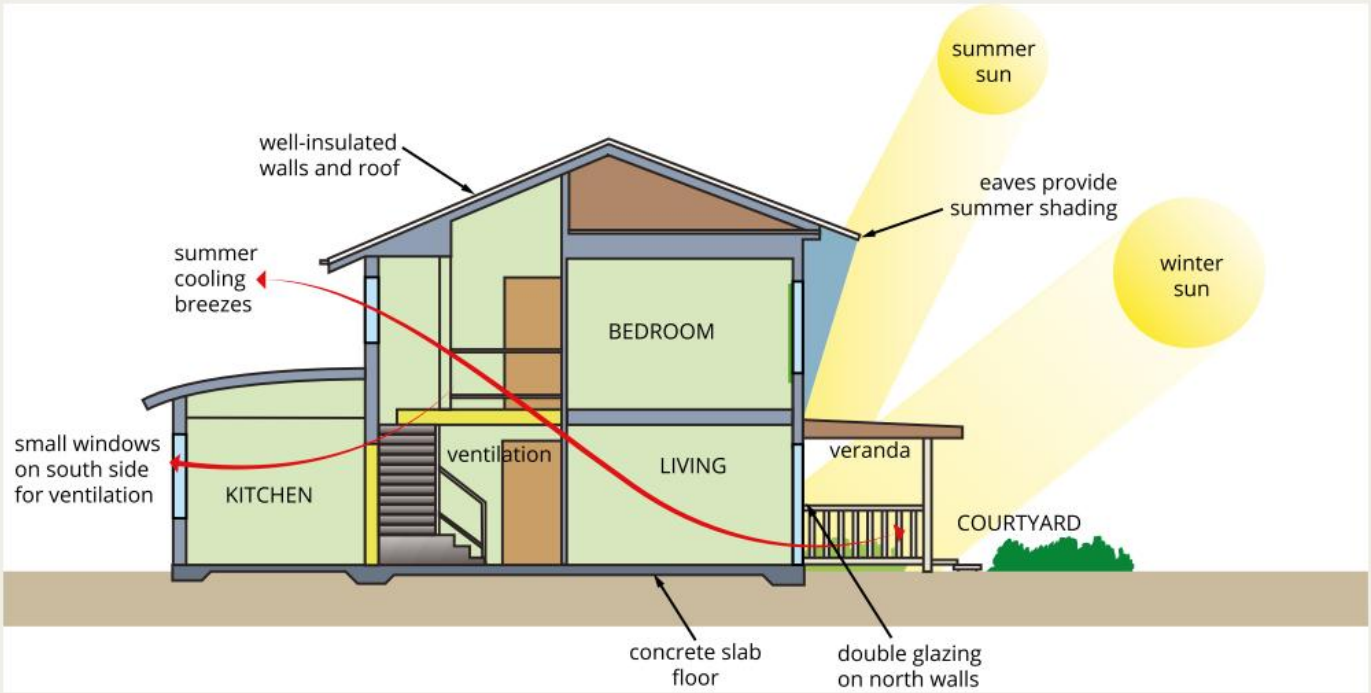


FIGURE 2.3.11 Aspects of good passive solar design applied to housing design can lead to significant energy savings.

Small windows to the south provide ventilation but reduce heat loss on the shady side of the house. Blank walls heavily shaded by trees or overhangs avoid the sun of hot summer afternoons and shield against the prevailing cold westerlies of winter.

Living areas positioned on the northern side allow the winter sun to warm high-use areas of the house. Rooms that are used not during the day, such as bedrooms, can be sited on the southern side of the house. Heavy curtains and double glazing (Figure 2.3.12) can reduce conductive heat loss at night and in winter, and reduce solar energy gains in summer. Conventional single glazing allows heat to be lost through conduction. Double glazing provides additional thermal resistance by adding a sealed space between two glass panes. The air gap conducts much less heat. Increasingly, argon gas is used to fill the space between the panes instead of air, because it has a lower conductivity than air. Good use of double glazing can reduce heat loss or gain by at least 50%.

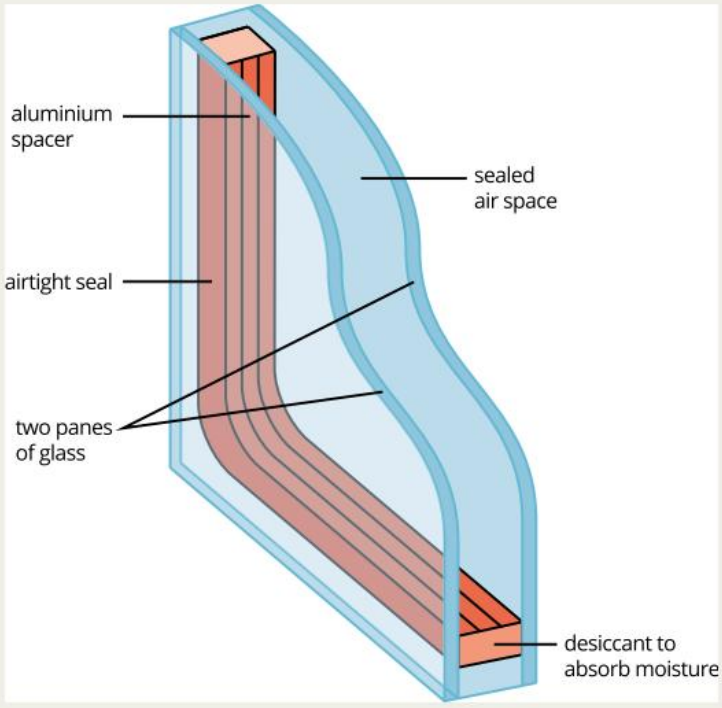


FIGURE 2.3.12 Double-glazed window construction reduces heat loss through windows that would otherwise transfer considerable energy through conduction.

The familiar Queenslander house uses thermal processes to allow as much passive cooling as possible, and is a specific design response to local conditions: hot and humid weather with high rainfall. High stumps allow cool air to flow underneath the house and large amounts of rain to flow past without flooding the house. A deep veranda shades the centre of the house from the hot sun and promotes a breeze to flow around the house. Large doors and windows are lined up to allow a breeze to flow through the house; and roof features allow hot air to escape through the roof cavity.

Review

1. State three ways of shading a house from the Sun's heat in summer.
2. Having windows double-glazed instead of single-glazed can reduce heat loss from homes.
   - **a** Explain whether this heat loss is due to radiation, convection or conduction.
   - **b** Explain why this reduces heat loss.

2.3 Review

SUMMARY

- Conduction is the process of heat transfer within a material or between materials without the overall transfer of the substance itself.
- All materials will conduct heat to a greater or lesser degree. Materials that readily conduct heat are called good thermal conductors. Materials that conduct heat poorly are called thermal insulators.
- Whether a material is a good conductor depends on the method of conduction.
  - Heat transfer by molecular collisions alone occurs in poor to very poor conductors.
  - Heat transfer by molecular collisions and free electrons occurs in good to very good conductors.
- The rate of conduction depends on the temperature difference between two materials, the thickness of the material, the surface area and the nature of the material.
- Convection is the transfer of heat within a fluid (liquid or gas).
- Convection involves the mass movement of particles within a system over a distance.
- A convection current forms when there is warm fluid rising and cool fluid falling.
- Any object whose temperature is greater than absolute zero emits thermal energy by radiation.
- Radiant transfer of thermal energy from one place to another occurs by means of electromagnetic waves.
- When electromagnetic radiation falls on an object, it will be partially reflected, partially transmitted and partially absorbed.
- The rate of emission or absorption of radiant heat will depend on the:
  - temperature difference between the object and the surrounding environment
  - surface area and surface characteristics of the object
  - wavelength of the radiation.

KEY QUESTIONS

Retrieval

1 List the properties of a material that affect its ability to conduct heat.

2 Fibreglass insulation batts are thick and lightweight, and they make a house more energy-efficient. On a cold July night, the external temperature in the roof of an insulated house is 6°C. The air temperature near the ceiling inside the house is 20°C.
Complete the paragraph below by choosing the correct response from the choices given in brackets to explain the effects of ceiling insulation in this situation.
The insulation batts stop the thermal energy from [**escaping**/**entering**] the house. The air in the batts has [**high**/**low**] conductivity and the thermal energy is [**able**/**not able**] to move easily through the batts.

3 List the states of matter in which convection can occur.

4 Identify the initial direction of the transfer of heat in a convection current.

Comprehension

5 Explain why the process of conduction by molecular collision is slow.

6 Pilots of glider aircraft or hang-gliders, some birds such as eagles and some insects rely on 'thermals' to give them extra lift. Explain how these rising columns of air are established.

7 The wavelength and frequency of emitted radiation depends on the internal energy of an object. Complete the sentences below by choosing the correct option from those provided in the brackets.
The higher the temperature of the object, the [**higher**/**lower**] the frequency and the [**longer**/**shorter**] the wavelength of the radiation emitted. For example, if a particular object emits radiation in the visible range, a cooler object could emit light in the [**infrared**/**ultraviolet**] range of the electromagnetic spectrum.

8 Explain why it is impossible for heat to travel from the Sun to Earth by conduction or convection.

9 Explain how a down-filled quilt keeps a person warm in winter.

2.3 Review *continued*

Analysis

10 Stainless steel saucepans are often manufactured with a copper base. Determine the most likely reason for this.

11 On a cold day, the plastic or rubber handles of a bicycle feel much warmer than the metal surfaces. Explain this in terms of the thermal conductivity of each material.

12 Convection is referred to as a method of heat transfer through fluids. Evaluate whether it is possible for solids to pass on their heat energy by convection.

13 On a hot day, the top layer of water in a swimming pool can heat up while the lower, deeper parts of the water can remain quite cold. Explain, using the concept of convection, why this happens.

14 Three identical, sealed beakers are filled with near-boiling water. One beaker is painted matte black, one is dull white and the third is gloss white.

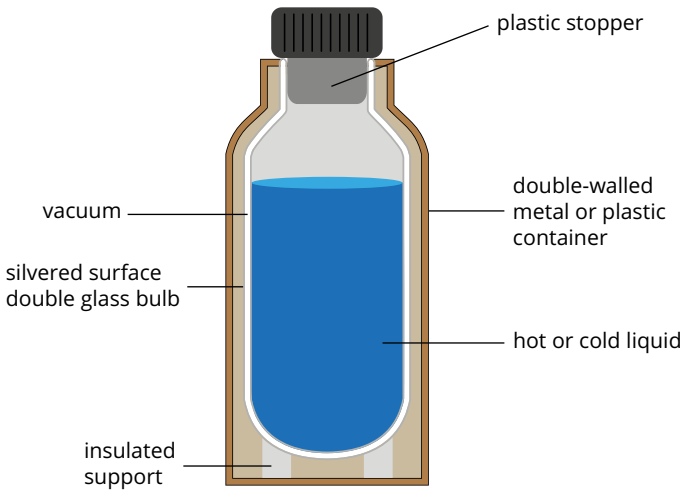
a Predict which beaker will cool fastest.

b Predict which beaker will cool slowest.

15 Computer chips generate a lot of thermal energy that must be dispersed for the computer to function efficiently. Devices called heat sinks are used to help this process. Predict what the heat sinks are made of.

16 A vacuum flask has a tight-fitting stopper at the top. The double glass bulb has silvered inner surfaces and has had most of the air evacuated from it. It is located inside a protective outer case with insulated supports. Assess how this design makes a vacuum flask good at keeping liquids hot inside.

Vacuum or Dewar flask



2.4 Specific heat capacity

BY THE END OF THIS MODULE, YOU SHOULD BE ABLE TO:

- understand that the amount of energy required to raise the temperature of a substance depends on the mass of the substance
- understand that the amount of energy required to raise the temperature of a substance depends on what substance it is
- understand that the amount of energy required to raise the temperature of a substance depends on the state of the substance
- analyse, compare and predict the amount of energy required to raise the temperature of a substance.

A small volume of water in a kettle will experience a greater change in temperature than a larger volume, if heated for the same time. A metal object left in the sunshine gets hotter faster than a wooden object. Large heaters warm rooms faster than small heaters.

These simple observations suggest that the mass, material and amount of energy transferred influence any change of temperature.

CHANGING TEMPERATURE OF A SUBSTANCE

The temperature of a substance is a measure of the average kinetic energy of the particles inside the substance. To increase the temperature of the substance, the kinetic energy of its particles must increase. This happens when heat is transferred to that substance. The amount the temperature increases depends on a number of factors.

The greater the mass of a substance, the greater the energy required to change the kinetic energy of all the particles. So, the heat required to raise the temperature by a given amount, ΔQ, is proportional to the mass, m, of the substance.

$$\Delta Q \propto m$$

The more heat that is transferred to a substance, the more the temperature of that substance increases. The amount of energy transferred, ΔQ, is therefore proportional to the change in temperature, ΔT.

$$\Delta Q \propto \Delta T$$

Heating experiments using different materials will confirm that these relationships hold true regardless of the material being heated. However, heating the same masses of different materials will show that the amount of energy required to heat a given mass of a material through a particular temperature change also depends on the nature of the material being heated. For example, a volume of water requires more energy to change its temperature by a given amount than the same volume of methylated spirits. For some materials, temperature change occurs more easily than for others.

Combining these observations, the amount of energy added to or removed from the substance is proportional to the change in its temperature, its mass and its specific heat capacity (provided a material does not change state). The **specific heat capacity** of a material changes when the material changes state.

Table 2.4.1 lists the specific heat capacities for some common materials. You can see that it also lists the average value for the human body, which takes into account the various materials within the body and the proportion that each material contributes to the body's total mass.

TABLE 2.4.1 Approximate specific heat capacities of common substances

Material	c (J kg^{-1} K^{-1})
lead	130
mercury	140
brass	370
copper	390
iron	440
glass	840
aluminium	900
air	1000
steam (water)	2000
ice (water)	2100
ethanol	2460
methylated spirits	2500
human body	3500
liquid water	4200

The specific heat capacity of a material, c, is the amount of energy that must be transferred to change the temperature of 1 kg of the material by 1°C or 1 K.

The specific heat capacity is calculated using the equation:

$Q = mc\Delta T$

where

Q is the heat energy transferred in joules (J)

m is the mass in kilograms (kg)

c is the specific heat capacity of the material ($J\,kg^{-1}\,K^{-1}$)

ΔT is the change in temperature (°C or K).

Worked example 2.4.1

CALCULATIONS USING SPECIFIC HEAT CAPACITY

A hot water tank contains 135 L of water. Initially the water is at 20.0°C. Calculate the amount of energy that must be transferred to the water to raise the temperature to 70.0°C.

Thinking	Working
Calculate the mass of water. 1 L of water = 1 kg	Volume = 135 L Mass = 135 kg
ΔT = final temperature – initial temperature	$\Delta T = 70.0 - 20.0 = 50.0$°C
From Table 2.4.1: $c_{water} = 4200\,J\,kg^{-1}\,K^{-1}$. Use the equation $Q = mc\Delta T$.	$Q = mc\Delta T$ $= 135 \times 4200 \times 50.0$ $= 28\,350\,000$ J $= 28.4$ MJ

➤ Try yourself 2.4.1

CALCULATIONS USING SPECIFIC HEAT CAPACITY

A bath contains 75 L of water. Initially the water is at 50.0°C. Calculate the amount of energy that must be transferred from the water to cool the bath to 30.0°C.

Worked example 2.4.2

COMPARING SPECIFIC HEAT CAPACITIES

Different states of matter of the same substance have different specific heat capacities. Calculate the ratio of the specific heat capacity of liquid water to that of ice.

Thinking	Working
See Table 2.4.1 for the specific heat capacities of water in different states.	$c_{water} = 4200\,J\,kg^{-1}\,K^{-1}$ $c_{ice} = 2100\,J\,kg^{-1}\,K^{-1}$
Divide the specific heat of water by the specific heat of ice. Note that ratios have no units because the units of the two quantities are the same and cancel out.	$\text{Ratio} = \frac{c_{water}}{c_{ice}}$ $= \frac{4200}{2100}$ $= 2$

➤ Try yourself 2.4.2

COMPARING SPECIFIC HEAT CAPACITIES

Calculate the ratio of the specific heat capacity of liquid water to that of steam.

SPECIFIC HEAT CAPACITY OF WATER

Note the high specific heat capacity of water in Table 2.4.1. It is about 10 times higher than that of most metals listed. The specific heat capacity of water is higher than those of most common materials. As a result, water makes a very useful cooling and heat storage agent, and is used in areas such as generator cooling towers and car-engine radiators.

Life on Earth also depends on the specific heat capacity of water. About 70% of the Earth's surface is covered by water, and these water bodies can absorb large quantities of thermal energy without great changes in temperature. Oceans both heat up and cool down more slowly than the land areas next to them. This helps to maintain a relatively stable range of temperatures for life on Earth.

Scientists are now monitoring the temperatures of the deep oceans in order to determine how the ability of oceans to store large amounts of energy might affect climate change.

2.4 Review

SUMMARY

- The specific heat capacity, c, of a substance is a measure of the amount of energy that must be transferred to change the temperature of 1 kg of material by 1°C or 1 K. Its units are $J\,kg^{-1}\,K^{-1}$.
- When heat is transferred to or from a system or object, the temperature change depends upon the amount of energy transferred, the mass of the material(s) and the specific heat capacity of the material(s): $Q = mc\Delta T$.
- A substance will have different specific heat capacities in different states (solid, liquid, gas).

KEY QUESTIONS

Retrieval

1 Equal masses of water and aluminium are heated through the same temperature range. Using the values of c from Table 2.4.1, identify the material that requires the most energy to achieve this result.

2 Determine which has more thermal energy: 10.0 kg of iron at 20.0°C or 10.0 kg of aluminium at 20.0°C.

Comprehension

3 100.0 mL of water is heated to change its temperature from 15.0°C to 20.0°C. Calculate how much energy is transferred to the water to achieve this temperature change.

4 150 mL of water is heated from 10.0°C to 50.0°C. Calculate the amount of energy required for this temperature change to occur.

Analysis

5 Equal amounts of energy are absorbed by equal masses of aluminium and water. Deduce the ratio of the temperature rise of the aluminium to that of water.

6 If 4.0 kJ of energy is required to raise the temperature of 1.0 kg of paraffin by 2.0°C, calculate how much energy (in kJ) is required to raise the temperature of 5.0 kg of paraffin by 1.0°C.

7 A cup holds 250 mL of water at 20.0°C. If 10.5 kJ of heat energy is transferred to the water, determine the temperature the water will reach.

8 A block of iron is left to cool. After cooling for a short time, 13.2 kJ of energy has been transferred away from the block of iron and its temperature has decreased by 30.0°C. Determine the mass of the block of iron.

2.5 Phase changes and latent heat

BY THE END OF THIS MODULE, YOU SHOULD BE ABLE TO:

- understand changes of state
- understand latent heat
- calculate the energy required to change a substance's state
- interpret a phase change diagram.

If water is heated, its temperature will rise. If enough energy is transferred to the water, eventually the water will boil. The water changes state (from liquid to gas). The **latent heat** is the energy released or absorbed during a change of state. Latent means hidden or unseen. While a substance is in the process of changing state, its temperature remains constant. For example, the energy used when ice melts into water is 'hidden' in the sense that the temperature doesn't rise while the change of state is occurring.

ENERGY AND CHANGE OF STATE

Look at the example of a heating graph for water shown in Figure 2.5.1. In this experiment, heat energy is added at a constant rate, but the increase in the temperature of the water is not always constant. In some sections the temperature increases at a constant rate, but in other sections the temperature remains unchanged (the horizontal sections). In the sections of constant temperature, the material is changing state. The temperature remains constant during the change in state from ice to liquid water and again from liquid water to steam.

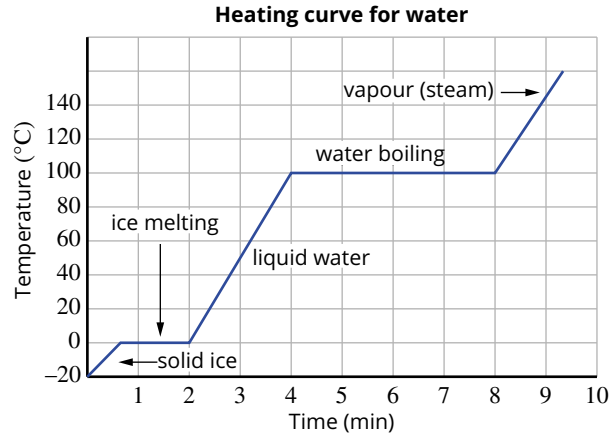


FIGURE 2.5.1 A heating curve for water

LATENT HEAT

The energy needed to change the state of a substance (e.g. solid to liquid, liquid to gas) is called latent heat. Latent heat is the 'hidden' energy that has to be added or removed from a material in order for the material to change state. The energy required, Q, to change the state of a substance of mass m, can be calculated using the latent heat of the substance, L.

$$Q = mL$$

where

Q is the heat energy transferred in joules (J)
m is the mass in kilograms (kg)
L is the latent heat ($J\,kg^{-1}$).

The latent heat is calculated using the equation:

$Q = mL$

where

Q is the heat energy transferred in joules (J)

m is the mass in kilograms (kg)

L is the latent heat ($J\,kg^{-1}$).

Latent heat of fusion (melting)

The temperature of a solid increases as thermal energy is transferred to the solid. The particles within the solid gain internal energy (as kinetic energy and some potential energy) and their speed of vibration increases. At the point where the solid begins to melt, the particles move further apart, reducing the strength of the bonds holding them in place. At this point, instead of increasing the temperature, the extra energy increases the potential energy of the particles, reducing the interparticle or intermolecular forces. No change in temperature occurs because all the extra energy supplied is used in reducing these forces between particles.

The amount of energy required to melt a solid is exactly the same as the amount of potential energy released when the liquid re-forms into a solid. It is termed the **latent heat of fusion**.

The amount of energy required will depend on the particular solid. The energy required, Q, to change a solid of mass m to a liquid can be calculated using the latent heat of fusion, L_{fusion}.

$$Q = mL_{fusion}$$

It takes almost 80 times as much energy to turn 1 kg of ice into water (with no temperature change) as it does to raise the temperature of 1 kg of water by 1°C. It takes a lot more energy to overcome the large intermolecular forces within the ice than it does to simply add kinetic energy in raising the temperature. The latent heats of fusion for some common materials are listed in Table 2.5.1.

For a given mass of a substance:
Heat energy transferred = mass of substance × specific latent heat of fusion

$$Q = mL_{fusion}$$

TABLE 2.5.1 The latent heats of fusion for some common materials

Substance	Melting point (°C)	L_{fusion} (J kg^{-1})
silver	961	0.88×10^5
oxygen	–219	0.14×10^5
lead	327	0.25×10^5
ethanol	–114	1.05×10^5
water	0	3.34×10^5

Worked example 2.5.1

LATENT HEAT OF FUSION

Calculate how much energy must be removed from 2.5 L of water at 0.0°C to produce a block of ice at 0.0°C. Express your answer in kJ.

Thinking	Working
Cooling from liquid to solid involves the latent heat of fusion, as the energy is removed from the water. Calculate the mass of water involved. 1 L of water = 1 kg	2.5 L = 2.5 kg
Use Table 2.5.1 to find the latent heat of fusion for water.	$L_{fusion} = 3.34 \times 10^5$ J kg^{-1}
Use the equation: $Q = mL_{fusion}$	$Q = mL_{fusion}$ $= 2.5 \times 3.34 \times 10^5$ $= 8.35 \times 10^5$ J
Convert to kJ.	840 kJ of energy is removed.

➤ Try yourself 2.5.1

LATENT HEAT OF FUSION

Calculate how much energy must be removed from 5.5 kg of liquid lead at 327°C to produce a block of solid lead at 327°C. Express your answer in kJ.

Latent heat of vaporisation (boiling)

It takes much more energy to convert a liquid to a gas than it does to convert a solid to a liquid. This is because, to convert to a gas, the intermolecular bonds must be broken. During the change of state, the energy supplied is used solely in overcoming the intermolecular bonds. The temperature will not rise until all of the material in the liquid state is converted to a gas, assuming that the liquid is evenly heated. For example, when liquid water is heated to boiling point, a large amount of energy is required to change its state from liquid to steam (gas). The temperature will remain at 100°C until all of the water has turned into steam. Once the water is completely converted to steam, then the temperature can start to rise again.

The amount of energy required to change a liquid to a gas is exactly the same as the potential energy released when the gas returns to a liquid. It is called the **latent heat of vaporisation**.

The amount of energy required will depend on the particular substance. The energy required, Q, to change a liquid of mass m to a gas can be calculated using the latent heat of vapourisation, L_{vapour}.

$$Q = mL_{vapour}$$

Note that, in just about every case, the latent heat of vaporisation of a substance will be different from the latent heat of fusion for that substance. The latent heats of vaporisation for some common materials are listed in Table 2.5.2.

In many instances, it is necessary to consider the energy required to heat a substance as well as change its state. Problems like this are solved by considering the rise in temperature separately from the change of state.

For a given mass of a substance:
Heat energy transferred = mass of substance × specific latent heat of vaporisation

$$Q = mL_{vapour}$$

TABLE 2.5.2 The latent heat of vaporisation of some common materials

Substance	Boiling point (°C)	L_{vapour} (J kg^{-1})
oxygen	−183	2.2×10^5
ethanol	78	8.7×10^5
lead	1750	9.0×10^5
water	100	22.6×10^5
silver	2193	23.0×10^5

Worked example 2.5.2

CHANGE IN TEMPERATURE AND STATE

50.0 mL of water is heated from a room temperature of 20.0°C to its boiling point at 100.0°C. The water is boiled at this temperature until it has completely evaporated. Calculate how much energy in total was required to raise the temperature and boil the water.

Thinking	Working
Calculate the mass of water involved. 1 L of water = 1 kg	50.0 mL of water = 0.050 kg
Find the specific heat capacity of water from Table 2.4.1.	$c = 4200\,\text{J kg}^{-1}\,\text{K}^{-1}$
Use the equation $Q = mc\Delta T$ to calculate the heat energy required to change the temperature of water from 20°C to 100°C.	$Q = mc\Delta T$ $= 0.050 \times 4200 \times (100.0 - 20.0)$ $= 16\,800\,\text{J}$
Find the specific latent heat of vaporisation of water from Table 2.5.1.	$L_{vapour} = 22.6 \times 10^5\,\text{J kg}^{-1}$
Use the equation $Q = mL_{vapour}$ to calculate the latent heat required to boil water.	$Q = mL_{vapour}$ $= 0.05 \times 22.6 \times 10^5$ $= 113\,000\,\text{J}$
Find the total energy required to raise the temperature and change the state of the water.	Total $Q = 16\,800 + 113\,000$ $= 1.30 \times 10^5\,\text{J}$ $= 130\,\text{kJ}$

➤ Try yourself 2.5.2

CHANGE IN TEMPERATURE AND STATE

3.0 L of water is heated from a fridge temperature of 4.0°C to its boiling point at 100.0°C. The water is boiled at this temperature until it has completely evaporated. Calculate how much energy in total was required to raise the temperature and boil the water.

EVAPORATION AND COOLING

If you spill some water on the floor then come back in a couple of hours, the water will probably be gone. It will have evaporated. It has changed from a liquid into a vapour at room temperature in a process called **evaporation**. The reason for this is that the water particles, if they have sufficient energy, are able to escape through the surface of the liquid into the air. Over time, no liquid remains.

Evaporation is more noticeable in **volatile** liquids such as methylated spirits, mineral turpentine, perfume and liquid paper. The surface bonds are weaker in these liquids and they evaporate rapidly. This is why you should never leave the lids off bottles of these liquids. Volatile liquids are often stored in narrow-necked bottles for this reason.

The rate of evaporation of a liquid can depend on:

- the volatility of the liquid—more-volatile liquids evaporate faster
- the surface area—greater evaporation occurs when greater surface areas are exposed to the air
- the temperature—hotter liquids evaporate faster
- the humidity—less evaporation occurs in more humid conditions
- air movement—if a breeze is blowing over the surface of the liquid, evaporation is more rapid.

Whenever evaporation occurs, higher-energy particles escape the surface of the liquid, leaving the lower-energy particles behind (Figure 2.5.2). As a result, the average kinetic energy of the particles remaining in the liquid decreases and the temperature drops. Humans use this cooling principle when sweating to stay cool. When rubbing alcohol is dabbed on your arm before an injection, the cooling of the volatile liquid numbs your skin.

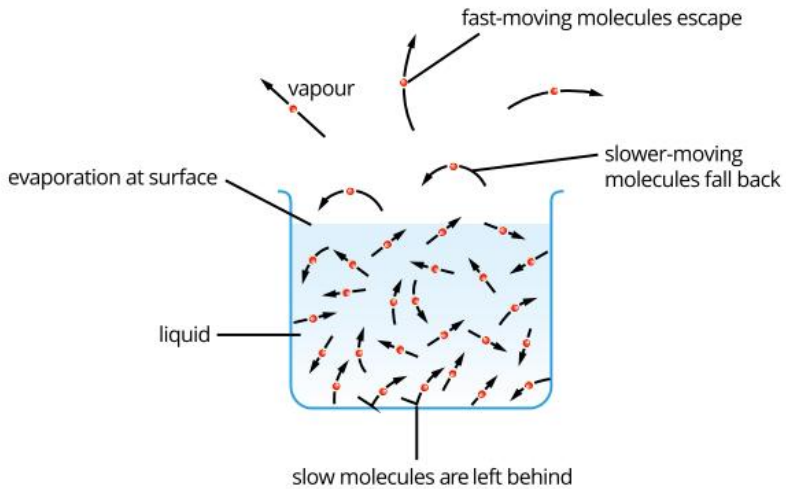


FIGURE 2.5.2 Fast-moving molecules with high kinetic energy can escape the liquid, leaving molecules with lower kinetic energy behind.

HEATING CURVES

Figure 2.5.3 is a heating graph for water. It is also called a phase change diagram. The graph shows the temperature change when a substance is heated at a constant rate and it changes state from a solid to a liquid to a gas. These graphs can provide information on the specific heat capacity of each phase and latent heats of fusion and vaporisation of a substance.

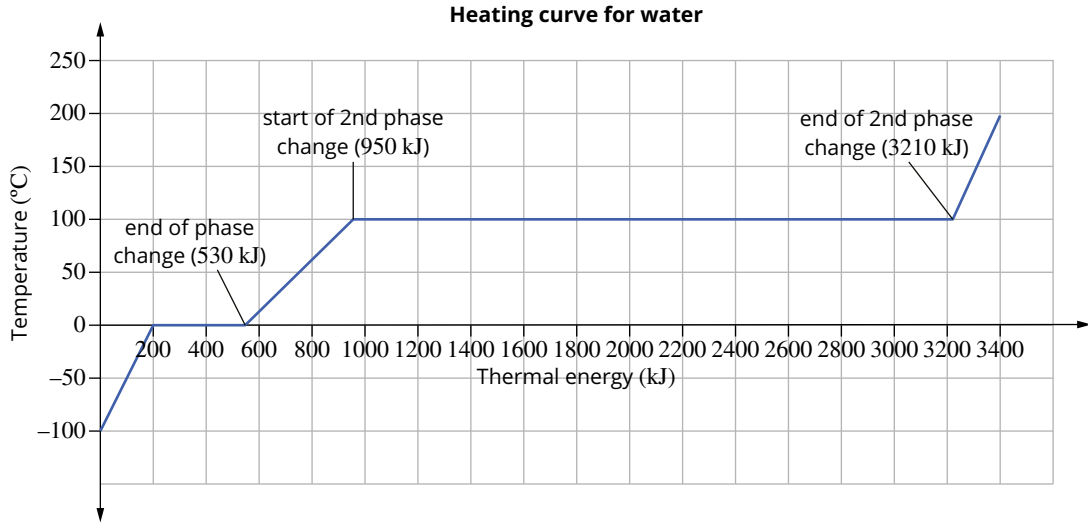


FIGURE 2.5.3 A heating graph for water

Determining latent heats from a heating curve

The horizontal sections of the graph represent the phase changes in the substance. The heat energy going into the substance is being used to increase the potential energy and change phase. By determining how much heat energy (Q) is going into a substance for a phase change to occur, the latent heat for that phase change can be calculated.

Worked example 2.5.3

DETERMINING LATENT HEAT OF FUSION USING A HEATING CURVE

1.0 kg of water has been heated from ice through to steam. Use the appropriate section of Figure 2.5.3 to determine the latent heat of fusion of water.

Thinking	Working
Find the heat required to change the ice to water. On the graph, the first phase change is from 200 KJ to 530 kJ.	Q = 530 kJ – 200 KJ = 330 kJ
Rearrange the equation $Q = mL_F$ to make L_F the subject. Q = 330 000 J m = 1.0 kg	$Q = mL_F$ $L_F = \frac{Q}{m}$ $= \frac{330000}{1}$ = 330 000 J kg^{-1}

➤ Try it yourself 2.5.3

DETERMINING LATENT HEAT OF FUSION USING A HEATING CURVE

1.0 kg of water has been heated from ice through to steam at a temperature of 190°C. Use the appropriate section of Figure 2.5.3 to determine the latent heat of vaporisation of water.

Determining specific heat capacities from a heating curve

The sloped sections of the heating graph indicate when a phase (solid, liquid or gas) is undergoing a temperature change. These are the sections where the specific heat capacity applies. From the gradient of the graph (in these sections), the specific heat capacity can be calculated for each phase.

Worked example 2.5.4

DETERMINING SPECIFIC HEAT CAPACITY USING A HEATING CURVE

1.0 kg of water has been heated from ice through to steam. Use the slope of the appropriate section of Figure 2.5.3 to determine the specific heat capacity of water.

Thinking	Working
Find the gradient of the line for the liquid phase.	Gradient $= \frac{\text{rise}}{\text{run}}$ $= \frac{100}{420\,000}$ $= 2.38 \times 10^{-4}$
For a heating curve, the rise is the change in temperature, T, and the run is the change in energy transferred, ΔQ.	Gradient $= \frac{\text{rise}}{\text{run}} = \frac{\Delta T}{\Delta Q}$
Rearrange the equation $Q = mc\Delta T$.	$Q = mc\Delta T$ $\frac{\Delta T}{\Delta Q} = \frac{1}{mc}$
The mass is 1.0 kg, so $m = 1$.	The gradient is $\frac{1}{c}$.
Use the gradient and the result that the gradient is $\frac{1}{c}$ to find c.	$\frac{1}{c} = 2.38 \times 10^{-4}$ $c = \frac{1}{2.38 \times 10^{-4}}$ $= 4200\ \text{J kg}^{-1}\text{K}^{-1}$

➤ Try yourself 2.5.4

DETERMINING SPECIFIC HEAT CAPACITY USING A HEATING CURVE

1.0 kg of water has been heated from ice through to steam. Use the slope of the appropriate section of Figure 2.5.3 to determine the specific heat capacity of steam.

2.5 Review

SUMMARY

- When a solid material changes state, energy is needed to separate the particles by overcoming the attractive forces between the particles.
- Latent heat is the energy required to change the state of 1 kg of material at a constant temperature.
- In general, for any mass of material the energy required (or released) is $Q = mL$.
- The latent heat of fusion, L_{fusion}, is the energy required to change 1 kg of a material between the solid and liquid states.
- The latent heat of vaporisation, L_{vapour}, is the energy required to change 1 kg of a material between the liquid and gaseous states.
- The latent heat of fusion of a material will be different from (and usually less than) the latent heat of vaporisation for that material.
- Evaporation is when a liquid turns into gas at room temperature. The temperature of the liquid falls as this occurs.
- The rate of evaporation depends on the volatility, temperature and surface area of the liquid and the presence of air movement.
- A heating curve or phase change diagram shows the change in temperature when a substance is heated at a constant rate and changes from a solid to a liquid to a gas. It can be used to find the latent heat and specific heat capacity of a substance.

KEY QUESTIONS

Refer to the values in Table 2.5.1 and Table 2.5.2. You may also need to refer to Table 2.4.1.

Retrieval

1 State and explain two factors that affect the rate of evaporation of sweat.

2 Define 'latent heat'.

Comprehension

3 Explain why the temperature does not change during the boiling phase on a heating curve.

4 Determine the amount of heat energy that must be transferred away from 100.0 g of steam at 100.0°C to change it completely to a liquid.

5 Explain in terms of the molecules behaviour, why cooling takes places as a result of evaporation.

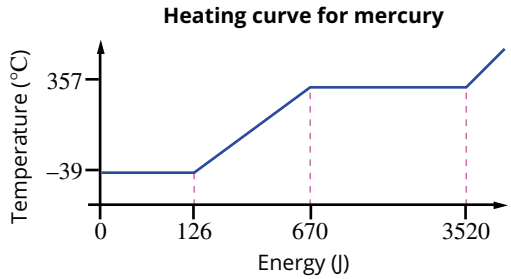
Analysis

6 Explore why being burnt with steam (at 100°C) is far worse than being burnt by boiling water (don't try this).

7 Consider why coffee stays hot longer if the mug has a lid.

8 Determine how many kJ of energy are required to melt exactly 100.0 g of ice initially at –4.00°C. Assume no loss of energy to surroundings.

9 The graph below represents the heating curve for mercury, a metal that is a liquid at normal room temperature. Thermal energy is added to 10.0 g of solid mercury, initially at a temperature of –39°C, until all of the mercury has evaporated.



a Explain why the temperature remains constant during the first part of the graph.

b Identify the melting point of mercury, in degrees Celsius.

c Identify the boiling point of mercury, in degrees Celsius.

d From the graph, determine the latent heat of fusion of mercury.

e From the graph, determine the latent heat of vaporisation of mercury.

10 When running, some (heat) energy is lost by the evaporation of sweat. If a runner loses 1.0 MJ of energy via sweating, calculate an approximate mass of sweat evaporated from the runner.

11 In some heating curves, the portion of the graph related to heating the gas is not a straight line but rather it is curved. Explain the physical significance of this curved graph.

2.6 Calorimetry

BY THE END OF THIS MODULE, YOU SHOULD BE ABLE TO:

- understand how heat flows from a hot object to a cold object
- understand thermal equilibrium
- understand the conservation of energy with regard to thermal processes.

THERMAL EQUILIBRIUM

If you leave a hot cup of coffee on a table, it will cool down until it is at room temperature. If you put ice into a warm drink, it will quickly melt leaving the entire drink a little cooler than before the ice was added. If two objects are in **thermal contact**, energy can flow between them. For example, if an ice cube is placed in a copper pan, the ice molecules are in thermal contact with the copper atoms. Assuming that the copper is warmer than the ice, thermal energy will flow from the copper to the ice. When two objects in thermal contact stop having a flow of energy between them , they are in **thermal equilibrium**. If a frozen piece of steak is placed in a container of warm water, energy is transferred from the water to the steak. The steak gains energy and warms up. The water loses energy and cools down. Eventually the transfer of energy between the steak and water will stop. This point is called thermal equilibrium, and the steak and water will be at the same temperature.

At the point of thermal equilibrium, the temperature of the two objects will be the same. The average kinetic energy of the two objects will also be the same because average kinetic energy is a measure of temperature, as shown in Module 2.2. The flow of thermal energy when two objects are in thermal contact is due to a transfer of kinetic energy as molecules collide.

ZEROTH LAW OF THERMODYNAMICS

The topic of thermal physics involves phenomena associated with energy transfer between objects at different temperatures. Since the 19th century, scientists have developed four laws for this subject. The first two will be studied in this chapter.

The first, second and third laws had been known and understood for some time. Then another law was also determined. This final law was considered to be so important that it was decided to place it first, and so it is called the zeroth law of **thermodynamics**.

The zeroth law of thermodynamics relates to thermal equilibrium and thermal contact and allows temperature to be defined. Objects in thermal contact with each other will tend towards thermal equilibrium. So if a thermometer is placed in a glass of water, the thermometer and the water will tend towards thermal equilibrium with each other, allowing the thermometer to measure the temperature of the water. If cordial is added to the glass of water, the water and cordial will come to a thermal equilibrium. The thermometer will also be in thermal equilibrium with the water and so the thermometer and the cordial will also be the same temperature.

> **The zeroth law of thermodynamics:**
> If objects A and B are each in thermal equilibrium with object C, then objects A and B are in thermal equilibrium with each other.

Conservation of energy

In physics, quantities that are conserved are very important. Energy is one of these conserved quantities. Energy cannot be created or destroyed; it simply changes form. In a closed system, a system from which no thermal energy can escape, if two objects are in thermal contact, the thermal energy lost by one object is the thermal energy gained by the other object; i.e. $Q_{lost} = Q_{gained}$.

> **Heat lost by one substance = heat gained by the other substance**
> $Q_{lost} = Q_{gained}$

FIGURE 2.6.1 A scientist uses a bomb calorimeter to measure a temperature change to determine the thermal energy transfer.

FIGURE 2.6.2 The Styrofoam cup is a makeshift calorimeter that insulates the process and the thermometer measures the temperature change. The beaker provides stability.

Calorimetry is the activity of measuring an amount of thermal energy. Calorimetry determines the specific heat capacities and latent heats of different substances because of the conservation of energy. To provide a closed system, scientists use insulated instruments called calorimeters to measure amounts of heat (Figure 2.6.1). Calorimeters can be used to measure the energy produced in a chemical reaction or temperature change when two different objects (at different temperatures) are combined. In a high school laboratory, a foam cup can be used to simulate the insulating environment of a calorimeter (Figure 2.6.2). This set-up could be used to determine the specific heat capacity of an unknown metal. The metal can be heated to a known temperature, and then added to some water. The metal and water are allowed to come to equilibrium and the temperature increase of the water will allow the calculation of the specific heat capacity of the metal, as shown in Worked example 2.6.1.

Worked example 2.6.1

DETERMINING SPECIFIC HEAT CAPACITY USING CALORIMETRY

A 20.0 g piece of metal is heated to 100.0°C and then placed in a foam cup containing 50.0 mL of water at 24.0°C. The final temperature of the water and metal cube is 27.0°C. Calculate the specific heat capacity of the metal.

Thinking	Working
Calculate the mass of water involved. 1 L of water = 1 kg	50.0 mL of water = 0.050 kg
Find the specific heat capacity of water from Table 2.4.1 on page 23.	$c = 4200\,\text{J kg}^{-1}\,\text{K}^{-1}$
Use the equation $Q = mc\Delta T$ to calculate the heat energy required to change the temperature of water from 24°C to 27°C.	$Q_{water} = mc\Delta T$ $= 0.05 \times 4200 \times (27 - 24)$ $= 630\,\text{J}$
Recall that, due to conservation of energy, the heat gain by the water will be the heat lost by the metal.	$Q_{metal} = 630\,\text{J}$
Convert the mass of the metal to kilograms.	20.0 g of metal = 0.020 kg
Rearrange $Q_{metal} = mc\Delta T$ to make c the subject.	$Q_{metal} = mc\Delta T$ $c = \frac{Q_{metal}}{m\Delta T}$
Substitute in the values and find the specific heat capacity for a temperature change from 100.0°C to 27.0°C.	$c = \frac{Q_{metal}}{m\Delta T}$ $= \frac{630}{0.02 \times (100 - 27)}$ $= 430\,\text{J kg}^{-1}\,\text{K}^{-1}$

➤ Try yourself 2.6.1

DETERMINING SPECIFIC HEAT CAPACITY USING CALORIMETRY

WS 1.1.6

A 34.6 g piece of metal has been heated to 97.0°C. This is then placed in a Styrofoam cup containing 71 mL of water at 20.0°C. The final temperature of the water and metal cube is 29.5°C. Calculate the specific heat capacity of the metal.

2.6 Review

SUMMARY

- If two objects are in thermal contact, thermal energy will flow from the hot object to the cold object until the two objects are at the same temperature. This is known as thermal equilibrium.
- The zeroth law of thermodynamics states that if objects A and B are each in thermal equilibrium with object C, then objects A and B are in thermal equilibrium with each other. A, B and C must be at the same temperature.
- Conservation of energy states that heat cannot be created or destroyed. This means that the thermal energy lost by one substance is gained by another.
- Calorimetry is the measurement of heat. It can be used to determine the specific heat capacity or latent heat of a substance.

KEY QUESTIONS

Retrieval

1 Define 'calorimetry'.

2 Define 'thermal equilibrium'.

Comprehension

3 Explain why two objects that are in thermal equilibrium with a third object must also be in thermal equilibrium with each other.

4 Explain why putting ice (at 0°C) into a drink is much more effective at cooling your drink down than putting water at 0°C into your drink.

Analysis

5 A 1.4 kg piece of metal has been heated to 60.0°C. This is then placed in an insulated tank containing 18.3 kg of water at 29.0°C. The final temperature of the water and metal cube is 29.5°C. Determine the specific heat capacity of the metal and from this deduce what metal you think it is.

6 On a hot summer's day, 25 bags of ice (5.0 kg each) at –6.00°C are added to a swimming pool at 30.0°C. The water in the swimming pool has a mass of 10000.0 kg. Calculate is the final temperature of the swimming pool.

7 A calorimeter with a mass of 90.0 g and a specific heat capacity of 420 $J kg^{-1} K^{-1}$ contains 310 g of a liquid at 15.0°C. An electric heater provides energy at a rate of 20.0 $J s^{-1}$, which warms the liquid to 19.0°C in 3.0 min. Assuming there are no energy losses to the surrounds, calculate the specific heat capacity of the liquid.

2.7 Mechanical work and efficiency

BY THE END OF THIS MODULE, YOU SHOULD BE ABLE TO:

- understand that thermal energy has the capacity to do mechanical work
- understand the conservation of energy and the first law of thermodynamics
- calculate the efficiency of an energy transfer.

WORK

In the mid 1800s, James Joule, a British brewer, performed a series of experiments that showed the equivalence of heat and mechanical energy (Figure 2.7.1). In his heat equivalency experiment, a mass was dropped, converting potential energy to kinetic energy. This dropping mass pulled a cord turning a spindle. This spindle then turned some paddles, which heated the liquid, and the temperature change was measured. The kinetic energy of the turning paddles caused the surrounding liquid to increase in temperature. Through this experiment, Joule measured the heat capacity of water with a surprising level of accuracy for the time.

Work is done when energy is transformed and this causes an object to be moved. In Joule's experiment, the paddle turning did work on the liquid, increasing the average kinetic energy of the molecules, thus increasing the temperature of the water. Joule's experiment converted potential energy and then kinetic energy from the falling mass to kinetic energy of the spindle and paddles, and then to thermal energy that heated the liquid.

Any system with thermal energy has the capacity to do mechanical work. For example, heat is created by the chemical reactions in an engine. The heat expands a gas, which moves a piston and work is done.

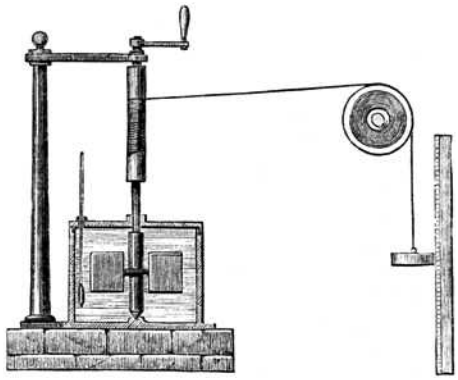


FIGURE 2.7.1 Joule's heat equivalency experiment. James Prescott Joule used this apparatus to determine that mechanical work was equivalent to heat. The mass would drop, pulling the cord and turning the spindle. The turning spindle would turn the paddles, heating the liquid. The change in temperature of the liquid was measured by the thermometer.

THE FIRST LAW OF THERMODYNAMICS

In a closed system, energy is always conserved. Energy can change forms but is never lost or destroyed. The first law of thermodynamics states that energy simply changes from one form to another and the total internal energy in a system is constant. The internal energy of the system can be changed by heating or cooling, or by work being done on or by the system.

Any change in the internal energy, ΔU, of a system is equal to the energy added by heating, $+Q$, or removed by cooling, $-Q$, minus the work done on, $-W$, or work done by, $+W$, the system.

$$\Delta U = Q - W$$

The internal energy, U, of a system is defined as the total kinetic and potential energy of the system. As the average kinetic energy of a system is related to its temperature and the potential energy of the system is related to the state, then a change in the internal energy of a system means that either the temperature changes or the state changes.

- If heat, Q, is added to the system, then the internal energy, U, rises by either increasing the temperature or changing state from solid to liquid or liquid to gas. Similarly, if work, W, is done on a system, then the internal energy rises and the system will once again increase in temperature or change state by melting or boiling. When heat is added to a system or work is done on a system, ΔU is positive.
- If heat, Q, is removed from the system, then the internal energy, U, decreases by either decreasing temperature or changing state from liquid to solid or gas to liquid. Similarly, if work, W, is done by the system, then the internal energy decreases and the system will once again decrease in temperature or change state by condensing or solidifying. When heat is removed from a system or work is done by a system, ΔU is negative.

Any change in the internal energy, ΔU, of a system is equal to the energy added by heating, $+Q$, or removed by cooling, $-Q$, minus the work done on, $-W$, or work done by, $+W$, the system.
$\Delta U = Q - W$

- If heat is added to the system and work is done by the system, then the magnitude of the energy into the system compared to the magnitude of the energy out of the system determines whether the internal energy increases (ΔU is positive) or decreases (ΔU is negative).

Worked example 2.7.1

CALCULATING THE CHANGE IN INTERNAL ENERGY

A 1 L beaker of water has 25 kJ of work done on it and loses 30 kJ of thermal energy to the surroundings. Calculate the change in energy of the water.

Thinking	Working
Heat is removed from the system, so Q is negative. Work is done on the system, so W is negative.	$\Delta U = Q - W$ $= -30 - (-25)$
Note that the units are kJ, so express the final answer in kJ.	$= -5$ kJ

➤ Try yourself 2.7.1

CALCULATING THE CHANGE IN INTERNAL ENERGY

A student places a heating element and a paddle-wheel apparatus in an insulated container of water. She calculates that the heater transfers 2530 J of thermal energy to the water and the paddle does 240 J of work on the water. Calculate the change in internal energy of the water.

EFFICIENCY

Energy can never be created or destroyed; however, it may transform into less useful forms of energy. In any heat transfer in the real world, some of the heat is 'lost' to the surroundings. This heat loss reduces the useable energy. The percentage of energy that is effectively transformed in an energy transfer process is called its efficiency.

The efficiency of transferring energy from one form to another is expressed as:

$$\text{Efficiency } (\eta) = \frac{\text{useful energy transferred}}{\text{total energy}} \times \frac{100}{1}\%$$

$$\eta = \frac{\text{energy output}}{\text{energy input}} \times \frac{100}{1}\%$$

$\eta = \frac{\text{energy output}}{\text{energy input}} \times \frac{100}{1}\%$

Worked example 2.7.2

CALCULATING EFFICIENCY

A particular Bunsen burner provides 76 000 J of heat to a beaker of water. The useful energy that heated the water is 27 000 J. The rest of the heat is lost to the environment. Calculate the efficiency of this process.

Thinking	Working
Recall the equation for efficiency. Substitute the given values into the equation and calculate η.	Output = 27 000 J Input = 76 000 J $\eta = \frac{\text{energy output}}{\text{energy input}} \times \frac{100}{1}\%$ $= \frac{27000}{76000} \times \frac{100}{1}\%$ $= 36\%$

➤ Try yourself 2.7.2

CALCULATING EFFICIENCY

A particular barbeque produces 295 000 J of energy but the heat absorbed by the food 81 000 J. Determine the efficiency of this process.

2.7 Review

SUMMARY

- Thermal energy has the capacity to do mechanical work.
- The first law of thermodynamics states that energy simply changes from one form to another and the total energy in a system is constant.
- Any change in the internal energy (ΔU) of a system is equal to the energy added by heating ($+Q$) or removed by cooling ($-Q$), minus the work done on ($-W$) or by ($+W$) the system: $\Delta U = Q - W$.
- The efficiency, η, of an energy transfer from one form to another is given by η:

$$\eta = \frac{\text{energy output}}{\text{energy input}} \times \frac{100}{1}\%$$

KEY QUESTIONS

Retrieval

1 Describe what James Joule was trying to demonstrate with his experiment depicted in Figure 2.7.1.

2 Define 'conservation of energy'.

3 Explain whether it is possible to have greater than 100% efficiency in a thermal energy transfer.

Comprehension

4 Calculate the efficiency of a power station that creates 1.4×10^7 J of heat energy and converts this to 5.0 MJ of electrical energy.

5 Explain why conservation of energy and efficiency are not contradicting each other.

Analysis

6 In Joule's experiment, dropping the mass provided 98 J of energy to 100.0 g of castor oil in an insulated vessel. The specific heat capacity of castor oil is 1800 J kg^{-1} K^{-1}. Calculate by how much the temperature of the castor oil rose.

7 A hot block of iron does 50.0 kJ of work on a cold floor. The block of iron also transfers 20.0 kJ of heat energy to the air. Calculate the change in energy (in kJ) of the iron block.

8 A chef vigorously stirs a pot of cold water and does 150 J of work on the water. The water also gains 75 J of thermal energy from the surroundings. Calculate the change in energy of the water.

9 A scientist very carefully does mechanical work on a container of liquid sodium. The liquid sodium loses 300.0 J of energy to its surroundings but gains 250.0 J of energy overall. Calculate how much work the scientist did.

MP 1

Finding the relationship between temperature and heat

Conduct an experiment that obtains data to be analysed by:

- plotting a scatter graph (with correct title and symbols, units and labels on the axes)
- formulating the equation of a linear trendline
- interpreting the data/graph to draw a conclusion
- writing a report that uses scientific conventions and language.

Research and planning

Aim

- To examine the relationship between temperature and heat through experiment.

Rationale (scientific background to the experiment)

All states of matter—liquid, solid, or gas—are made of moving particles. The average kinetic energy of these particles is related to temperature. The kinetic energy of each of the individual particles cannot be directly measured, so temperature scales, such as the Celsius and Fahrenheit scales, are used to measure temperature.

The thermal energy, or internal energy, of a material includes the kinetic energy of the atoms or molecules as well as the potential energy between the atoms and molecules. Heat is a measure of the energy transferred from a hotter material to a cooler material. When you say you are going to 'heat something up', you are actually causing heat to flow into something to increase the average kinetic energy of its atoms or molecules.

By applying heat to a beaker of water at a constant rate, it is possible to find a relationship between the heat applied (by measuring the time the water is heated) and its temperature (a measure of the average kinetic energy of the molecules).

Timing

60 minutes

The water will take a long time to boil, so this activity should be started at the beginning of the lesson.

Materials

- 2 thermometers or a temperature sensor
- 600 mL beaker
- hotplate
- 250 mL water
- stopwatch
- heat glove or oven mitt
- 2 retort stands and clamps

Safety

- Do not directly touch hot items like the hot plate, beaker, and water.
- Keep the boiling water away from other electrical equipment like a computer.
- Wear a lab coat, goggles and gloves as recommended by your teacher.

Method

Risk assessment

Before you commence this practical activity, you must conduct a risk assessment. Complete the template in your Skills and Assessment book or download it from your eBook.

1. Turn on the hotplate to commence heating.
2. Part fill the beaker with water (250 mL).
3. Place a thermometer into the beaker and secure it using a retort stand and clamp so that the tip of the thermometer is submerged in the liquid but not touching the wall of the beaker.
4. Place the water-filled 600 mL beaker with thermometer on the hotplate.
5. Record the temperature of the water at 30 second intervals.
6. Monitor the temperature of the water and when it gets to 80°C, stop recording data.
7. With teacher assistance, use the heat glove to remove the beaker from the hotplate.
8. Allow the liquids and hotplate to cool before cleaning up.

Variables

i. Independent: time the sample is on the hotplate
ii. Dependent: temperature of the water
iii. Controlled: mass of water, initial temperature of water, setting on hotplate

Analysing

Raw data

Mass of beaker: _____

Mass of beaker and water: _____

Copy the following table into your book and use it to record all your data.

	T_1	T_2	T_3	T_4	T_5	T_6	T_7	T_8	T_9	T_{10}
Time (s)										
Water temperature (°C)										

Processed data

➤ Reflect and check that your data analysis demonstrates these characteristics

- ❑ Effective investigation of phenomena is demonstrated by the collection of sufficient and relevant raw data.
- ❑ Accurate application of algorithms, visual and graphical representations of data is demonstrated by appropriate processing and presentation of data to aid the analysis and interpretation of data.

Analysis

➤ Reflect and check that your analysis demonstrates these characteristics

- ❑ Systematic and effective analysis of evidence is demonstrated by a thorough and appropriate error analysis.
- ❑ Systematic and effective analysis of evidence is demonstrated by a thorough identification of relevant trends, patterns and relationships.
- ❑ Insightful and valid interpretation of evidence is demonstrated by drawing a valid and defensible conclusion based on the analysis.

1 Plot your results on a graph, with time on the horizontal axis and temperature on the vertical axis. Label the axes, include units and add a title for your graph.

2 Draw a line of best fit.

Calculations

3 Calculate the gradient of the line of best fit. Using the general equation for a straight line, $y = mx + c$, write an equation for the relationship between time and temperature.

4 Are there any points on your graph that do not fit the trend? Explain why this may have been the case.

5 State the value, units and meaning of the gradient and y-intercept.

6 Compare your graph and equation value with the values obtained by other groups. Are they the same?

Interpreting and communicating

Conclusion

1 The aim of the experiment was to determine the relationship between temperature and heat by measuring the temperature of a beaker of water as it was heated. Were you able to find a linear relationship between time and temperature?

2 Write a scientific report that describes your experiment, results and conclusions. Refer to Chapter 1 for more information about writing a scientific report.

Evaluation

3 Considering your analysis and conclusion, did the experiment provide an effective method of finding a relationship between the time the water was heated and the temperature of the water?

Improvements

4 If you were to repeat the experiment, what would you do differently?

Include in your answer:

- how you would change the methodology and how this might improve the results
- what skills you used to perform the tasks and how your technique could be improved
- how the collection of data could be made more reliable and the uncertainty reduced.

Extension

5 Do you think this methodology could be applied to determine the relationship between temperature and heat for any substances?

6 Identify any limitations to using this method for other substances.

➤ Reflect and check that your evaluation demonstrates these characteristics

- ❑ Critical evaluation of processes is demonstrated by a discussion of the reliability and validity of the experimental process supported by evidence such as the quality of the data (as quantified in the error analysis).
- ❑ Critical evaluation of the conclusion is demonstrated by a discussion of the veracity of the conclusions with respect to the error analysis and limitations or sufficiency of the data.
- ❑ Insightful evaluation of processes and conclusions is demonstrated by a suggestion of improvements or extensions to the experiment that are logically derived from the analysis of the evidence.

MP 2

Determining the specific heat capacity of a substance with a focus on error propagation

Conduct an experiment that determines the specific heat capacity of a substance, ensuring that measurement uncertainties associated with mass and temperature are propagated. Where the mean is calculated, determine the absolute uncertainty of the mean.

Research and planning

Aim

- To find the specific heat capacity of a substance through experimentation.

Rationale (scientific background to the experiment)

The amount of energy added to (or taken away from) a substance is proportional to the change in its temperature, its mass and its specific heat capacity.

The mathematical relationship between the heat energy transferred, Q, and temperature change, ΔT, for a substance of mass m is given by:

$$Q = mc\Delta T$$

where

Q is the heat energy transferred in joules (J)

m is the mass of material being heated in kilograms (kg)

ΔT is the change in temperature (°C or K)

c is the specific heat capacity of the material ($J\,kg^{-1}\,K^{-1}$).

In this experiment, a metal sample is heated by placing it in a beaker of boiling water. The temperature of the metal will increase as it absorbs energy from the water. The metal sample is then placed in a calorimeter cup and the temperature measured as the water in the cup and the metal sample reach equilibrium.

By measuring the temperature of the water before the metal is added and as it comes to equilibrium, it is possible to find the heat energy given to the water by the metal. Then by measuring the mass of the metal and its change in temperature, it is possible to find its specific heat capacity.

Timing

45 minutes

Materials

- thermometer
- balance (1 per classroom)
- hotplate
- 600 mL beaker
- tongs
- 3 calorimeter cups
- retort stand and clamps
- 1 L water
- metal samples (at least five masses of the same metal)
- 15 cm string for each sample

Safety

- When using the hotplate, be very careful not to burn your hands or fingers.
- Use a 600 mL beaker for boiling water that can withstand high heat, such as a pyrex beaker. Other beakers may shatter when exposed to high heat.
- Boiling water can cause severe burns. Be very careful when using boiling water, and do not carry the beaker without insulated gloves or tongs when it is hot.
- All glass beakers can break when dropped. Be very careful not to drop any of the glassware used in this lab. If an accident does occur, follow the proper cleaning and disposal procedure instituted by your teacher.

Method

Risk assessment

Before you commence this practical activity, you must conduct a risk assessment. Complete the template in your Skills and Assessment book or download it from your eBook.

1. Create a hot-water bath by filling the beaker $\frac{3}{4}$ full of water and placing the beaker on the hotplate.
   Note: To speed up this step, use a kettle to boil the water first.
2. Set the hotplate temperature to boil the water in the beaker.
3. Add equal amounts of water to the three calorimeter cups.
4. Use the balance to measure the mass of each calorimeter cup, and its uncertainty, and then record this in the data analysis section.
5. Add equal amounts of water to the calorimeter cups (so they are approximately $\frac{3}{4}$ full), and record the mass of each calorimeter cup and water, with its uncertainty, in the data analysis section.
   Note: The calorimeter cups and beaker are only $\frac{3}{4}$ full so that the water level does not spill over the edge of the cup or beaker when you submerge the metal sample.
6. Record the mass of each metal sample, and its uncertainty, in the data analysis section.
7. Tie a 15 cm piece of string to each metal sample. Tie the other end of the string to a retort stand so that the metal sample is suspended in the water rather than touching the bottom of the beaker.

8 Check the temperature in each calorimeter to ensure it is room temperature, and record this value in the data analysis section as the initial temperature of the water in the calorimeters.
9 Allow the hot-water bath to come to a boil.
10 Place the first metal sample in the hot-water bath, and allow it to equilibrate for 5 to 10 minutes.
11 Use the thermometer to measure the temperature of the hot water, and record this and its uncertainty.
12 Place the thermometer in the first calorimeter cup.
13 Quickly but carefully transfer the first metal sample from the hot-water bath to the calorimeter cup.
14 Place the second metal sample in the hot-water bath.
15 Check the temperature in the calorimeter cup three times at 30-second intervals. Once the temperature in the calorimeter reaches equilibrium (remains constant), make a note of the temperature and its uncertainty.
16 Place the thermometer in the second calorimeter cup.
17 Quickly but carefully transfer the second metal sample from the hot-water bath to the calorimeter cup.
18 Place the third metal sample in the hot-water bath.
19 Check the temperature in the calorimeter cup three times at 30-second intervals. Once the temperature in the calorimeter reaches equilibrium (remains constant), make a note of the temperature and its uncertainty.
20 Place the thermometer in the third calorimeter cup.
21 Quickly but carefully transfer the third metal sample from the hot-water bath to the calorimeter cup.
22 Check the temperature in the calorimeter cup three times at 30-second intervals. Once the temperature in the calorimeter reaches equilibrium (remains constant), make a note of the temperature and its uncertainty.
23 Repeat the process for the other two samples.
24 Make sure your hotplate is turned off, and carefully clean up as instructed by your teacher.

Variables

i Independent: mass of the metal samples
ii Dependent: change in temperature of the water in the calorimeter cup
iii Controlled: initial temperature of the metal, initial temperature of the water, type of metal sample, surrounding temperature, and mass of the water

Analysing

Raw and processed data

➤ Reflect and check that your data analysis demonstrates these characteristics

- ❑ Effective investigation of phenomena is demonstrated by the collection of sufficient and relevant raw data.
- ❑ Accurate application of algorithms, visual and graphical representations of data is demonstrated by appropriate processing and presentation of data to aid the analysis and interpretation of data.

After recording temperature data for all five of your samples, calculate the change in temperature, ΔT, for both the calorimeter water and the metal sample.

Then calculate the heat transferred to the calorimeter water by the metal sample using $Q = mc\Delta T$ and $c_{water} = 4200\,J\,kg^{-1}\,°C^{-1}$. For an example of the calculation see Worked example 2.6.1 on page 34, then use that value of Q with $Q = mc\Delta T_{metal}$ to find the specific heat capacity of the metal.

Remember to propagate your uncertainties through your calculations to give an uncertainty with each specific heat capacity calculated. See Chapter 1 or your teacher for guidance.

Sample 1

Mass of the calorimeter cup: _____

Mass of the calorimeter cup plus water: _____

TABLE 1.1 Mass and temperature data

Sample 1	T_{final} (°C)	Uncertainty in T_{final} (°C)	$T_{initial}$ (°C)	Uncertainty in $T_{initial}$ (°C)	ΔT (°C)	Uncertainty in ΔT (°C)	m (kg)	Uncertainty in m (kg)
Calorimeter water								
Metal sample								

Sample 2

Mass of the calorimeter cup: _____

Mass of the calorimeter cup plus water: _____

TABLE 1.2 Mass and temperature data

Sample 2	T_{final} (°C)	Uncertainty in T_{final} (°C)	$T_{initial}$ (°C)	Uncertainty in $T_{initial}$ (°C)	ΔT (°C)	Uncertainty in ΔT (°C)	m (kg)	Uncertainty in m (kg)
Calorimeter water								
Metal sample								

Sample 3

Mass of the calorimeter cup: _____

Mass of the calorimeter cup plus water: _____

TABLE 1.3 Mass and temperature data

Sample 3	T_{final} (°C)	Uncertainty in T_{final} (°C)	$T_{initial}$ (°C)	Uncertainty in $T_{initial}$ (°C)	ΔT (°C)	Uncertainty in ΔT (°C)	m (kg)	Uncertainty in m (kg)
Calorimeter water								
Metal sample								

Sample 4

Mass of the calorimeter cup: _____

Mass of the calorimeter cup plus water: _____

TABLE 1.4 Mass and temperature data

Sample 4	T_{final} (°C)	Uncertainty in T_{final} (°C)	$T_{initial}$ (°C)	Uncertainty in $T_{initial}$ (°C)	ΔT (°C)	Uncertainty in ΔT (°C)	m (kg)	Uncertainty in m (kg)
Calorimeter water								
Metal sample								

Sample 5

Mass of the calorimeter cup: _____

Mass of the calorimeter cup plus water: _____

TABLE 1.5 Mass and temperature data

Sample 5	T_{final} (°C)	Uncertainty in T_{final} (°C)	$T_{initial}$ (°C)	Uncertainty in $T_{initial}$ (°C)	ΔT (°C)	Uncertainty in ΔT (°C)	m (kg)	Uncertainty in m (kg)
Calorimeter water								
Metal sample								

Analysis

➤ Reflect and check that your analysis demonstrates these characteristics

- ❑ Systematic and effective analysis of evidence is demonstrated by a thorough and appropriate error analysis.
- ❑ Systematic and effective analysis of evidence is demonstrated by a thorough identification of relevant trends, patterns and relationships.
- ❑ Insightful and valid interpretation of evidence is demonstrated by drawing a valid and defensible conclusion based on the analysis.

1 Calculate the specific heat capacity, c, of the metal, using $Q = mc\Delta T$ for each sample. Enter these values in the table below.

TABLE 1.6 Combined results from 5 trials

	Sample 1	Sample 2	Sample 3	Sample 4	Sample 5	Average
Specific heat capacity						
Uncertainty in specific heat capacity						

2 Take the average of these 5 samples to find a specific heat capacity of the metal. To calculate the absolute uncertainty of the mean use:

uncertainty in $c = \pm\frac{c_{max} - c_{min}}{2}$ (see Chapter 1).

3 Explain some of the factors that might have caused your calculated values for specific heat capacity to be inaccurate and how these factors could be avoided.

Interpreting and communicating

Conclusion

1 The aim of the experiment was to determine the specific heat capacity of a metal sample. Were you able to find a value for the specific heat capacity of the metal?

2 Use Table 2.4.1 on page 23 to identify the specific heat capacity of the metal. How does your experimental value compare to this? Is the value given in Table 2.4.1 within your uncertainty range?

3 Can you identify the type of metal from its specific heat capacity?

Evaluation

4 Considering your analysis and conclusion, did the experiment provide an effective method of finding the specific heat capacity of the metal?

5 Was the level of uncertainty that you calculated in Question 2 reasonable?

Improvements

6 If you were to repeat the experiment, what would you do differently?

Include in your answer:

- how you would change the methodology and how this might improve the results
- what skills you used to perform the tasks and how your technique could be improved
- how the collection of data could be made more reliable and the uncertainty reduced.

Extension

7 Do you think this methodology could be applied to determine the specific heat capacity of any metal?

8 Identify any limitations to using this method for other metals.

➤ Reflect and check that your data analysis demonstrates these characteristics

- ❑ Critical evaluation of processes is demonstrated by a discussion of the reliability and validity of the experimental process supported by evidence such as the quality of the data (as quantified in the error analysis).
- ❑ Critical evaluation of the conclusion is demonstrated by a discussion of the veracity of the conclusions with respect to the error analysis and limitations or sufficiency of the data.
- ❑ Insightful evaluation of processes and conclusions is demonstrated by a suggestion of improvements or extensions to the experiment that are logically derived from the analysis of the evidence.

Chapter review

WS 1.1.7 WS 1.1.8 TR 1.1

02

KEY TERMS

absolute zero
absorption
calorimetry
conduction
conductor
convection
electromagnetic spectrum
emission
evaporation
frequency
heat
incident
insulator
internal energy
Kelvin
kinetic energy
kinetic particle model
latent heat
latent heat of fusion
latent heat of vaporisation
model
Maxwell–Boltzmann distribution
potential energy
radiation
specific heat capacity
temperature
thermal contact
thermal energy
thermal equilibrium
thermodynamics
volatile
wavelength
work

KEY QUESTIONS

Retrieval

1 Identify which of the following statements can be said to describe particles of matter, according to the kinetic particle model.
- **A** They are in constant motion at any temperature.
- **B** They are stationary at all temperatures.
- **C** They are in motion above a certain temperature.

2 **a** An uncooked chicken is placed into an oven that has been preheated to 180°C. Identify which one or more of the following statements describes what happens as soon as the chicken is placed in the oven.
- **A** Thermal energy flows from the chicken into the hot air.
- **B** The chicken and the air in the oven are in thermal equilibrium.
- **C** Thermal energy flows from the hot air into the chicken.
- **D** The chicken and the air in the oven are not in thermal equilibrium.

b A chicken is inside an oven that has been preheated to 180°C. The chicken has been cooking for one hour and its temperature is also 180°C. Identify which of the following statements best describes this scenario.
- **A** Thermal energy flows from the chicken into the hot air.
- **B** The chicken and the air in the oven are in thermal equilibrium.
- **C** Thermal energy flows from the hot air into the chicken.
- **D** The chicken and the air in the oven are not in thermal equilibrium

3 Identify which one or more of the following temperatures cannot possibly exist.
- **A** 1 000 000°C
- **B** –50°C
- **C** –50 K
- **D** –300°C

4 Identify which of the following will affect the rate at which an object radiates thermal energy.
- **A** its temperature
- **B** its colour
- **C** its surface nature (shiny or dull)
- **D** none of these
- **E** all of A–C

5 Two cubes, one of silver and one of iron, have the same mass and temperature. A quantity of heat, Q, is removed from each cube. Identify which one of the following properties causes the final temperatures of the cubes to be different.
- **A** density
- **B** specific heat capacity
- **C** latent heat of vaporisation
- **D** volume

6 A painter spills some mineral turpentine onto a concrete floor. After a minute, most of the liquid is gone. Identify which of the following is correct.
- **A** Most of the liquid has boiled, becoming hotter.
- **B** Most of the liquid has evaporated and the remaining liquid becomes warmer as it does so.
- **C** Most of the liquid has evaporated with no change in temperature of the remaining liquid.
- **D** Most of the liquid has evaporated and the remaining liquid becomes colder as it does so.

7 State what the first law of thermodynamics says about the total internal energy of a closed system.

8 Light is shone on an object.
- **a** List three interactions that can occur between the light and the object.
- **b** State which of the interactions from part (a) are associated with a rise in temperature.

Comprehension

9 Consider two objects that are in thermal contact in a closed system. Explain the relationship between the heat lost from one object and the heat gained by the second object.

10 Two objects are in thermal contact. State and explain which of the following quantities will determine the direction of the transfer of energy between these objects: their masses, the area of contact between the two objects, the specific heat capacity of each object, the temperature of each object.

11 Explain how temperature differs from heat.

12 Convert:
- **a** 5.0°C to kelvin
- **b** 200.0 K to °C.

13 Explain why metals are more likely than wood to conduct heat.

14 Explain why energy cannot be transmitted through a solid by convection.

15 A steel BBQ plate of mass 20.0 kg has a specific heat capacity of 466 $J\,kg^{-1}\,K^{-1}$. Determine how much heat it will take to heat the plate from 25.0°C to 350.0°C.

16 A solid substance is heated but its temperature does not change. Explain what is occurring.

17 Calculate how many joules of energy are required to melt exactly 80.0 g of silver ($L_{fusion} = 0.88 \times 10^5\,J\,kg^{-1}$).

18 Two 20.0 g cubes of ice (at –4.00°C) are added to a 20.0°C cup of water (250.0 g). Determine the final temperature of the cup of water.

Analysis

19 Explain the difference between internal energy and thermal energy.

20 A solid and a liquid are at thermal equilibrium with each other. Determine whether the thermal energy and/or internal energy of the solid is the same as that of the liquid.

21 Explain the difference between solids, liquids and gases using the kinetic theory.

22 A body at a uniform temperature of 300.0 K and an internal energy of 6.0×10^6 J is split into two equal halves.
- **a** Determine whether any heat has been exchanged.
- **b** Determine the temperature of each half.
- **c** Determine the internal energy of each half.

23 Briana rides her bike to school. She notices that that the rubber handgrips feel warm but the metal frame feels cold. Explain why.

24 Calculate how much energy, in J, is needed to raise the temperature of a 1.0 kg block of aluminium by 20.0°C.

25 A 2.00 kg metal object requires 5.02×10^3 J of heat to raise its temperature from 20.0°C to 30.0°C. Determine the specific heat capacity of the metal in $J\,kg^{-1}\,K^{-1}$. Give your answer to the nearest whole number.

26 If 48 000 J of energy is given off when a 2.0 kg sample of a liquid cools by 12 K, determine the specific heat capacity of the liquid.

27 Assess which possesses the greater internal energy: 1.0 kg of water boiling at 100.0°C or 1.0 kg of steam at 100.0°C. Explain why.

28 A kettle that provides 2100 W of power (which is 2100 J per second) has been left boiling with 0.80 kg of water inside. Calculate how long it will take for the kettle to boil dry.

29 Hypothermia is the cooling of the body to levels considerably lower than normal. The body's functions slow and death can result. A person may survive 12 hours in air at 0°C before suffering hypothermia, but may survive only a few minutes in water at 0°C. Consider why this is so and how wetsuits can help you survive in cold water.

30 You have 30.0 g of ethanol at 22°C, which you pour into 90.0 g of water at 80.0°C. Assuming no heat is produced or lost during this process, calculate the final temperature of the mixture.

31 A heater that is 25% efficient receives 3000.0 J per second. Determine how much of this energy is put out as heat.

Knowledge utilisation

32 Create an analogy for the three main states of matter (solid, liquid and gas) to explain them to a younger student.

33 Design a cold storage room, powered by a small refrigeration unit, for keeping food fresh in a hot climate. Draw a sketch of your design, clearly showing its insulating features and materials and describe how it minimises all forms of heat transfer.

34 You have a small cube of an unknown metal that you want to identify. Your teacher has suggested that measuring its specific heat capacity would help you identify it. Design an experiment to measure the specific heat capacity of the cube.

CHAPTER

03 Ionising radiation and nuclear reactions

WS 1.2.1

This chapter examines the nature and properties of the nucleus of an atom, including the natural causes of nuclear instability and alpha, beta and gamma radiation. It also explains the importance of the rate of decay and the penetrating power of the radiation. The half-lives of radioactive substances are analysed using mathematical calculations and graphs. Finally, the energy released during nuclear fission and nuclear fusion reactions are calculated using Einstein's mass–energy relationship.

Syllabus subject matter

Topic 2 • Ionising radiation and nuclear reactions

NUCLEAR MODEL AND STABILITY

- describe the nuclear model of the atom characterised by a small nucleus surrounded by electrons
- explain why protons in the nucleus repel each other
- define the *strong nuclear force*
- explain the stability of a nuclide in terms of the operation of the strong nuclear force over very short distances, electrostatic repulsion and the relative number of protons and neutrons in the nucleus.

SPONTANEOUS DECAY AND HALF-LIFE

- explain natural radioactive decay in terms of stability
- define *alpha radiation*, *beta positive radiation*, *beta negative radiation* and *gamma radiation*
- describe alpha, beta positive, beta negative and gamma radiation, including the properties of penetrating ability, charge, mass and ionisation ability
- explain how an excess of protons, neutrons or mass in a nucleus can result in alpha, beta positive and beta negative decay
- solve problems involving balancing nuclear equations
- represent spontaneous alpha, beta positive and beta negative decay using decay equations, e.g.

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

$$^{60}_{27}\text{Co} \rightarrow {}^{60}_{28}\text{Ni} + {}^{0}_{-1}e + \bar{\nu}_e + \gamma$$

$$^{102}_{50}\text{Sn} \rightarrow {}^{102}_{49}\text{In} + {}^{0}_{+1}e + \nu_e + \gamma$$

- explain how a radionuclide will, through a series of spontaneous decays, become a stable nuclide
- define *half-life*
- solve radioactive decay problems involving whole numbers of half-lives.

ENERGY AND MASS DEFECT

- describe energy in terms of electron volts (eV) and joules (J)
- define *artificial transmutation*
- distinguish between artificial transmutations and natural radioactive decay
- define *nuclear fission*
- explain a neutron-induced nuclear fission reaction, including references to extra neutrons produced from many of these reactions
- research nuclear safety, considering the suitability of using the sources of information in terms of their credibility
- explain a fission chain reaction
- define *nuclear fusion*
- define *mass defect*, *binding energy* and *binding energy per nucleon*
- recall Einstein's mass–energy equivalence relationship
- solve problems involving Einstein's mass–energy equivalence relationship
- explain that more energy is released per nucleon in nuclear fusion than in nuclear fission because a greater percentage of the mass is transformed into energy.

SCIENCE AS A HUMAN ENDEAVOUR

- Radioisotopes and radiometric dating
- Harnessing nuclear power

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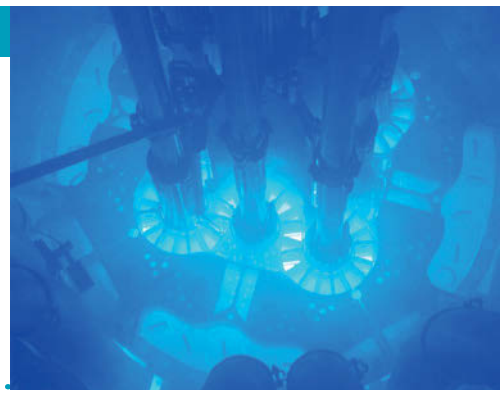
3.1 The nucleus

BY THE END OF THIS MODULE, YOU SHOULD BE ABLE TO:

- describe the nucleus in terms of the charges and masses of its constituent nucleons
- recall that a nucleon is a proton or a neutron
- recall that isotopes of an element have the same number of protons but different numbers of neutrons
- recall that the nucleus of an isotope is called a nuclide
- use the ${}^{A}_{Z}X$ notation to calculate the number of protons and neutrons in a nuclide.



The atom is the basic building block of all matter. The first **subatomic** particle, the **electron**, was discovered by English physicist J. J. Thomson in 1897. He then refined the first testable model of the atom, called the 'plum pudding model' (Figure 3.1.1). This model described the **neutral** atom as negatively charged 'plums' of electrons embedded in a loosely packed 'pudding' of positive charge.

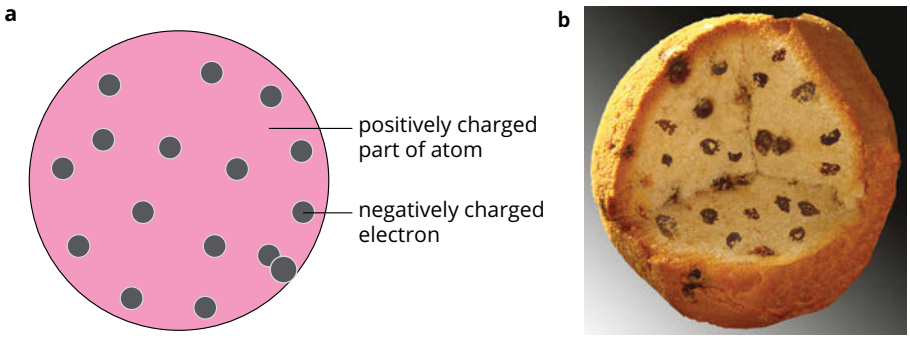


FIGURE 3.1.1 (a) The 1897 'plum pudding model' of the atom, the first truly physical model of the atom that could be tested, and (b) a real plum pudding.

In 1909, the New Zealand physicist Ernest Rutherford showed that the atom consisted of a very dense, positively charged nucleus surrounded by much smaller, negatively charged electrons.

NUCLEAR STRUCTURE

The proton

Rutherford also discovered that the nucleus of an atom is made up of positive charges called protons. A **proton** has a mass almost 2000 times that of the electron. The number of protons contained in a nucleus determines the species, or element, of the atom. For example, hydrogen always has one proton; helium always has two protons and so on.

The nucleus of an atom consists of positively charged protons and neutral neutrons surrounded by much lighter, negatively charged electrons.

The neutron

Rutherford knew that the mass of the protons in certain atoms did not add up to the mass of the nucleus. He suggested that there must be another particle contained in the nucleus that had to have no charge. The English physicist James Chadwick discovered this neutral particle, known as the neutron, in 1932. Table 3.1.1 summarises the properties of the three major particles found in atoms. The masses are given in kg and in **unified atomic mass units** (u); charge is given in **coulombs** (C).

TABLE 3.1.1 A summary of the properties of the three major particles found in atoms

Particle	Location	Charge (C)	Mass (kg)	Mass (u)	Relative mass (proton = 1)
electron	surrounding nucleus	-1.602×10^{-19}	$9.109\,384 \times 10^{-31}$	0.000 549	$\frac{1}{1836}$
proton	nucleus	$+1.602 \times 10^{-19}$	$1.672\,621\,71 \times 10^{-27}$	1.007 276	1
neutron	nucleus	0	$1.674\,927\,29 \times 10^{-27}$	1.008 665	1.0014

ISOTOPES AND NOTATION

In order to keep track of the number of particles that make up the nucleus of each atom, some notation will be introduced that describes how many protons and neutrons are in each nucleus.

Isotopes and nuclides

Protons and neutrons comprise the nucleus, so these particles collectively are called **nucleons** and the nucleus they make up is called a **nuclide**. An **isotope** is an atom that contains the same number of protons but a different number of neutrons than another atom with the same number of protons. It usually behaves the same way chemically, but has very different nuclear properties. Table 3.1.2 lists the naturally occurring isotopes of hydrogen. These isotopes are shown graphically in Figure 3.1.2.

TABLE 3.1.2 The naturally occurring isotopes of hydrogen. Note that protium is the same particle as a single proton and the ${}^{1}_{1}\mathrm{H}$ symbol is often used as the symbol for a proton.

Name of isotope	Number of protons in the nucleus	Number of neutrons in the nucleus	Number of nucleons in the nucleus	Symbol
protium	1	0	1	${}^{1}_{1}\mathrm{H}$ or ${}^{1}_{1}\mathrm{p}$
deuterium	1	1	2	${}^{2}_{1}\mathrm{H}$ or ${}^{2}_{1}\mathrm{D}$
tritium	1	2	3	${}^{3}_{1}\mathrm{H}$ or ${}^{3}_{1}\mathrm{T}$

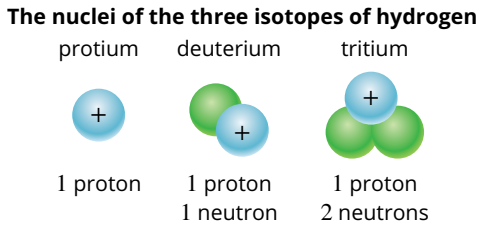


FIGURE 3.1.2 The nuclei of the three naturally occurring isotopes of hydrogen, showing the relative numbers of protons and neutrons in each case

Nuclear notation

The number of protons in a nucleus tells us the **atomic number**, Z, or the element itself. The number of neutrons in a nucleus is the **neutron number**, N. In most nuclides there are more neutrons than protons, and this ratio increases as the atomic number increases.

The sum of the number of protons and neutrons in a nucleus tells us the isotope of the element. This is the **mass number**, A.

$$A = Z + N$$

The nuclide is written using the atomic and mass numbers using the following notation, where X is the symbol for the element.

$$^{A}_{Z}\mathrm{X}$$

Sometimes the atomic number, Z, is left out because the symbol for the element describes the atomic number (e.g. carbon C will have 6 protons), but the top number is always bigger than or equal to the bottom number.

Another way to write an isotope is to use the name of the element followed by a hyphen (–) and then the mass number of the nuclide. Examples using nuclide notation are given in Table 3.1.3. The electron and neutron are also written using nuclide notation, as they will be used again later in this chapter.

TABLE 3.1.3 Selected isotopes and nuclides and their symbols

Isotope name	Atomic number	Neutron number	Mass number	Nuclide symbol
strontium-90	38	52	90	$^{90}_{38}\mathrm{Sr}$
carbon-12	6	6	12	$^{12}_{6}\mathrm{C}$
carbon-14	6	8	14	$^{14}_{6}\mathrm{C}$
plutonium-239	94	145	239	$^{239}_{94}\mathrm{Pu}$
helium-4	2	2	4	$^{4}_{2}\mathrm{He}$
a single electron	–1 (technically this is not the atomic number but charge of the electron)	0	0	$^{0}_{-1}\mathrm{e}$ or $^{0}_{-1}\beta$
a single neutron	0	1	1	$^{1}_{0}\mathrm{n}$

Nuclides are written using $^{A}_{Z}\mathrm{X}$ notation, where Z is the number of protons, A is the number of protons plus neutrons, and X is the symbol for the element.

Isotopes are written using element notation, where the element name is followed by a hyphen and the mass number of the isotope. For example, the carbon-12 isotope has a mass number of 12 and the carbon-14 isotope has a mass number of 14.

Worked example 3.1.1

WRITING NUCLIDES

Uranium has an isotope that contains 146 neutrons. Represent the nuclide of this isotope using the $^{A}_{Z}\mathrm{X}$ notation and element name notation.

Thinking	Working
Uranium is number 92 on the periodic table of elements (refer to Figure 3.2.2) so has an atomic number of 92.	$Z = 92$ Symbol U
The neutron number of 146 is given in the question.	$N = 146$
The mass number is the sum of the atomic number and neutron number.	$A = Z + N$ $A = 92 + 146$ $A = 238$
Write the nuclide using the $^{A}_{Z}\mathrm{X}$ notation.	$^{238}_{92}\mathrm{U}$ or $^{238}\mathrm{U}$
Use element name notation.	Uranium-238

➤ Try yourself 3.1.1

WRITING NUCLIDES

Consider the isotope of thorium, $^{230}_{90}\mathrm{Th}$. Identify the number of protons, nucleons and neutrons in this isotope.

3.1 Review

SUMMARY

- The nucleus of an atom consists of positively charged protons and neutral neutrons.
- Collectively, protons and neutrons are known as nucleons.
- Negatively charged electrons surround the nucleus.
- The nucleus of the atom is extremely small but contains most of the atom's mass.
- Isotopes of an element have the same number of protons but different numbers of neutrons.
- Isotopes of an element are chemically identical to each other, but have different physical properties.
- The atomic number, Z, is the number of protons in the nucleus.
- The mass number, A, is the number of nucleons in the nucleus, i.e. the combined number of protons and neutrons.
- Nuclides are represented as ${}^{A}_{Z}\mathrm{X}$.
- The nucleus of an isotope is known as a nuclide.

KEY QUESTIONS

Retrieval

1 Describe the 'plum pudding' model of the atom in terms of positive and negative charges.

2 Recall the particles that make up the nucleus of an atom.

Comprehension

3 Explain how the number of electrons in a neutral atom is determined.

4 Explain why electrons are usually not accounted for when masses of atoms are used.

5 Identify the number of neutrons in the ${}^{210}_{84}\mathrm{Po}$ nuclide.

6 Describe how many protons and how many neutrons there are in the ${}^{197}_{79}\mathrm{Au}$ nuclide.

7 Describe how many nucleons there are in the ${}^{235}_{92}\mathrm{U}$ nuclide.

Analysis

8 Determine the difference between an isotope and a nuclide.

9 Determine the difference between a nucleon and a neutron.

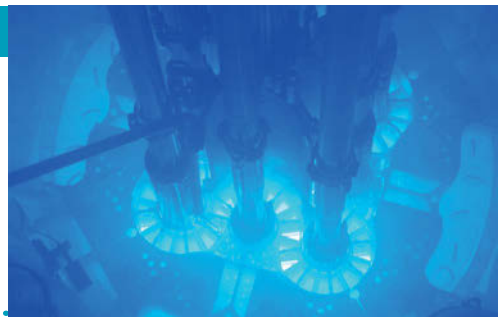
10 Determine the nuclide for a nucleus containing 6 neutrons and 6 protons.

11 Determine the nuclide for a nucleus containing 19 nucleons for an isotope of fluorine, symbol F.

3.2 Stability of the nucleus

BY THE END OF THIS MODULE, YOU SHOULD BE ABLE TO:

- understand that protons in the nucleus experience a repelling electrostatic force
- explain how the strong nuclear force acts as an attractive force on all nucleons
- explain why some nuclei are stable and some are unstable
- use a Segre plot to determine the stability of a given nuclide.



In 1896, the French physicist Henri Becquerel wrapped a metal Maltese cross in a piece of unexposed film and a chunk of uranium ore and left them in a desk drawer. On the following morning, he found that the film had become exposed and the shadow of the cross was very visible (Figure 3.2.1). The only object that could have done that was some kind of **radiation** originating from the uranium.

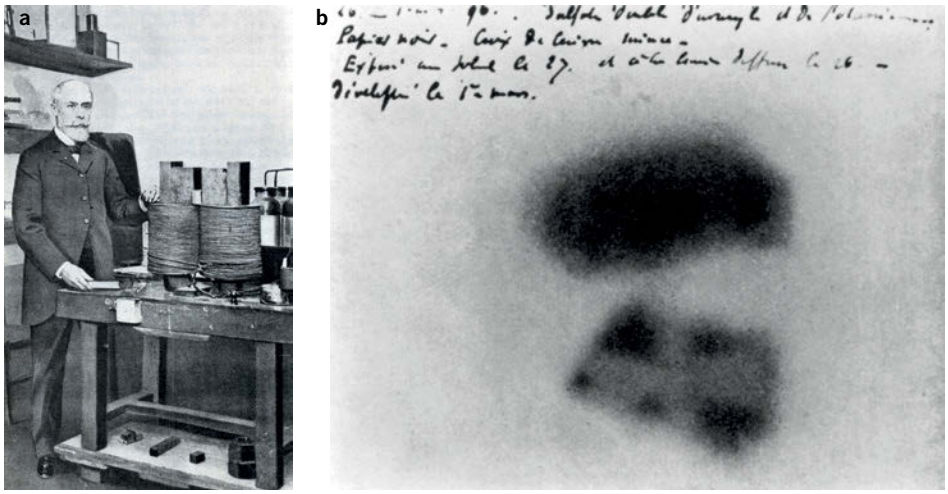


FIGURE 3.2.1 (a) Henri Becquerel in his lab in Paris in 1896, where he discovered radioactivity. (b) The shadow of a Maltese cross (the light grey cross) placed between a photographic plate and a uranium salt. The uranium salt emitted a strange form of radiation that exposed part of the plate (the black part surrounding the cross), leaving behind the shadow of the cross.

This phenomenon is called **radioactivity** and is the natural, spontaneous **decay** (breaking apart) of a nucleus into smaller pieces with the emission of other particles and/or energy in the form of **electromagnetic waves** (typically X-rays or gamma rays). In 1898, Marie Curie, a student of Becquerel's, discovered that thorium, radium and polonium also exhibit radioactivity.

STABLE AND UNSTABLE ISOTOPES

If a particular nuclide does not lose or gain any protons, neutrons or energy over time, then it is said to be stable. There are about 250 stable nuclides that exist in nature, with lead-208 being the heaviest naturally occurring stable nuclide. Examples of stable isotopes are carbon-12, helium-4, aluminium-27 and gold-197. In the periodic table of the elements shown in Figure 3.2.2, the elements that do not have any stable isotopes are highlighted by shading. The first 94 elements are naturally occurring.

Period	Group 1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18
1	1 H 1.01																	2 He 4.00
2	3 Li 6.94	4 Be 9.01											5 B 10.81	6 C 12.01	7 N 14.01	8 O 16.00	9 F 19.00	10 Ne 20.18
3	11 Na 22.99	12 Mg 24.31											13 Al 26.98	14 Si 28.09	15 P 30.97	16 S 32.06	17 Cl 35.45	18 Ar 39.95
4	19 K 39.10	20 Ca 40.08	21 Sc 44.96	22 Ti 47.90	23 V 50.94	24 Cr 52.00	25 Mn 54.94	26 Fe 55.85	27 Co 58.93	28 Ni 58.71	29 Cu 63.54	30 Zn 65.37	31 Ga 69.72	32 Ge 72.59	33 As 74.92	34 Se 78.96	35 Br 79.91	36 Kr 83.80
5	37 Rb 85.47	38 Sr 87.62	39 Y 88.91	40 Zr 91.22	41 Nb 92.91	42 Mo 95.94	43 Tc (99)	44 Ru 101.07	45 Rh 102.91	46 Pd 106.4	47 Ag 107.87	48 Cd 112.40	49 In 114.82	50 Sn 118.69	51 Sb 121.75	52 Te 127.60	53 I 126.90	54 Xe 131.30
6	55 Cs 132.91	56 Ba 137.34	57 La 138.91	72 Hf 178.49	73 Ta 180.95	74 W 183.85	75 Re 186.2	76 Os 190.2	77 Ir 192.2	78 Pt 195.09	79 Au 196.97	80 Hg 200.59	81 Tl 204.37	82 Pb 207.19	83 Bi 208.98	84 Po (210)	85 At (210)	86 Rn (222)
7	87 Fr (223)	88 Ra (226)	89 Ac (227)	104 Rf (261)	105 Db (262)	106 Sg (263)	107 Bh (264)	108 Hs (277)	109 Mt (268)	110 Ds (271)	111 Rg (272)	112 Cn (277)	113 Nh (284)	114 Fl (289)	115 Mc (288)	116 Lv (293)	117 Ts (294)	118 Og (294)

Lanthanides

58 Ce 140.12	59 Pr 140.91	60 Nd 144.24	61 Pm (145)	62 Sm 150.35	63 Eu 151.96	64 Gd 157.25	65 Tb 158.92	66 Dy 162.50	67 Ho 164.93	68 Er 167.26	69 Tm 168.93	70 Yb 173.04	71 Lu 174.97

Actinides

90 Th 232.04	91 Pa (231)	92 U 238.03	93 Np (237)	94 Pu (242)	95 Am (243)	96 Cm (247)	97 Bk (247)	98 Cf (249)	99 Es (254)	100 Fm (253)	101 Md (256)	102 No (254)	103 Lr (257)

Every isotope of these elements is radioactive.

FIGURE 3.2.2 This periodic table of the elements highlights all elements that have no stable isotopes.

FIGURE 3.2.3 The universal symbol for a radioactive substance

FIGURE 3.2.4 The 4.8 kg plutonium-238 oxide radioisotope thermionic generator that is used by the *Curiosity* rover as a source of power on the surface of Mars. The red glow is due to the energy given off by the radioactive decay of the $^{238}_{94}$Pu nuclei.

If the number of protons or neutrons in a given nuclide changes over time, or if the nucleus has an excess of energy, then the nuclide is said to be unstable or **radioactive**, and the isotope itself is called a **radioisotope**. The unstable nucleus is known as a **radionuclide**. The universal symbol for a radioactive substance is shown in Figure 3.2.3. Sometimes the process of losing protons, neutrons or energy is enough for the leftover nuclide to become stable; at other times the leftover nuclide may still be radioactive.

There are thousands of radioisotopes, most of which have been artificially created in **nuclear reactors** and **particle accelerators**. Figure 3.2.4 shows the red glow of the radioisotope plutonium-238 due to its own rapid decay. Many isotopes of plutonium are used as a heat source and a source of electricity to power space probes, such as in this generator on the *Curiosity* rover on the surface of Mars.

NUCLEAR FORCES

Remember that the nucleus consists of positively charged protons and neutral neutrons in very close proximity to each other. A fundamental law of physics states that charged particles have a force acting on them that causes them to move if the force is not balanced. This is known as the **coulomb force** or **electrostatic force**. The force is repulsive for two particles of the same charge, and attractive for two particles of opposite charge. Note that there is no coulomb force between two neutrons or between a neutron and a proton, because a neutron carries no charge.

Protons are all positively charged, so you would expect them to repel each other, causing the nucleus to break apart. If this was the case, there should be no elements heavier than hydrogen (with only one proton) in our universe. There are elements heavier than hydrogen in our universe, so what keeps protons from flying apart?

A large nucleus such as uranium-238 contains 92 protons, which all exert a repulsive force on each other, yet you know that uranium exists and that the nucleus somehow stays together. Figure 3.2.5 shows the relative sizes, to scale, of the isotopes hydrogen-1 (i.e. a single proton) and uranium-238.

The coulomb or electrostatic force is a force that acts to repel all protons.

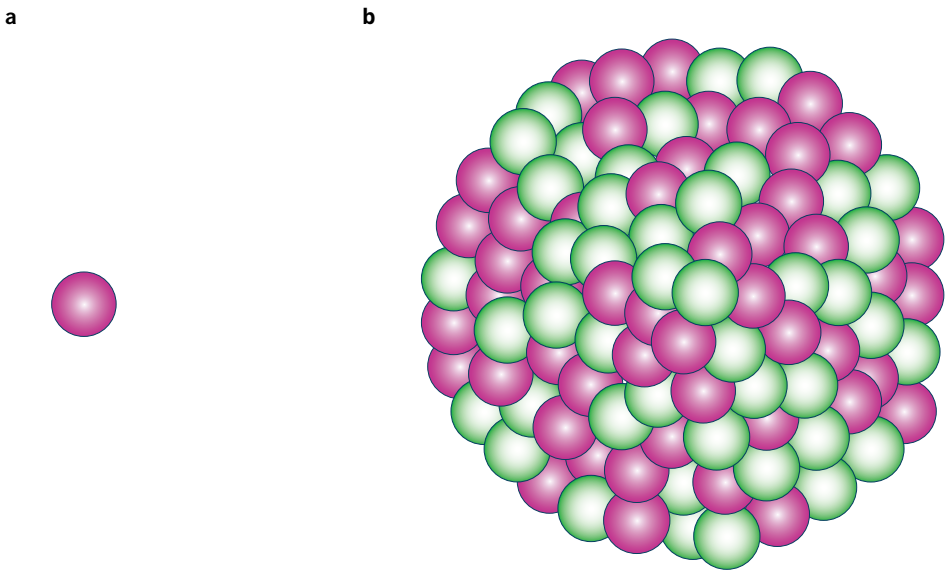


FIGURE 3.2.5 The relative sizes of (a) the hydrogen-1, and (b) the uranium-238 isotopes drawn to scale. Uranium-238 is just over eight times larger in radius than a proton.

The strong nuclear force

To overcome this apparent instability and keep the nucleus together, there must be another force operating that is larger than the repulsive force. This extra force is known as the **strong nuclear force** (SNF).

There are several important aspects of SNF:

- It is one of the four fundamental forces that exist in the universe. The others are the electromagnetic or coulomb force, gravity and the weak nuclear force.
- It is *mostly* an attractive force.
- It acts only in the nucleus on protons and neutrons.
- It acts at very short distances of up to 1 fm (10^{-15} m) on adjacent nucleons.

Think of the SNF as a piece of hoop-and-loop fastening tape (e.g. velcro) wrapped around the protons. Only when the protons are close enough will the tape attach and hold the protons together. If the protons are too far apart then the tape cannot stick and the protons will be forced away from each other. Figure 3.2.6 shows how the SNF holds the protons and neutrons together in a nucleus, and without it the nucleus would fly apart.

The more protons there are in a nucleus, the larger the repulsive force. This means that the SNF must also act on neutrons to keep the nucleus from flying apart. If more protons are added to a nucleus, then more neutrons must be added for the SNF to balance the coulomb force. For some nuclides, only one more or one fewer neutrons is the difference between stability and instability.

The strong nuclear force is an attractive force that acts on very close nucleons.

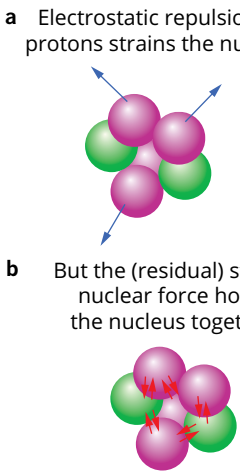


FIGURE 3.2.6 (a) The repulsive coulomb forces act on the protons (in pink) in a nucleus, tearing it apart, and (b) the SNF (shown here as red arrows) keeps the nucleus stable.

SEGRE PLOTS

A nuclide may have too many protons relative to the number of neutrons in its nucleus for it to be stable. For it to become stable, one proton is spontaneously turned into a neutron, with the release of energy and other particles. This is known as beta positive decay and will be discussed further in Module 3.3.

Similarly, if a nuclide has too many neutrons relative to the number of protons in its nucleus it will also be radioactive. For it to become stable, one neutron is spontaneously turned into a proton, with the release of energy and other particles. This is the reverse of the previous example and therefore it is called beta negative decay.

A Segre plot is a graph of neutron number versus atomic number for various isotopes.

A graph of every isotope's neutron number, N, versus its atomic number, Z, is called a **Segre plot** (Figure 3.2.7).

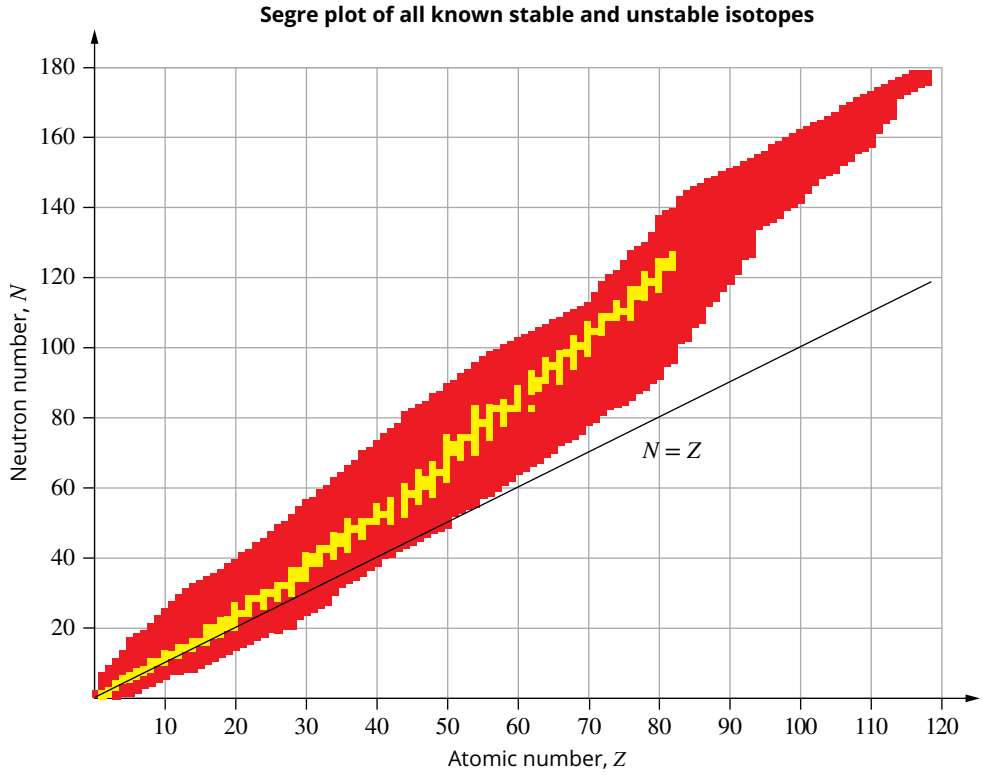


FIGURE 3.2.7 A graph of the neutron number, N, graphed against the atomic number Z, highlighting the stable nuclides (yellow) and radioactive nuclides (red). The black line represents nuclides that have an equal number of protons and neutrons.

In a Segre plot, yellow nuclides are stable, and the red nuclides are radioactive. Note that there are no stable nuclides beyond atomic number 82 (lead) and that there are no stable nuclides for atomic number 43 (technetium) or atomic number 61 (promethium). Nuclides located above any stable nuclide have too many neutrons, so they will become more stable by spontaneously losing neutrons. Nuclides below any stable nuclides have too many protons so they will lose protons to become stable.

The further away vertically from any stable nuclide, the more unstable a nuclide will be.

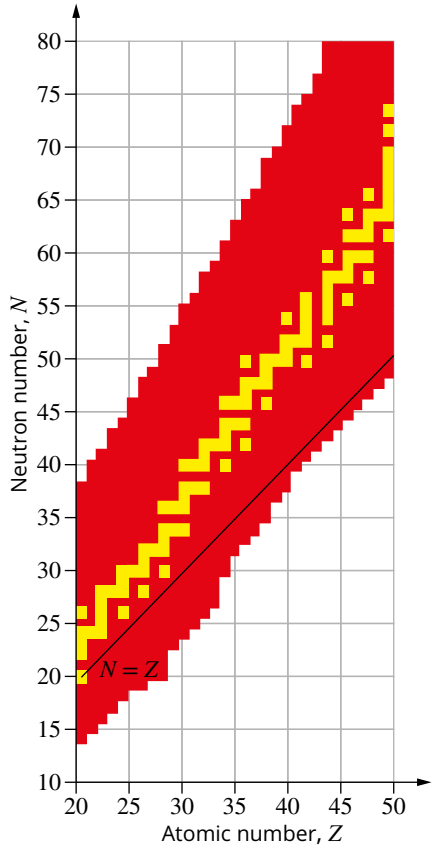
Notice that lighter isotopes (up to $Z = 10$) have the same number of neutrons as protons but, as the atomic number becomes greater than 10, the number of neutrons steadily becomes larger than the number of protons, up to about one-and-a-half times. This is seen in the upward trend away from the $N = Z$ line. This is because as the number of protons in a nucleus increases, the coulomb repulsive force increases, and more neutral particles are needed to balance that force so the SNF can act. There are only two stable nuclides that have more protons than neutrons ($^{1}_{1}\mathrm{H}$ and $^{3}_{2}\mathrm{He}$).

Worked example 3.2.1

USING A SEGRE PLOT

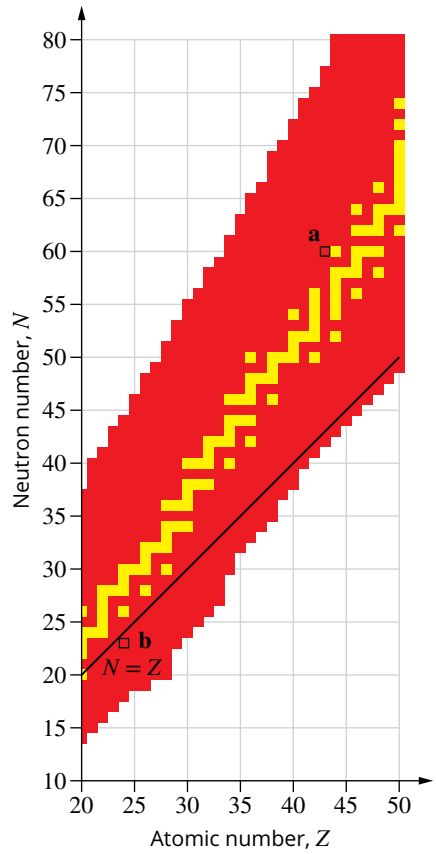
Use the part of the Segre plot given below to identify whether each nuclide is stable or radioactive. Predict how the nuclide will become more stable if it is radioactive.

Segre plot of all known stable and unstable isotopes from calcium ($Z = 20$) to tin ($Z = 50$)



a $^{103}_{43}\text{Tc}$

Thinking	Working
First, find each nuclide on the Segre plot and note its colour. To do this, the nuclide's notation is used to obtain the neutron number, N, and atomic number, Z. Remember that the bottom number is Z and the top number is the mass number, which is the atomic number plus the neutron number. Therefore the neutron number will be the top number minus the bottom number.	$Z = 43$ $N = 103 - 43 = 60$

Now that Z and N are known, they can be located on the Segre plot, remembering that Z is the horizontal axis and N is the vertical axis. It would be a good idea to highlight these on the graph.	**Segre plot of all know stable and unstable isotopes from calcium ($Z = 20$) to tin ($Z = 50$)** 
If a nuclide is above the main yellow line of stable nuclides then it has too many neutrons to be stable, so it will turn a neutron into a proton (i.e. lose a neutron), therefore $^{103}_{43}$Tc will turn a neutron into a proton to become stable.	$^{103}_{43}$Tc is radioactive and will try to become stable by turning a neutron into a proton.

b $^{47}_{24}$Cr

Thinking	Working
First, find the nuclide on the Segre plot and note its colour. Use the nuclide's notation to obtain the neutron number, N, and atomic number, Z. Remember that the bottom number is Z and the top number is the mass number, which is the atomic number plus the neutron number. Locate Z and N on the Segre plot above, remembering that Z is the horizontal axis and N is the vertical axis.	$Z = 24$ $N = 47 - 24 = 23$
If a nuclide is below the main yellow line then it has too many protons to be stable, so it will turn a proton into a neutron (i.e. lose a proton), therefore $^{47}_{24}$Cr will turn a proton into a neutron to become stable.	$^{47}_{24}$Cr is radioactive and will try to become stable by turning a proton into a neutron.

➤ Try yourself 3.2.1

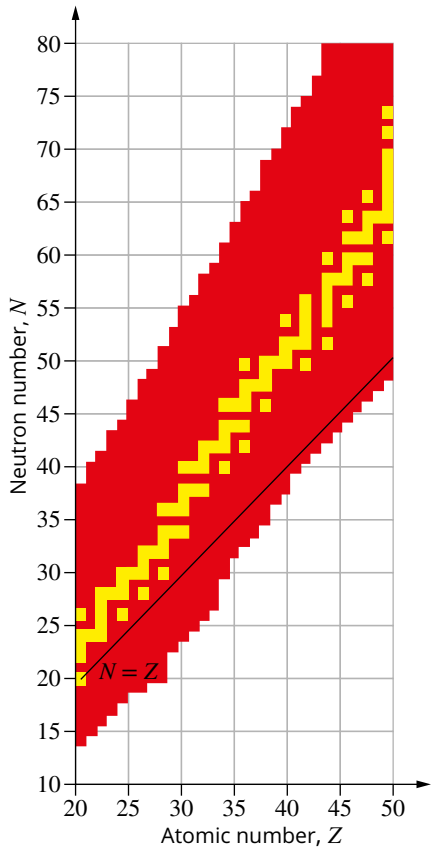
USING A SEGRE PLOT

Use the part of the Segre plot given below to identify whether each nuclide is stable or radioactive. Predict how the nuclide will become more stable if it is radioactive.

a $^{108}_{48}Cd$

b $^{80}_{30}Zn$

Segre plot of all known stable and unstable isotopes from calcium ($Z = 20$) to tin ($Z = 50$)



PA 1.2.1

3.2 Review

SUMMARY

- In a nucleus, protons repel each other due to the coulomb, or electrostatic force.
- The strong nuclear force keeps the nucleus together by acting as an attractive force on all nucleons.
- The strong nuclear force only acts over very short distances, in the order of 10^{-15} m.
- The radius of a nucleus increases with atomic number.
- The relative number of neutrons compared to the number of protons increases as the atomic number increases.
- A Segre plot shows all stable and radioactive nuclides known.
- A Segre plot is used to determine if a nuclide is stable and, if not, how it will become more stable.

KEY QUESTIONS

Retrieval

1 Recall the force that causes protons to repel.

2 Describe what a Segre plot shows.

3 Recall whether a natural isotope can be radioactive. If so, list two examples of such an isotope.

4 Recall whether a synthetic, or human-made, isotope can be stable. If so, give an example of one of these isotopes.

Comprehension

5 Explain how the strong nuclear force tries to keep the nucleus together.

6 $^{4}_{2}\text{He}$ is a very stable nuclide and contains two protons and two neutrons. $^{197}_{79}\text{Au}$ is also a very stable nuclide yet it contains many more neutrons than protons in its nucleus. Explain why both nuclides can be stable even though they have very different ratios of protons to neutrons in their nuclei.

7 Explain why isotopes with a large number of protons compared to the number of neutrons tend to be radioactive.

Analysis

8 Differentiate between a stable isotope and a radioisotope.

9 Bromine-79 is stable, but bromine-76 is radioactive. Imagine that you have just one atom of each isotope.

a Deduce whether their atomic numbers and mass numbers are the same or different. Justify your answers.

b Compare the way these atoms would interact chemically with other atoms.

10 $^{204}_{80}\text{Hg}$ is a stable nuclide of mercury and $^{205}_{80}\text{Hg}$ is a radioactive nuclide of mercury. Consider why the second nuclide is unstable.

11 There is empirical evidence to suggest that there are several values of the number of nucleons in a nucleus that tend to cause that particular nuclide to be exceptionally stable or less unstable than it would normally have been. These values are known as magic numbers and they are 2, 8, 20, 28, 50, 82 and 126. For example, $^{208}_{82}\text{Pb}$ is a stable isotope of lead and it has magic numbers in its nucleus because there are 82 protons and 126 neutrons, with those numbers being magic. Analyse these magic numbers and comment on the stability of the following nuclides. (You may use the Segre plot in Figure 3.2.7 to help you.)

a $^{16}_{8}\text{O}$

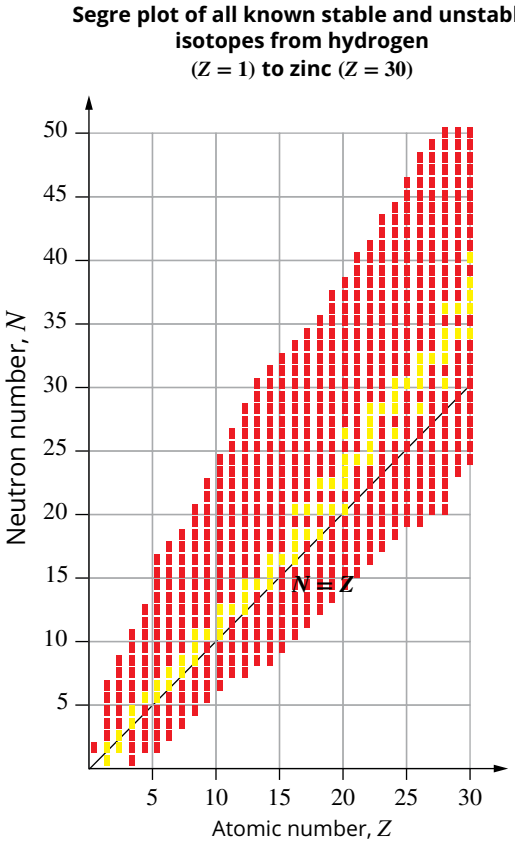
b $^{78}_{28}\text{Ni}$

c $^{100}_{50}\text{Sn}$

d $^{4}_{2}\text{He}$

e $^{39}_{20}\text{Ca}$

12 Consider the Segre plot below and the periodic table in Figure 3.2.2 on page 54 to help you answer the following.



a Identify how many stable isotopes have more protons than neutrons, and name them.

b Determine the mass number of the only stable isotope of beryllium ($Z = 4$).

c Identify the stable nuclides that have a neutron number of 22.

d Identify how many stable isotopes there are of iron ($Z = 26$).

e Identify the heaviest nuclide that has an equal number of protons and neutrons in its nucleus.

13 Deduce whether the following nuclides are stable or radioactive. For any nuclides that are radioactive, state how they might decay to give a more stable nuclide.

a $^{36}_{16}\text{S}$

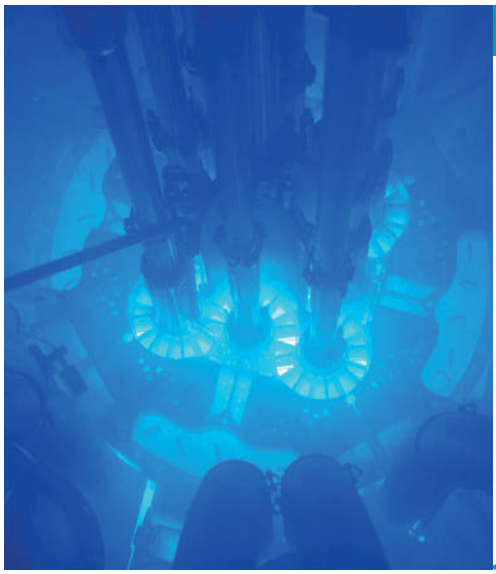
b $^{33}_{13}\text{Al}$

c $^{58}_{27}\text{Co}$

d $^{20}_{9}\text{F}$

e $^{1}_{0}\text{n}$

3.3 Nuclear decay



BY THE END OF THIS MODULE, YOU SHOULD BE ABLE TO:

- understand that nuclear decay is a process in which a radioactive nucleus becomes more stable by emitting energy, particles, or both
- distinguish between the three main types of radioactive decay—alpha, beta and gamma—in terms of energy, particles created and penetrating ability
- describe the particles produced in each of the three main types of radioactive decay
- describe ionising radiation and its effects
- understand that transmutation is the process of changing one element into another element
- write equations and predict the particles created in alpha, beta and gamma decay reactions
- understand that in any nuclear reaction both atomic number and mass number are conserved.

In the previous module it was explained why some nuclei are unstable by looking at general patterns in the numbers of protons and neutrons in the nucleus. In this module it will be shown that unstable nuclei become more stable by natural decay, in which unstable nuclei emit particles or energy or both.

ALPHA, BETA AND GAMMA DECAY

Any unstable nuclei will spontaneously decay into lighter nuclei. Heavier nuclei have more energy than they need and will become more stable by the emission of one or more particles, or electromagnetic waves. In this way, the unstable nucleus loses energy and becomes more stable.

In the early experiments with radioactivity, emissions from a sample of radium were directed through a magnetic field (Figure 3.3.1). The emissions followed three distinct paths, which suggested that three different forms of radiation were being emitted. The emissions each had different charges, masses and speeds.

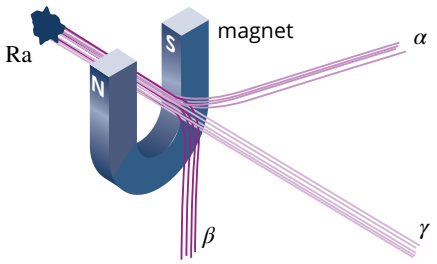


FIGURE 3.3.1 Applying a magnetic field shows that there are three different types of emissions from a radium source.

Transmutation

In many types of decay, a radioactive nucleus will lose one or more particles to become stable. The nucleus that is unstable is known as the **parent nucleus**. The particles that the parent nucleus emits may be any subatomic particle, leaving behind a nucleus called the **daughter nucleus**.

If the parent nucleus loses a proton or a neutron, the mass number of the daughter nucleus will be different. If the parent nucleus loses a proton, then the atomic number of the daughter nucleus will be different, which means that a new element has been created. When this occurs naturally, the process of creating a new element is called **transmutation** or **nuclear transmutation**. Transmutation occurs naturally in decay reactions, but it can be forced to occur as **artificial transmutation** in particle accelerators and nuclear reactors.

Transmutation is the process of creating a new element by changing the number of protons in a nucleus.

Worked example 3.3.1a

TRANSMUTATION 1

Molybdenum-101 is a radioactive isotope of the element molybdenum. It becomes more stable via a decay process in which one of its neutrons spontaneously turns into a proton. Write the daughter nucleus formed in nuclide and isotope notation.	
Thinking	**Working**
Molybdenum-101 can also be written as $^{101}_{42}$Mo. From this, the number of protons and neutrons in the nuclide can be determined. (The periodic table of elements is shown in Figure 3.2.2.)	$Z = 42$ $A = 101$ So, $N = A - Z = 101 - 42 = 59$
One of the neutrons of molybdenum-101 turns into a proton. This means that the number of neutrons in the daughter nucleus decreases by one, and the number of protons increases by one.	New N = old $N - 1 = 59 - 1 = 58$ New Z = old $Z + 1 = 42 + 1 = 43$
From the periodic table in Figure 3.2.2, it is seen that atomic number 43 is technetium, Tc.	$Z = 43$ is technetium, Tc
Write the isotope mass number, which is the sum of the atomic number and neutron number.	$A = Z + N = 43 + 58 = 101$
Write the nuclide using $^{A}_{Z}$X notation.	$^{101}_{43}$Tc or ^{101}Tc
Write using isotope name notation.	Technetium-101

Worked example 3.3.1b

TRANSMUTATION 2

Americium-241 is also radioactive and is used in non-photoelectric smoke detectors. It decays by the emission of two protons and two neutrons.	
a Write the daughter nucleus formed in nuclide and isotope notation.	
Thinking	**Working**
Americium-241 can also be written as $^{241}_{95}$Am. From this the number of protons and neutrons in this nuclide can be determined. (The periodic table of elements is shown in Figure 3.2.2.)	$Z = 95$ $A = 241$ So, $N = A - Z = 241 - 95 = 146$
Americium-241 emits two protons and two neutrons in its decay process. This means that $^{241}_{95}$Am loses two protons and two neutrons from its nucleus. Its daughter nuclide will have an atomic number two less than 95 and a neutron number two less than 146.	New N = old $N - 2 = 146 - 2 = 144$ New Z = old $Z - 2 = 95 - 2 = 93$
From the periodic table in Figure 3.2.2, it is seen that atomic number 93 is neptunium, Np.	$Z = 93$ is neptunium, Np

Write the isotope mass number, which is the sum of the atomic number and neutron number.	$A = Z + N = 93 + 144 = 237$
Write the nuclide is using ${}^{A}_{Z}X$ notation.	${}^{237}_{93}Np$ or ${}^{237}Np$
Write using isotope name notation.	Neptunium-237
b Is the daughter nucleus stable or radioactive?	
Thinking	**Working**
Neptunium has an atomic number greater than 82, and, from Figure 3.2.2, it is seen that this means all neptunium isotopes are radioactive. Also, the Segre plot in Figure 3.2.7 shows that there are no stable (i.e. yellow) isotopes beyond atomic number 82, so neptunium-237 is radioactive.	Neptunium-237 is radioactive because its atomic number, 93, is higher than the heaviest stable element, lead-82.

➤ Try yourself 3.3.1

TRANSMUTATION

The following isotopes are radioactive and each decays via the process described in brackets. Write the nuclide and isotope of the daughter nucleus formed and determine if it is stable. You may use the periodic table in Figure 3.2.2 on page 54, or Segre plot in Figure 3.2.7 on page 56 to help you.

a ${}^{23}_{12}Mg$ (decays when a proton spontaneously turns into a neutron)

b ${}^{8}_{3}Li$ (decays when a neutron spontaneously turns into a proton)

c ${}^{222}_{86}Rn$ (decays when two protons and two neutrons are emitted)

You might have noticed that in each of the decay examples involving protons and neutrons turning into each other the mass number did not change. This is because both particles are nucleons and these nuclei are not changing the *total* number of nucleons, just the number of each type.

Ionising radiation

In Module 3.2, you were shown some examples of particles that are changed or emitted from a radioactive nucleus. As well as particles, an unstable nucleus can also emit energy in the form of electromagnetic radiation, or waves (typically X-rays, gamma rays and some ultraviolet radiation). This radiation is often very high in energy and when it interacts with matter it can completely remove electrons from an atom. This process is known as **ionisation** and the radiation that causes it is known as **ionising radiation**.

Ionising radiation is quite dangerous to living tissue, because the ionised atoms that are left behind after the radiation are very reactive and seek out molecules to combine with. If this occurs in the nuclei of vulnerable cells, unwanted chemical reactions can take place, which can cause cancer.

Alpha particles are the nuclei of helium-4 atoms, and are therefore strongly positively charged. If an alpha particle passes through air, it will remove two electrons from any oxygen or nitrogen molecule in the air and leave it with a positive charge. The alpha particles are said to have ionised the air (Figure 3.3.3).

Lower-energy electromagnetic radiation such as radio waves, microwaves, infrared, visible light and ultraviolet-A radiation is non-ionising. Exposure to this radiation, even in significant amounts, has no serious consequences. Non-ionising radiation does not have enough energy to change the chemistry of the atoms and molecules that make up body cells.

Ionising radiation is a particle or type of energy that can cause electrons to be removed from an atom thereby leaving it charged. Alpha particles, beta particles, neutrons and high-energy electromagnetic radiation such as ultraviolet rays, X-rays and gamma rays are all examples of ionising radiation. The universal symbol for ionising radiation is shown in Figure 3.3.2.

FIGURE 3.3.2 The international symbol for ionising radiation

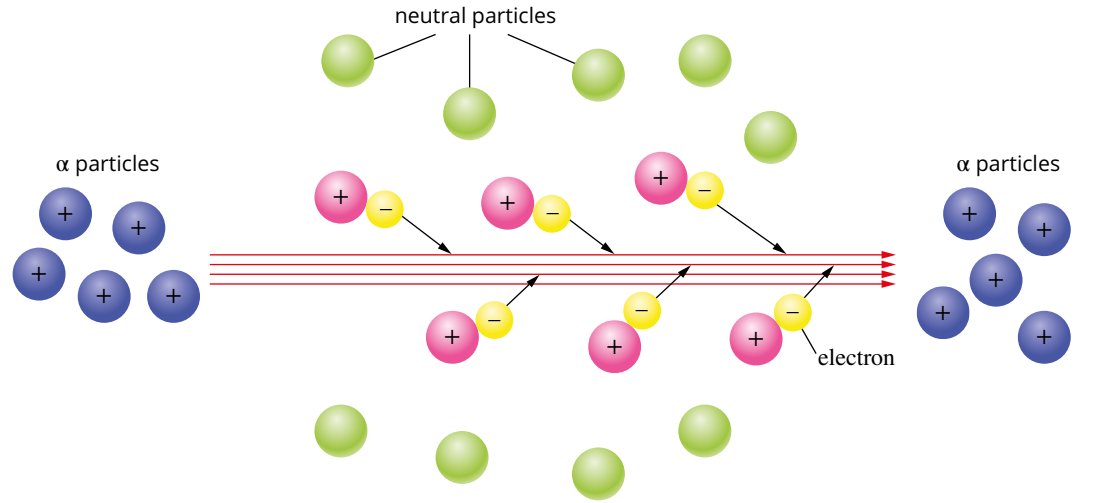


FIGURE 3.3.3 Alpha particles ionise air particles.

Types of decay

There are three main types of natural nuclear decay. In all cases, the daughter nucleus is left with less energy than the parent nucleus. They are, in order of increasing ionisation ability:

- alpha decay
- beta decay
- gamma decay.

Table 3.3.1 summarises three main types of natural nuclear decay in terms of their charge, mass, ionising ability and ability to pass through matter (**penetrating ability**).

TABLE 3.3.1 The three main types of natural decay. Note that beta decay can be either beta$^+$ or beta$^-$ depending on the particles involved.

Decay type	Symbol	Particle or radiation	Charge	Mass	Emitted by	Ionisation ability	Penetrating ability
alpha	$^4_2$He or $^4_2\alpha$	particle (nucleus of helium-4 isotope)	+2	6.644657×10^{-27} kg 4.001506 u	mostly radioactive isotopes heavier than lead ($Z = 82$)	high	low
beta$^+$	$^0_1\beta$ or $^0_1$e	particle (high speed positron, or positively charged electron)	+1	$9.109\,384 \times 10^{-31}$ kg 5.485799×10^{-4} u	most radioactive nuclei	medium	medium
beta$^-$	$^0_{-1}\beta$ or $^0_{-1}$e	particle (high speed electron)	–1	$9.109\,384 \times 10^{-31}$ kg 5.485799×10^{-4} u	most radioactive nuclei	medium	medium
gamma	$^0_0\gamma$	gamma ray	0	0	most radioactive nuclei	low	high

The penetrating ability of each of the decay types is summarised in Figure 3.3.4.

Other types of nuclear decay include electron capture (in which an inner electron is captured by the unstable nucleus causing a proton to turn into a neutron), or a single proton or neutron being emitted by the nucleus. These are relatively rare when compared to alpha, beta and gamma decay.

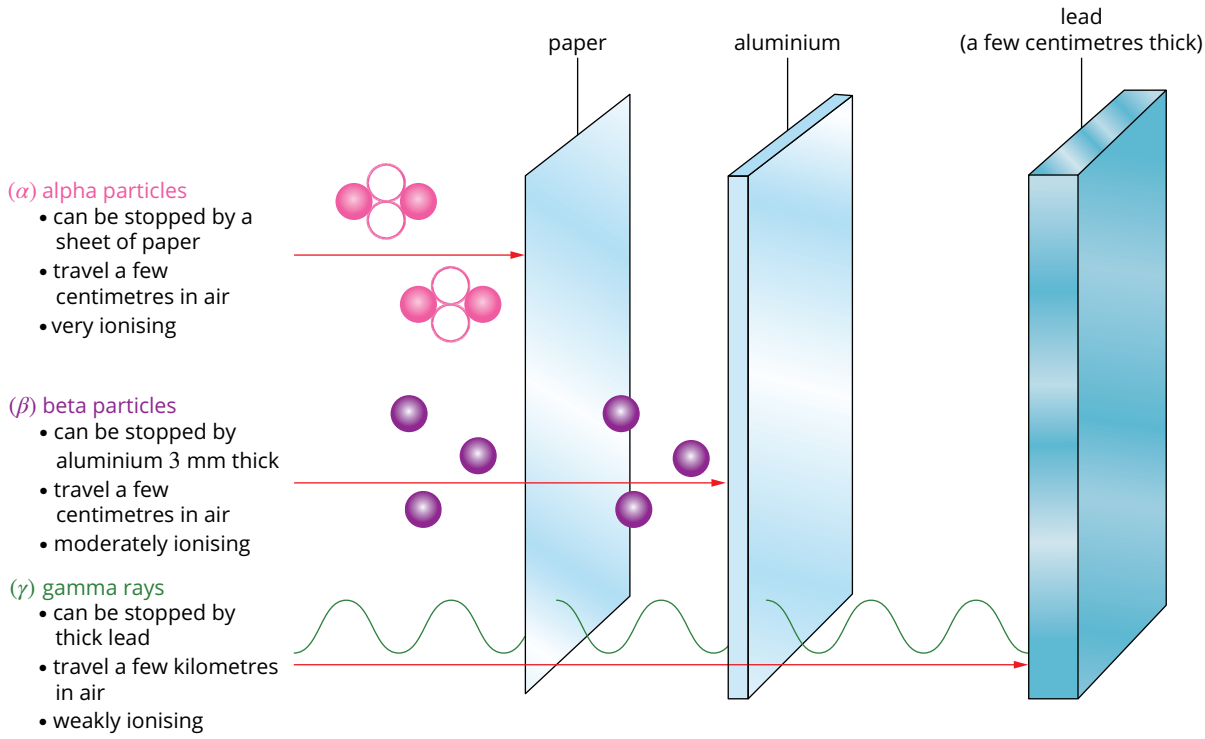


FIGURE 3.3.4 The penetrating abilities of alpha, beta and gamma radiation

Alpha decay

Alpha decay, or **alpha radiation**, typically occurs when a heavy, radioactive nucleus becomes more stable by emitting an alpha particle. The alpha particle is the nucleus of the helium-4 atom, which contains two protons and two neutrons and therefore has a doubly positive charge. It is one of the most stable particles in the universe.

An example of alpha decay is shown in Figure 3.3.5, in which a radioactive americium-241 nucleus decays by emitting an alpha particle to leave behind the daughter nucleus neptunium-237.

Of the types of decay:
- alpha radiation has the lowest penetrating ability but the highest ionising ability.
- gamma radiation has the highest penetrating ability but the lowest ionising ability.

Alpha decay occurs when a radioactive nucleus emits an alpha particle, $^4_2$He, a particle with two protons and two neutrons. The atomic number of the daughter nucleus decreases by two, and the mass number decreases by four.

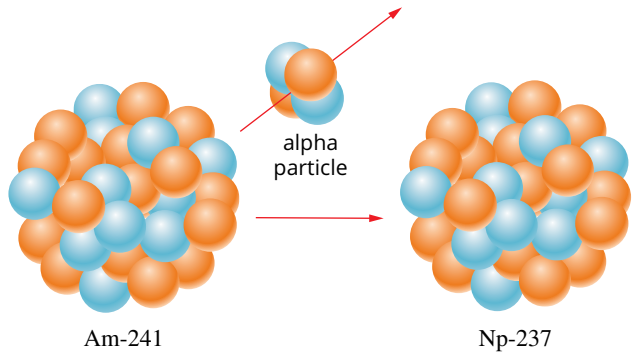


FIGURE 3.3.5 In this example of alpha particle decay, a radioactive nucleus gains some stability by expelling an alpha particle, or the nucleus of a helium-4 isotope.

During alpha decay, the radioactive parent nucleus emits an alpha particle, which carries away some of the excess energy. The resulting daughter nucleus has two fewer protons and two fewer neutrons. The mass number of the daughter nucleus is therefore four units less.

Alpha decay was first observed by Rutherford in 1899 and was used in his famous gold foil experiment. The alpha particles emitted by radioactive nuclei are the heaviest particle that can be emitted by a nucleus in any decay reaction. The large mass means that the alpha particle is relatively slow moving (up to 10% of the speed of light, or 30 000 km s^{-1}) and therefore has a lower than usual energy when compared to the other types of decay.

Alpha particles can be stopped by only a few centimetres of air, so they do not have a high penetrating ability and are generally safe to humans if exposure is outside of the body. If alpha-emitting nucleus are ingested into the body, then the proximity of the source of alpha particles to living tissue can be hazardous.

An alpha particle has low energy as well as a double positive charge, so it can ionise nearby atoms very easily. In fact, the majority of helium found on Earth is from the alpha decay of heavy radioactive nuclei underground. The alpha particles emitted by this decay process ionise the oxygen or nitrogen in the air to make neutral helium gas.

Worked example 3.3.2

ALPHA DECAY

Identify the isotope of the daughter nucleus when plutonium-244 alpha decays.	
Thinking	**Working**
Plutonium-244 can also be written as $^{244}_{94}$Pu. From this the number of protons and neutrons can be determined.	$Z = 94$ $A = 244$ So, $N = A - Z = 244 - 94 = 150$
Alpha decay occurs when the parent nucleus loses two protons and two neutrons.	New N = old $N - 2 = 150 - 2 = 148$ New Z = old $Z - 2 = 94 - 2 = 92$
From the periodic table in Figure 3.2.2 it is seen that atomic number 92 is uranium, U.	$Z = 92$ is uranium, U
Write the isotope mass number, which is the sum of the atomic number and neutron number.	$A = Z + N = 92 + 148 = 240$
Write the nuclide is using $^{A}_{Z}$X notation.	$^{240}_{92}$U or ^{240}U
Write using isotope name notation.	Uranium-240

➤ Try yourself 3.3.2

ALPHA DECAY

Alpha decay mostly occurs in nuclei heavier than atomic number 82, but it also can occur in much lighter nuclei. $^{8}_{4}$Be is an example of a very light radioactive nuclide that alpha decays.

Determine the daughter nuclide produced after this decay and name this nuclide.

Beta decay

Beta decay is the second type of natural decay that a radioactive nucleus undergoes to become more stable. It has two modes, which involve a spontaneous change of a nucleon:

- In **beta negative radiation** a neutron changes into a proton.
- In **beta positive radiation** a proton changes into a neutron.

The weak nuclear force (WNF) is responsible for both types of decay, as they both allow the parent nucleus to become more stable by rearranging the number of protons and neutrons into a more energy-favourable ratio.

An example of beta negative radiation is shown in Figure 3.3.6, in which caesium-137 decays into barium-137 by the emission of a beta negative particle (a fast-moving electron) as well as an antineutrino.

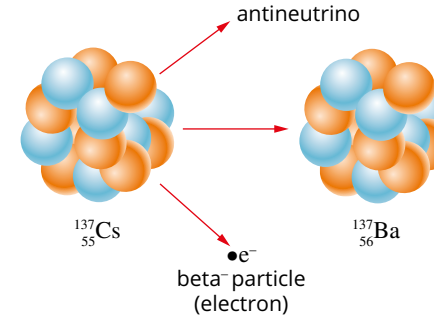


FIGURE 3.3.6 In this example of a beta negative decay, a radioactive nucleus gains some stability by emitting a beta negative particle (an electron) along with an antineutrino.

An example of beta positive radiation is shown in Figure 3.3.7, in which carbon-11 decays into boron-11 by the emission of a beta positive particle (a fast-moving **positron**) as well as a neutrino.

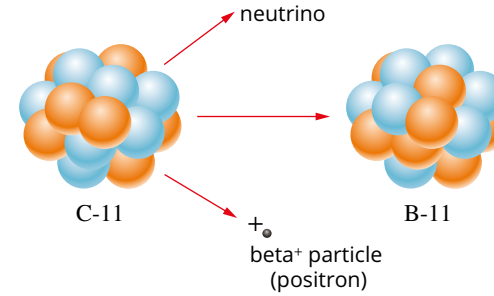


FIGURE 3.3.7 In this example of a beta positive decay, a radioactive nucleus gains some stability by emitting a beta positive particle (a positron) along with a neutrino.

- A **neutrino** ($^{0}_{0}\nu_{e}$) is a tiny, neutral and almost massless particle that is always seen in association with a positron.
- An **antineutrino** ($^{0}_{0}\overline{\nu}_{e}$) has the almost the same properties as a neutrino but is always seen in association with an electron.

Both of these particles are now known to exist in gigantic numbers in the universe.

First observed in 1899 also by Rutherford, beta negative radiation occurs when the atomic number of the daughter nucleus increases by one and the neutron number decreases by one, giving no net change to the mass number of the daughter nucleus. This is a typical decay pattern for radioactive nuclei that have too many neutrons for the number of protons. These nuclei are *above* the yellow-coloured nuclei in the Segre plot in Figure 3.2.7.

In 1934, French physicists Frederic and Irene Joliot-Curie (the daughter of Marie) first observed beta positive radiation. This occurs when one proton in the nucleus turns into a neutron. The atomic number of the daughter nucleus decreases by one and the neutron number increases by one, also giving no net change to the mass number of the daughter nucleus. This is a typical decay pattern for radioactive nuclei that have too many protons for the number of neutrons, i.e. they are *below* the yellow nuclei in the Segre plot in Figure 3.2.7.

In both types of beta decay, when a nucleon spontaneously changes, the parent nucleus emits two other particles to carry away excess energy: a beta particle and a neutrino or antineutrino. The **beta particle** moves at approximately 99% of the speed of light.

- In beta negative radiation, the beta particle is a negatively charged electron ($^{0}_{-1}\beta$ or $^{0}_{-1}e$).
- In beta positive radiation, the beta particle is a positively charged positron ($^{0}_{1}\beta$ or $^{0}_{1}e$).

A positron is a particle with the same properties as the electron, except that it has a positive charge and does not make up everyday matter. Note that the electron that is emitted during beta negative decay comes directly from the nucleus, not from the electron cloud surrounding the nucleus.

The beta particle has a single positive or negative charge, so it moves very fast, is about 8000 times lighter than an alpha particle and its penetrating power is greater than that of the alpha particle. The beta particle can travel through a few metres of air or a few millimetres of aluminium foil before being absorbed.

The high speed of the beta particle also does not allow for it to ionise nearby atoms very well.

A summary of the two modes of beta decay is given in Table 3.3.2.

TABLE 3.3.2 A summary of the two modes of beta decay

Type of beta decay	Nuclear process	Daughter nucleus atomic number	Daughter nucleus neutron number	Daughter nucleus mass number	Particles emitted
beta positive	one proton changes into one neutron	one less than the parent's atomic number	one more than the parent's neutron number	same as parent nucleus	positron and neutrino (${}^{0}_{1}\beta$ and ${}^{0}_{0}\nu_e$)
beta negative	one neutron changes into one proton	one more than the parent's atomic number	one less than the parent's neutron number	same as parent nucleus	electron and antineutrino (${}^{0}_{-1}\beta$ and ${}^{0}_{0}\overline{\nu}_e$)

Beta negative decay occurs when a radioactive nucleus emits a high-speed electron, ${}^{0}_{-1}\beta$, and an antineutrino, ${}^{0}_{0}\overline{\nu}_e$. The atomic number of the daughter nucleus increases by one but the mass number stays the same.

Beta positive decay occurs when a radioactive nucleus emits a high-speed positron, ${}^{0}_{1}\beta$, along with a neutrino, ${}^{0}_{0}\nu_e$. The atomic number of the daughter nucleus decreases by one but the mass number stays the same.

Worked example 3.3.3

BETA DECAY

State the daughter nucleus and the particles emitted when the following beta decays occur.

a Caesium-137 decays via beta negative decay.

Thinking	Working
Caesium-137 can also be written as ${}^{137}_{55}$Cs. From this the number of protons and neutrons can be determined.	$Z = 55$ $A = 137$ So, $N = A - Z = 137 - 55 = 82$
Beta negative decay occurs when a neutron in the parent nucleus turns into a proton.	New N = old $N - 1 = 82 - 1 = 81$ New Z = old $Z + 1 = 55 + 1 = 56$
From the periodic table in Figure 3.2.2 (page 54), it is seen that atomic number 56 is barium, Ba.	$Z = 56$ is barium, Ba
To write the daughter isotope, the mass number is also needed, which is the sum of the atomic number and neutron number.	$A = Z + N = 56 + 81 = 137$
Write the nuclide using the ${}^{A}_{Z}$X notation.	${}^{137}_{56}$Ba or ^{137}Ba
Write the element using name notation.	Barium-137
This is beta negative decay, so the particles emitted during this process are an electron and antineutrino.	An electron and antineutrino (${}^{0}_{-1}\beta$ and ${}^{0}_{0}\overline{\nu}_e$) are emitted by the parent nucleus.

b Copper-64 decays via beta positive decay.	
Thinking	**Working**
Copper-64 can also be written as $^{64}_{29}$Cu. From this the number of protons and neutrons can be determined.	$Z = 29$ $A = 64$ So, $N = A - Z = 64 - 29 = 35$
Beta positive decay occurs when a proton in the parent nucleus turns into a neutron.	New N = old $N + 1 = 35 + 1 = 36$ New Z = old $Z - 1 = 29 - 1 = 28$
From the periodic table in Figure 3.2.2, it is seen that atomic number 28 is nickel, Ni.	$Z = 28$ is nickel, Ni
To write the daughter isotope, the mass number is also needed, which is the sum of the atomic number and neutron number.	$A = Z + N = 28 + 36 = 64$
Write the nuclide using $^{A}_{Z}$X notation.	$^{64}_{28}$Ni or ^{64}Ni
Write the element using name notation.	Nickel-64
This is beta positive decay, so the particles emitted during this process are a positron and a neutrino.	A positron ($^{0}_{1}\beta$) and a neutrino and ($^{0}_{0}\nu_e$) are emitted by the parent nucleus.

➤ Try yourself 3.3.3

BETA DECAY

Predict the daughter nuclides and the particles emitted when the following isotopes decay via the processes indicated.

a Carbon-11 decays via beta positive decay.

b A single neutron outside an atom will decay via beta negative decay.

Gamma decay

Gamma decay, or **gamma radiation**, was first observed by the French physicist Paul Villard in 1900 and is the third type of naturally occurring decay that allows a radioactive isotope to become more stable. Rather than the nucleus undergoing a change in the number of nucleons, gamma decay reduces the amount of energy an unstable nucleus has by emitting a **gamma ray**. The gamma ray is a very energetic part of the electromagnetic spectrum that travels at the speed of light ($3.00 \times 10^{8}\,\text{m s}^{-1}$) and carries off some of the excess energy of the radioactive nucleus, thereby making the nucleus more stable.

An example of gamma decay is shown in Figure 3.3.8, where a radioactive plutonium-240 nucleus decays by emitting a gamma ray without any change in the number of nucleons.

Because they are an electromagnetic wave, gamma rays have no charge and no mass, so they do not cause a change in the number of protons or neutrons in the nucleus. Gamma rays are the most energetic of the particles or radiation emitted by a radioactive nucleus, and therefore have a very high penetrating ability. This is so high that a few centimetres of lead are required to stop any gamma rays.

The direct ionising ability of gamma rays is quite low, as they are neutral and move at the speed of light. In fact, they will usually pass straight through tissue. They do, however, cause indirect ionisation through interaction with atoms and the subsequent beta particles they create.

Gamma decay occurs when an energetic, radioactive nucleus emits a gamma ray, $^{0}_{0}\gamma$. There is no change to the mass number or atomic number of the daughter nuclide.

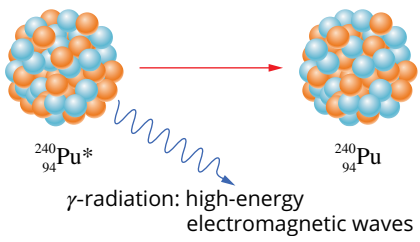


FIGURE 3.3.8 An example of gamma decay, by which a radioactive nucleus gains some stability by emitting energy in the form of a gamma ray. Note that the * indicates that a particular nuclide has an excess of energy when compared to the daughter nuclide.

DECAY REACTIONS

Alpha, beta and gamma decay can be conveniently written as nuclear equations, which show the atomic and mass numbers of the parent nucleus, daughter nucleus and emission products. In nuclear equations, the initial nuclides (reactants) are always on the left-hand side of an arrow showing the direction of the decay; the daughter nuclides and other products on the right-hand side.

> **i** A decay equation is a short way of writing the reactants and products of any decay reaction. The mass numbers and atomic numbers are always conserved.

Alpha decay equations

Alpha decay equations are relatively simple to write because they only have one reactant and two products plus energy.

An example of a nuclear equation is the alpha decay of uranium-238 (Figure 3.3.9).

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

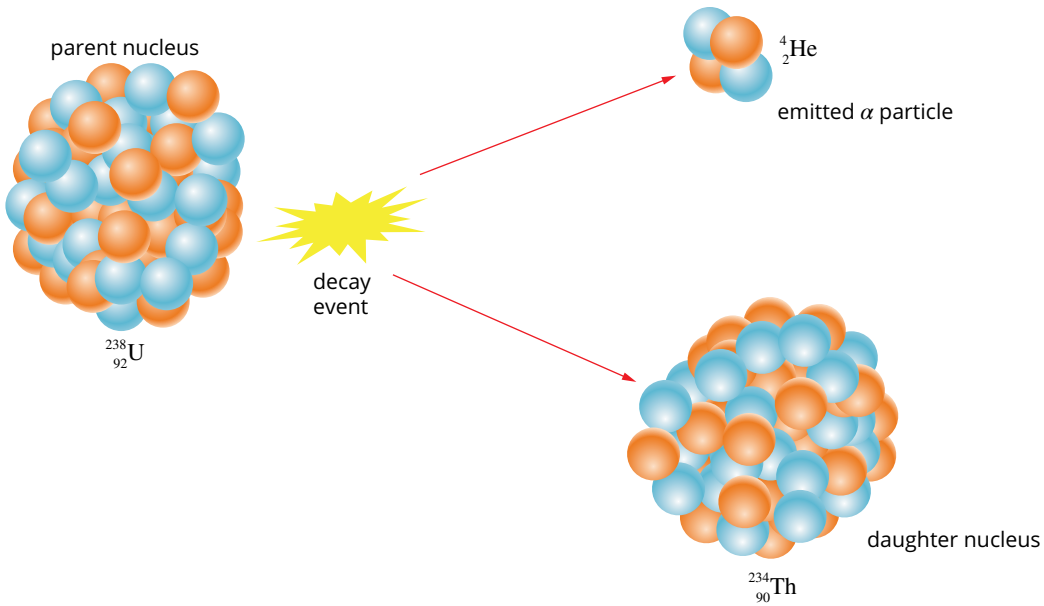


FIGURE 3.3.9 The alpha decay of uranium-238

This is a decay reaction, so there is only one reactant, the uranium-238. This is a natural decay process, so the arrow indicates that this reaction will take place to release energy and give two products: thorium-234 as the daughter isotope and the alpha particle ($^{4}_{2}$He).

Note that in nuclear equations the mass numbers and atomic numbers are all conserved. This means that the total of the mass numbers on each side of the arrow are equal, and the total of the atomic numbers on each side are equal.

Because any decay reaction is going to result in the daughter nucleus becoming more stable by losing energy, energy appears on the right-hand side of the equation.

Beta decay equations

In beta decay equations, the conservation of mass and atomic numbers are especially important because there is a change in atomic number but no change in the mass number. Also keep in mind that in nuclear physics an electron has an atomic number of –1.

Beta decay equations also have one reactant, but they have three products plus energy.

An example of a beta decay reaction is shown below in Figure 3.3.10.

$$^{60}_{27}\text{Co} \rightarrow {}^{60}_{28}\text{Ni} + {}^{0}_{-1}\beta + {}^{0}_{0}\overline{\nu}_{e} + \text{energy}$$

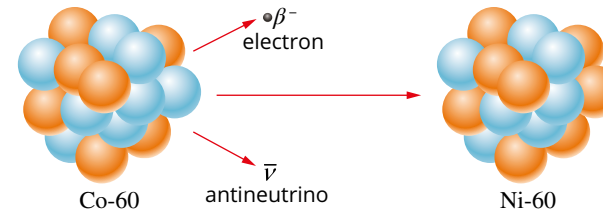


FIGURE 3.3.10 The beta negative decay of cobalt-60

Again, with any decay equation there is one reactant: the cobalt-60 isotope. You can see from the products that this is a beta negative decay because the daughter nucleus has gained a proton, and the other emitted particles are an electron and antineutrino.

Inside the cobalt-60 nucleus, a single neutron is undergoing the following reaction:

$$^{1}_{0}\text{n} \rightarrow {}^{1}_{1}\text{H} + {}^{0}_{-1}\beta + {}^{0}_{0}\overline{\nu}_{e} + \text{energy}$$

An isotope that decays via beta positive decay is protactinium-230. This is shown in Figure 3.3.11 with the equation:

$$^{230}_{91}\text{Pa} \rightarrow {}^{230}_{90}\text{Th} + {}^{0}_{1}\beta + {}^{0}_{0}\nu_{e} + \text{energy}$$

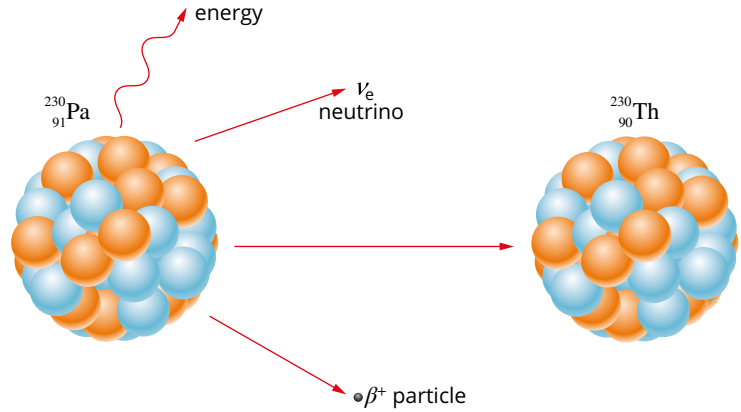


FIGURE 3.3.11 The beta positive decay of protactinium-230

In this reaction, mass numbers are conserved: 230 = 230 + 0 + 0

The atomic numbers are also conserved: 91 = 90 + 1 + 0

With all beta decay the mass number does not change, so you expect the two emitted particles—the beta particle and neutrino/antineutrino—to have very little mass compared to the parent and daughter nuclei. Inside the protactinium-230 nucleus, one proton undergoes the following reaction:

$$^{1}_{1}\text{H} \rightarrow {}^{1}_{0}\text{n} + {}^{0}_{1}\beta + {}^{0}_{0}\nu_{e} + \text{energy}$$

Gamma decay equations

Gamma decay equations are the most straightforward decay equations to write. This is because there is no change in mass number or atomic number, so the parent and daughter nuclei are basically the same apart from a decrease in the energy of the parent nucleus.

To distinguish the parent nucleus from the daughter nucleus in gamma decay, an asterisk (*) is used to indicate that the parent nucleus has more energy than the daughter nucleus.

An example of a gamma decay occurs when xenon-131* emits a gamma ray to become stable, as shown in Figure 3.3.12. The equation is:

$$^{131}_{54}\text{Xe}^{*} \rightarrow {}^{131}_{54}\text{Xe} + {}^{0}_{0}\gamma + \text{energy}$$

The element xenon has not changed in gamma decay; the mass number is 131, and the atomic number is 54. The * is used to indicate the unstable $^{131}_{54}\text{Xe}^{*}$ nucleus before it emits the gamma ray and energy and becomes stable.

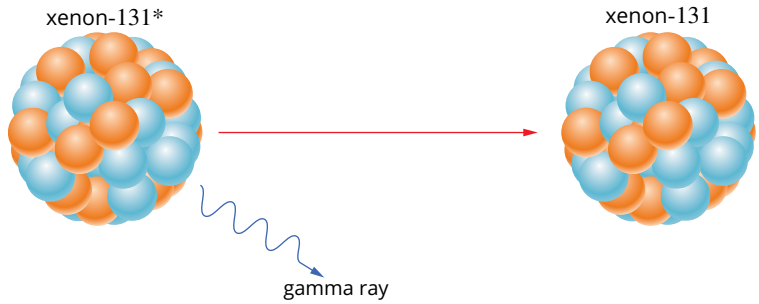


FIGURE 3.3.12 The gamma decay of xenon-131*

Worked example 3.3.4

RADIOACTIVE DECAY 1

Strontium-90 decays by radioactive emission to form yttrium-90. The equation for this is:

$$^{90}_{38}\text{Sr} \rightarrow {}^{90}_{39}\text{Y} + \text{X}$$

where X is the emitted particle or particles. Determine the atomic and mass numbers for X and identify the type of radiation being emitted.

Thinking	Working
The mass numbers of 90 are already balanced so the mass number of X, A_x, must be 0.	Left-hand side $A = 90$ Right-hand side $A = 90 + A_x$ $90 = 90 + A$ $A = 90 - 90 = 0$
The atomic numbers are not balanced, so the atomic number of X, Z_X, needs to be found.	Left-hand side $Z = 38$ Right-hand side $Z = 39 + Z_x$ $38 = 39 + Z_x$ $Z_x = 38 - 39 = -1$
X has atomic number of –1, and a mass number of zero.	X is an electron, $^{0}_{-1}\beta$, and is emitted in beta negative radiation along with an antineutrino, $^{0}_{0}\overline{\nu}\text{e}$.

➤ Try yourself 3.3.4

RADIOACTIVE DECAY 1

Polonium-218 decays by emitting an alpha particle followed by a gamma ray. The nuclear equation of the alpha decay is:

$$^{218}_{84}\text{Po} \rightarrow \text{X} + {}^{4}_{2}\alpha$$

Determine the atomic number and mass number of X, and then use the periodic table in Figure 3.2.2 to identify the element.

Worked example 3.3.5

RADIOACTIVE DECAY 2

Determine the unknown particles or nuclei in the following incomplete reactions and identify the type of decay that is occurring.	
a $^{192}_{78}Pt^* \rightarrow X + {}^{0}_{0}\gamma + \text{energy}$	
THINKING	**WORKING**
The mass numbers have to be balanced, so 192 on the left-hand side has to equal the sum of the mass numbers on the right-hand side, with A_x being the mass number of X.	$192 = A_x + 0$ The mass number of X is 192.
Similarly, the atomic number of X will be 78. This means that the decay is gamma decay (also indicated by the * next to the parent nucleus).	The atomic number of X is 78, and the decay type is gamma.
X is the more stable nuclide $^{192}_{78}Pt$.	X is $^{192}_{78}Pt$
b $^{47}_{24}Cr \rightarrow {}^{47}_{23}V + X + {}^{0}_{0}\nu_e + \text{energy}$	
THINKING	**WORKING**
On the right-hand side of the equation you see a neutrino, ${}^{0}_{0}\nu_e$. Neutrinos are always associated with positrons, which means that this decay is beta positive decay.	This decay type is beta positive decay because neutrinos are always associated with positrons.
So X will be a positron, ${}^{0}_{1}\beta$.	X is a positron, or ${}^{0}_{1}\beta$.

➤ Try yourself 3.3.5

RADIOACTIVE DECAY 2

Determine the unknown particles or nuclei in the following incomplete reactions and identify the type of decay that is occurring.

a $^{242}_{96}Cm \rightarrow X + {}^{4}_{2}He + \text{energy}$

b $^{35}_{16}S \rightarrow {}^{35}_{17}Cl + X_1 + X_2 + \text{energy}$

c $X_1 \rightarrow {}^{290}_{116}Lv + {}^{4}_{2}He + X_2$

Decay series

A decay series is a sequence of various radioactive decays by successive daughter nuclei that eventually forms a stable nuclide.

Every radioactive nucleus has an excess of energy. The process of decay removes some of that energy so that a more stable daughter nucleus remains. Quite often the daughter nucleus itself is also radioactive, so it will also decay, producing a 'grand'-daughter nucleus. This is known as a **decay series** and will always continue if the successive daughter nuclei are radioactive. A decay series ends when the daughter nucleus is stable. Note that most radioactive isotopes have several different pathways of obtaining a stable isotope and many of them involve many individual decay reactions.

Examples of decay series include the decay series of uranium-238, which ends in the stable isotope lead-206, and of actinium-235, which eventually ends with lead-207.

The decay of thorium-232 is an example of a decay series that has 10 distinct decay reactions. It ends in the stable isotope lead-208:

$$^{232}_{90}\text{Th} \rightarrow {}^{228}_{88}\text{Ra} + {}^{4}_{2}\text{He} + \text{energy}$$

$$^{228}_{88}\text{Ra} \rightarrow {}^{228}_{89}\text{Ac} + {}^{0}_{-1}\beta + {}^{0}_{0}\bar{\nu}_e + \text{energy}$$

$$^{228}_{89}\text{Ac} \rightarrow {}^{228}_{90}\text{Th} + {}^{0}_{-1}\beta + {}^{0}_{0}\bar{\nu}_e + \text{energy}$$

$$^{228}_{90}\text{Th} \rightarrow {}^{224}_{88}\text{Ra} + {}^{4}_{2}\text{He} + \text{energy}$$

$$^{224}_{88}\text{Th} \rightarrow {}^{220}_{86}\text{Rn} + {}^{4}_{2}\text{He} + \text{energy}$$

$$^{220}_{86}\text{Rn} \rightarrow {}^{216}_{84}\text{Po} + {}^{4}_{2}\text{He} + \text{energy}$$

$$^{216}_{84}\text{Po} \rightarrow {}^{212}_{82}\text{Pb} + {}^{4}_{2}\text{He} + \text{energy}$$

$$^{212}_{82}\text{Pb} \rightarrow {}^{212}_{83}\text{Bi} + {}^{0}_{-1}\beta + {}^{0}_{0}\bar{\nu}_e + \text{energy}$$

$$^{212}_{83}\text{Bi} \rightarrow {}^{208}_{81}\text{Tl} + {}^{4}_{2}\text{He} + \text{energy} \quad \text{or} \quad {}^{212}_{83}\text{Bi} \rightarrow {}^{212}_{84}\text{Po} + {}^{0}_{-1}\beta + {}^{0}_{0}\bar{\nu}_e + \text{energy}$$

$$^{208}_{81}\text{Tl} \rightarrow {}^{208}_{82}\text{Pb} + {}^{0}_{-1}\beta + {}^{0}_{0}\bar{\nu}_e + \text{energy} \quad \text{or} \quad {}^{212}_{84}\text{Po} \rightarrow {}^{208}_{82}\text{Po} + {}^{4}_{2}\text{He} + \text{energy}$$

This is shown graphically in Figure 3.3.13. Note that the final reaction has two pathways but both finish with the stable isotope lead-208.

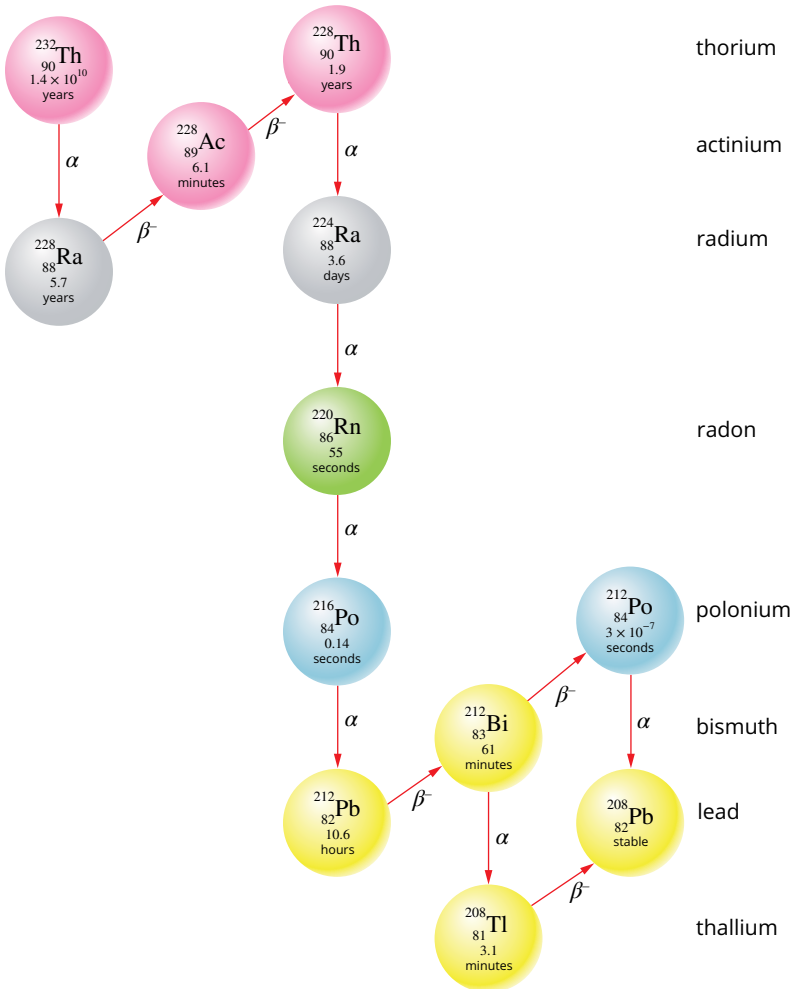


FIGURE 3.3.13 The decay series of thorium-232 into stable lead-208

Decay series are used in radioactive dating of rocks to obtain a reasonable estimate of the age of a rock by comparing the relative abundances of each element in the series to how much is expected after a given time.

3.3 Review

SUMMARY

- All decay reactions involve a parent nucleus losing energy to become a more stable daughter nucleus.
- There are three main types of decay: alpha, beta and gamma.
- The capacity to travel through a substance before absorption is called the penetrating ability.
- Ionisation is the process in which an atom loses or gains electrons to become positively or negatively charged.
- Ionising radiation consists of electromagnetic waves or alpha and beta particles that have enough energy to cause ionisation.
- When ionising radiation passes through human tissue, it may ionise atoms and molecules in the body's cells, which can lead to the development of cancerous cells.
- Transmutation is the process of changing one element into another.
- Alpha decay involves a radioactive nucleus emitting an alpha particle.
- An alpha particle consists of two protons and two neutrons and has relatively low penetrating ability but high ionising ability.
- Beta radiation involves the spontaneous changing of one nucleon into another nucleon inside a radioactive nucleus with the emission of a beta particle and its associated neutrino or antineutrino.
- Beta radiation is of medium penetrating ability and medium ionising ability.
- Beta positive radiation specifically involves a proton turning into a neutron with the emission of a positron and neutrino.
- Beta negative radiation specifically involves a neutron turning into a proton with the emission of an electron and antineutrino.
- Gamma radiation involves the emission of a high-energy gamma ray from a radioactive nucleus without a change in mass or atomic number.
- Gamma radiation has very high penetrating ability but a low ionisation ability.
- The decay of a radioactive nucleus can be written using a nuclear equation where the mass number and atomic numbers are both conserved.
- A daughter nucleus will also decay if it is not stable and this process will continue in a series until a stable nucleus is formed.
- In any decay reaction, both the atomic and mass numbers are conserved.

KEY QUESTIONS

Retrieval

1 Identify where in an atom alpha, beta and gamma radiation originate.

2 Define 'positron'.

3 Identify the type of radiation (alpha, beta or gamma) that can penetrate human skin but not 3 mm of aluminium.

4 Identify the mass numbers of the five stable nuclides of calcium (atomic number 20). Use the Segre plot (Figure 3.2.7, page 56) to answer this question.

5 Identify alpha, beta and gamma radiation in order of decreasing penetrating power.

6 Identify the type of radiation (alpha, beta or gamma) that:

a can easily penetrate aluminium foil

b is ejected when a neutron decays into a proton

c travels relatively slowly at typically around 10% of the speed of light

d travels at speeds of up to 90% of the speed of light

e has no charge.

Comprehension

7 Explain the difference between the two types of beta decay.

8 Describe the type of decay that occurs when a nucleus has too many protons.

9 Briefly explain why alpha particles have a very poor penetrating ability.

10 Explain why beta particles, not alpha or gamma, are the best to use for monitoring the thickness of thin metal sheets.

Analysis

11 Differentiate between alpha and beta radiation when compared to gamma radiation.

12 Determine the type of radiation (alpha, beta or gamma) that would be used to treat brain cancer, where the radiation needs to penetrate the skull and reach the site of the tumour.

13 Determine the unknown, X, for the following transmutation:

$$^{218}_{86}\text{Rn} \rightarrow {}^{214}_{84}\text{Po} + \text{X}$$

14 Determine the type of beta decay that occurs in this decay reaction and identify the particles Y and Z.

$$^{214}_{82}\text{Pb} \rightarrow {}^{214}_{83}\text{Bi} + \text{Y} + \text{Z}$$

15 For the unknown nuclides X and Y in each of these decay equations, determine the atomic number and mass number, and use the periodic table in Figure 3.2.2 to identify the unknown elements.

a $^{235}_{92}\text{U} \rightarrow {}^{4}_{2}\text{He} + \text{X}$

b $^{228}_{88}\text{Ra} \rightarrow \text{Y} + {}^{0}_{-1}\beta + {}^{0}_{0}\overline{\nu}$

16 Carbon-14 decays by beta negative emission to form nitrogen-14. The equation for this is:

$$^{14}_{6}\text{C} \rightarrow {}^{14}_{7}\text{N} + {}^{0}_{-1}\beta + {}^{0}_{0}\overline{\nu} + \text{energy}$$

a Determine how many protons and neutrons the nitrogen-14 isotope has.

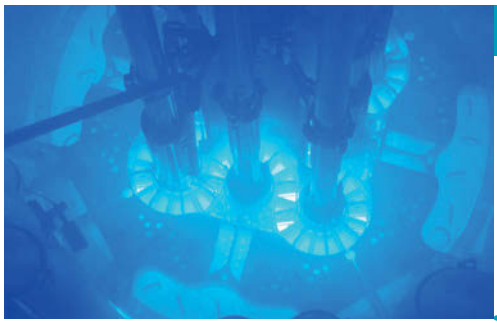
b Determine which nucleon on the left side of the equation has transformed into what other nucleon or particle(s) on the right side of the equation.

17 Deduce the missing part in each of the following decay equations.

a $^{45}_{20}\text{Ca} \rightarrow {}^{45}_{21}\text{Sc} +$

b $^{150}_{70}\text{Yb} \rightarrow {}^{146}_{68}\text{Er} +$

3.4 Half-life



BY THE END OF THIS MODULE, YOU SHOULD BE ABLE TO:

- recall that the rate of decay of a radioisotope is measured by its half-life $t_{\frac{1}{2}}$; this is the time that it takes for half of the radioisotope to decay
- calculate the number of nuclei remaining, using the half-life equation $N = N_o\left(\frac{1}{2}\right)^n$ from the number of half-lives elapsed
- use a graph of the number of radioactive nuclei remaining to determine the half-life of an isotope.

A radioactive nucleus decays by releasing energy or energy and other particles. The remaining daughter nucleus is more stable as a result. For an individual nucleus, this decay occurs randomly and is governed by the laws of quantum physics, but you can obtain information on how long it takes a large sample of a radioactive substance to decay.

When the number of nuclei in a sample of radioactive nuclei is graphed against time, a curved line is produced (Figure 3.4.1). This is an example of an exponential decay curve. Such curves have three important features:

- The number of undecayed nuclei is decreasing at a decreasing rate.
- The *y*-intercept of the graph represents the number of undecayed nuclei at time zero (the initial number of undecayed nuclei).
- The graph approaches but never reaches zero even after an infinite time. However, in nuclear decay if one nucleus remains and it decays, then there will be no nuclei left. (See Worked example 3.4.1.)

A graph of original nuclei remaining against time is a curve that decreases at a decreasing rate.

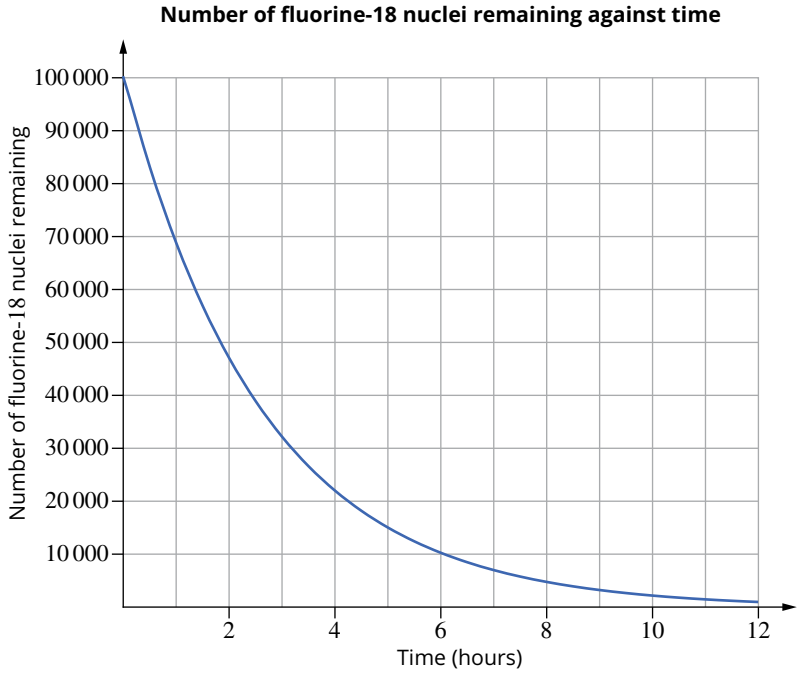


FIGURE 3.4.1 If a graph of the undecayed nuclei of fluorine-18 is made against time, it looks like this curve. This type of graph is known as an exponential decay curve.

HALF-LIFE CURVES

If the mass of all the original nuclei is graphed, instead of the numbers of nuclei, then the same-shaped exponential decay curve would result. The time taken for exactly half of the original number of nuclei to decay is called the **half-life**, $t_{\frac{1}{2}}$. Half-life is measured in any time unit and is not specifically linked to seconds. This means that after one half-life exactly half of the nuclei have decayed. After another half-life, half of the remaining nuclei decay, so $\frac{1}{4}$ of the original number of nuclei remain. After another half-life, $\frac{1}{8}$ of the original nuclei remain, and so on. Note that this does not imply that after two half-lives there is nothing remaining of the original nuclei, because the half-life is always measured with respect to the number remaining at the time.

Figure 3.4.2 shows the decay of polonium-218. If there are 100 million nuclei of polonium-218 nuclei at the start of a measurement, then after one half-life (3.1 minutes for polonium-218) the number of nuclei remaining will have dropped to 50 million. Over the next 3.1 minutes this number drops to 25 million and so on.

As time passes, a smaller and smaller proportion of the original radioisotope remains in the sample. Even a very small radioactive sample will contain billions of atoms. It is important to know that although the behaviour of such a large sample of nuclei can be mathematically predicted, the behaviour of one particular nucleus cannot. It has a 50% chance of decaying in each half-life.

The half-life of a radioactive nucleus is an indication of how stable it is. The shorter the half-life of a nucleus the more unstable it is, and the longer the half-life the more stable the nucleus is. All stable isotopes effectively have an infinite half-life because they basically do not ever decay.

Also, the half-life of a radioisotope is constant and cannot be changed by chemical reactions, heat and so on. Half-life is solely determined by the instability of the nuclei of the radioisotope.

Table 3.4.1 lists selected radioisotopes, their decay modes, half-lives and notes. Note that hydrogen-7 does not decay via one of the three main types of radiation.

TABLE 3.4.1 Selected isotopes

Isotope	Decay type	Half-life	Notes
tellurium-128	beta negative	2.2×10^{24} years	longest known half-life of any radioactive isotope
uranium-238	alpha	4.7×10^{9} years	used as a fuel in nuclear reactors and rock dating
potassium-40	beta negative	1.2×10^{9} years	the largest source of natural radioactivity in the human body
plutonium-239	alpha	24 110 years	used as a fuel in nuclear reactors and in nuclear weapons
carbon-14	beta negative	5730 years	used in carbon dating of fossils and in archaeology
americium-241	alpha	432 years	used in smoke alarms
strontium-90	beta negative	28.8 years	used in cancer therapy, energy in space probes and is a large component of the fallout from the Chernobyl and Fukushima nuclear reactor disasters
tritium (hydrogen-3)	beta negative	12.3 years	used as a fuel in nuclear fusion research and in nuclear weapons
astatine-210	beta positive	8.1 hours	the most stable isotope of the rarest naturally occurring element on Earth
beryllium-8	alpha	8.2×10^{-17} s	shortest-lived naturally occurring radioisotope
hydrogen-7	neutron emission	2.3×10^{-23} s	shortest-lived artificial isotope known

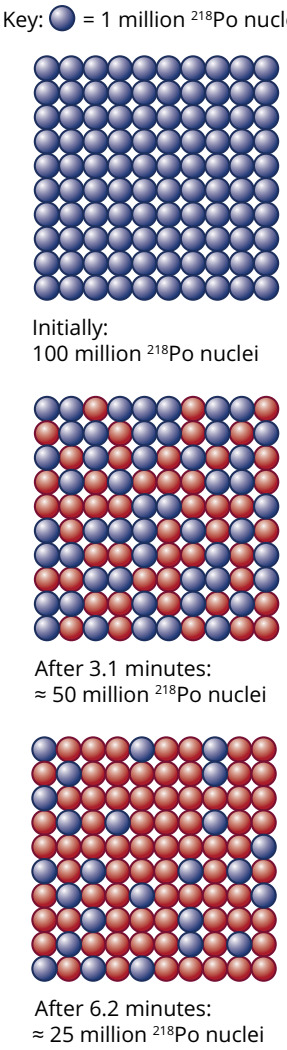


FIGURE 3.4.2 The decay of polonium-218 over two half-lives showing how only one quarter (25%) of the original radioisotope remains after two half-lives

The half-life, $t_{\frac{1}{2}}$, of a sample of radioactive nuclei is the time taken for exactly half of them to decay.

Figure 3.4.3 compares the decay curves for four different isotopes. The basic shape of the exponential decay curves are the same for each isotope, but the rate of decay is different, indicating different half-lives. Note that after 5 hours there is basically no change in the number of nuclei of cobalt-60, very little fluorine-18, and no nitrogen-13 remaining.

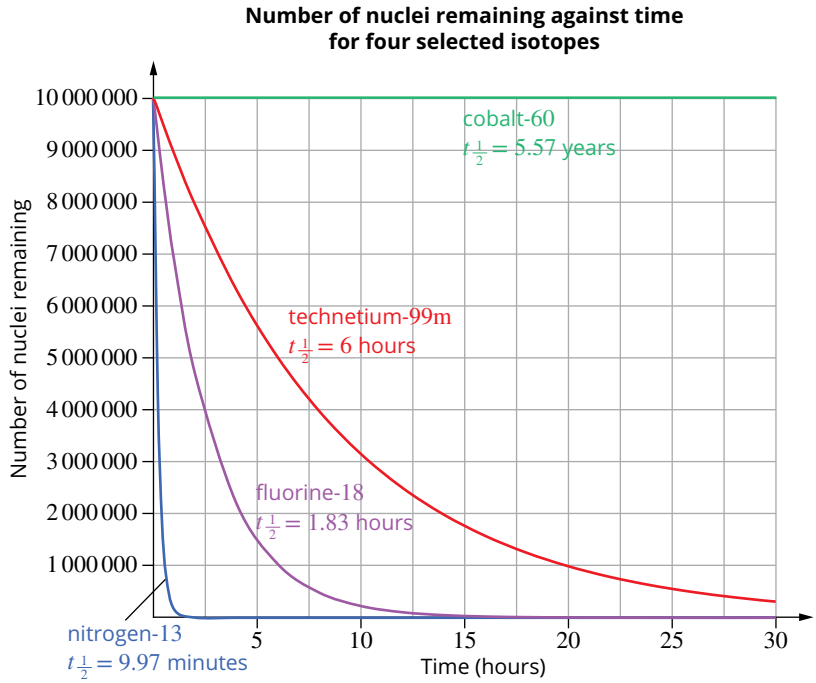


FIGURE 3.4.3 A comparison of four different isotopes with the same initial number of nuclei. The curves show the same exponential shape but have different rates of decay due to the different half-lives of the isotopes. Note that on this scale the Co-60 curve is a straight line. Also, the curves for nitrogen and fluorine do not theoretically touch the x-axis, but at this scale they appear to do so.

Using half-life graphs

Consider the radioisotope einsteinium-242 (Es-242). Its decay curve is shown in Figure 3.4.4. The percentage of Es-242 remaining drops by a factor of 2 each half-life. After one half-life there is only 50% of the nuclei remaining, and after two half-lives there is now only 25% of the nuclei remaining and so on.

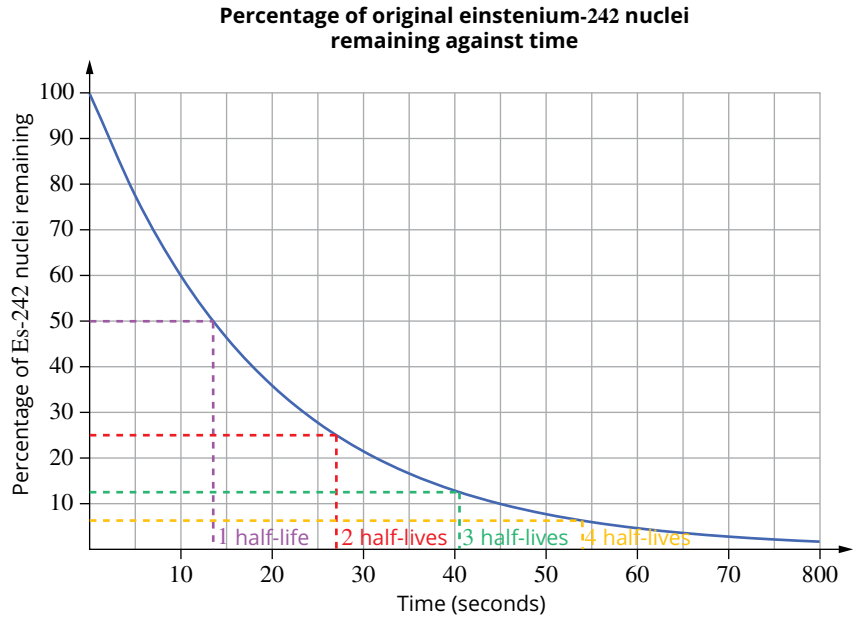


FIGURE 3.4.4 This decay curve of einsteinium-242 shows the percentage of original nuclei remaining against time and after each half-life.

Decay curves can be used to determine the half-life of an isotope by reading when the percentage of nuclei remaining drops to a certain value.

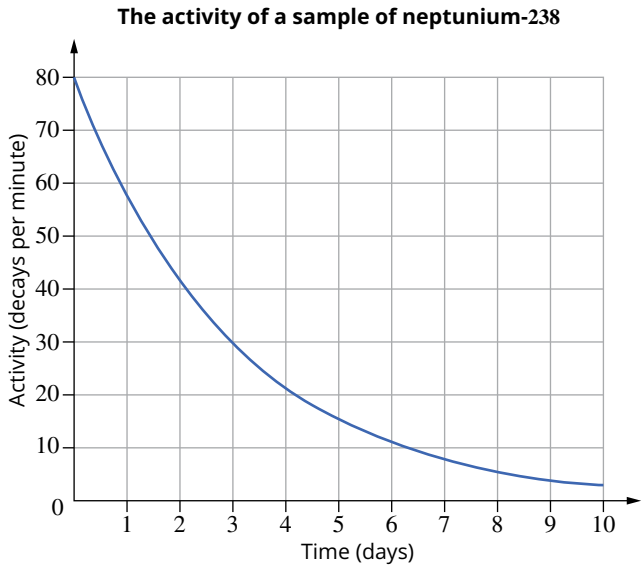
As shown in Figure 3.4.4, after one half-life there will be 50% of the nuclei remaining, and this occurs after about 13.5 seconds. After two half-lives 25% of the nuclei remain, and this occurs after about 27 seconds. Three half-lives take about 40.5 seconds. You expect the time between each half-life to be constant, because the percentage of the number of Es-242 nuclei is reducing by a factor of two each half-life. The time difference between each successive half-life is 13.5 seconds so you can be confident that this is the half-life of einsteinium-242.

A decay curve can be used to determine the half-life of a radioactive sample by reading off the time when exactly 50% of the initial number of nuclei in the sample remains.

Worked example 3.4.1

HALF-LIFE GRAPH

The following graph shows the activity, or number of decays per second, over a period of time for a sample of the radioactive isotope neptunium-238. Look carefully at the decay curve, or how the activity changes over time, of a sample of neptunium-238.



Use the graph to answer the following questions:

a Identify the activity of the sample at the start of the measurements.

b Deduce if the activity of the sample ever reaches zero.

c Determine the activity of the sample after 10 days.

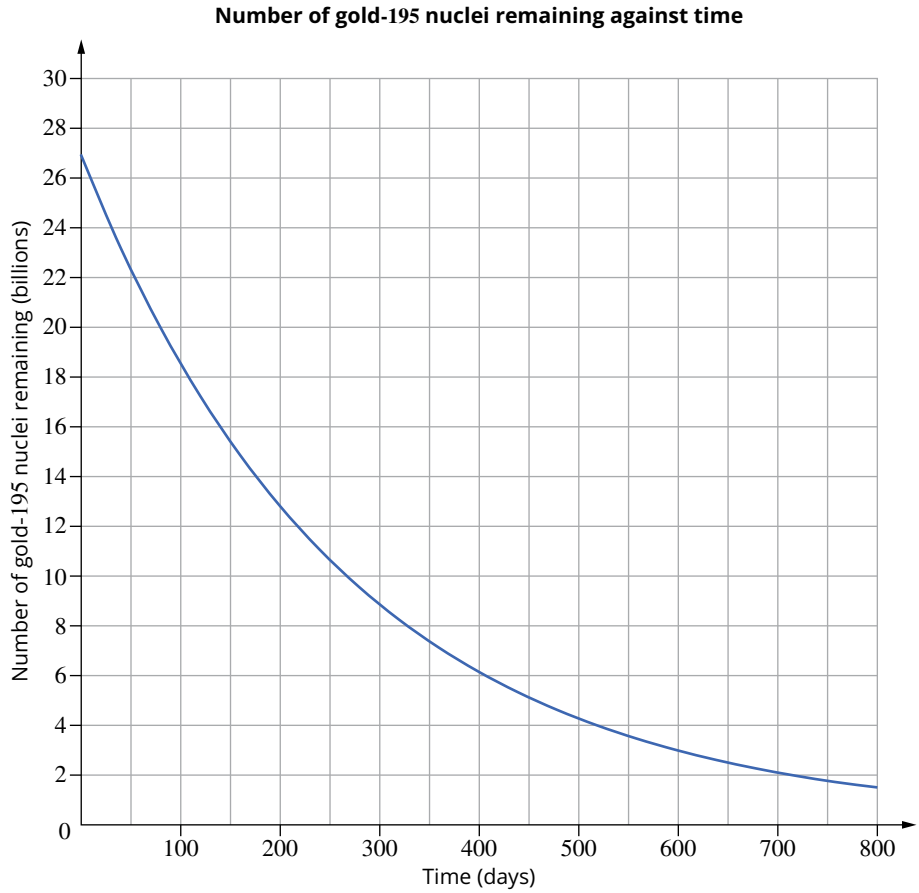
d Determine the half-life of $^{238}_{93}$Np.

Thinking	Working
a The activity at the start of the measurements is when time is zero: *y*-intercept.	When $t = 0$ the count rate is 80 counts per minute.
b Theoretically, an exponential decay curve cannot reach zero, but in radioactive decay the number of nuclei remaining can reach zero when there is one neptunium-238 nucleus left and it decays.	Yes, because if there is one remaining neptunium-238 nucleus and it decays then there are exactly zero nuclei left.
c The activity of neptunium-238 after 10 days is read off the *y*-axis when $t = 10$ days.	The activity of neptunium-238 after 10 days is about 3 decays per minute.
d The half-life of neptunium-238 is the time when half the initial number remains. The initial activity is 80 counts per minute, so the time taken to reduce to 40 counts per minute is the half-life. This is 2.1 days.	The half-life of neptunium-238 is 2.1 days.

➤ Try yourself 3.4.1

HALF-LIFE GRAPH

The decay curve of the radioactive isotope gold-195 is shown in the graph below. Use it to answer the following questions:



a Determine the initial number of gold-195 nuclei present.

b Identify when the number of gold-195 nuclei falls to 10% of its initial value.

c Determine the half-life of gold-195.

d Determine the number of nuclei remaining after three half-lives.

Calculations using half-life

If data of nuclei remaining or mass remaining is not available, then you can use a mathematical model of exponential decay to predict how many nuclei remain or the remaining mass after a given time.

The number of nuclei remaining after n half-lives is found by the equation:

$$N = N_0\left(\tfrac{1}{2}\right)^n$$

where

N is the number (or mass) of radioactive nuclei remaining

N_0 is the initial number (or mass) of radioactive nuclei

n is the number of half-lives elapsed.

The number of half-lives in a particular time period can be found using:

$$n = \frac{t}{t_{\frac{1}{2}}}$$

where

n is the number of half-lives

t is the period of time over which the radioactive nuclei have decayed

$t_{\frac{1}{2}}$ is the half-life of the radioactive nuclei.

Worked example 3.4.2

HALF-LIFE

A sample of the radioisotope thorium-234 contains 8.0×10^{12} nuclei. The half-life of thorium-234 is 24 days. Calculate how many thorium-234 nuclei will remain in the sample after 120 days.

Thinking	Working
The following information is given: Initial number of nuclei = 8.0×10^{12} Half-life = 24 days Time elapsed = 120 days	$N_0 = 8.0 \times 10^{12}$ $t_{\frac{1}{2}} = 24$ days $t = 120$ $N = ?$
Calculate how many half-lives in 120 days.	$n = \frac{120}{24}$ $= 5.0$ half-lives
Substitute $N_0 = 8.0 \times 10^{12}$ and $n = 5.0$ into the equation $N = N_0 \left(\frac{1}{2}\right)^n$. Calculate the number of nuclei remaining.	$N = N_0 \left(\frac{1}{2}\right)^n$ $= 8.0 \times 10^{12} \times \left(\frac{1}{2}\right)^5$ $= 2.5 \times 10^{11}$ nuclei

➤ Try yourself 3.4.2

HALF-LIFE

A sample of the radioisotope sodium-24 contains 4.0×10^{10} nuclei. The half-life of sodium-24 is 15 hours. Calculate the number of sodium-24 atoms remaining in the sample after 150 hours.

Worked example 3.4.3

HALF-LIFE EQUATION

A 0.1309 kg sample of the radioactive isotope iodine-131 was left in a cupboard for 40.1 days. When the cupboard was opened it was found that only 4.091 g of the isotope remained. If the mass of one nucleus of iodine-131 is 2.1737×10^{-25} kg, calculate the half-life of this isotope.

Thinking	Working
The following information is given: Initial mass = 0.1309 kg Time elapsed = 40.1 days Remaining mass after 40.1 days = 4.091 g Mass of one I-131 nucleus = 2.1737×10^{-25} kg	$m_0 = 0.1309$ kg $t = 40.1$ days $m = 4.091$ g Mass of nucleus = 2.1737×10^{-25} kg $t_{\frac{1}{2}} = ?$

The remaining mass is in g, which is 10^{-3} of 1 kg, so this needs to be converted to kg.	$4.091\,\text{g} = 4.091 \times 10^{-3}\,\text{kg}$
Before the half-life can be calculated, the number of half-lives elapsed in the 40.1 days is needed. To work this out, the number of nuclei initially and the number of nuclei remaining are needed. The masses of an individual nucleus, the initial and the remaining nuclei are all given, so divide the initial mass and the remaining mass by the mass of one nucleus to find how many nuclei there are initially and after 40.1 days.	N_0 = mass of initial sample divided by mass of one nucleus: $N_0 = \frac{m_0}{2.1737 \times 10^{-25}}$ $= \frac{0.1309}{2.1737 \times 10^{-25}}$ $= 6.022 \times 10^{23}$ N = mass of remaining sample divided by the mass of one nucleus: $N = \frac{m}{2.1737 \times 10^{-25}}$ $= \frac{4.091 \times 10^{-3}}{2.1737 \times 10^{-25}}$ $= 1.882 \times 10^{22}$
Now the rule for half-lives can be used to determine how many half-lives have occurred in the 40.1 days. Maths hint: Whenever you get a small decimal equal to $\frac{1}{2}$ raised to a power, invert the decimal (i.e. raise the decimal to the power of –1) to get a power of 2. Then it is much easier to determine the value of n because the inverted decimal will always be a power of 2, i.e. 2, 4, 8, 16, 32, 64, 128, etc. There have been 5.00 half-lives in the 40.1 days. Note that the initial mass and remaining mass could be used in the same rule and 5.00 would also be the number of half-lives.	$N = N_0 \left(\frac{1}{2}\right)^n$ $1.882 \times 10^{22} = 6.022 \times 10^{23} \times \left(\frac{1}{2}\right)^n$ $\frac{1.882 \times 10^{22}}{6.022 \times 10^{23}} = \left(\frac{1}{2}\right)^n$ $\frac{1}{32} = \left(\frac{1}{2}\right)^n$ $\left(\frac{1}{2}\right)^5 = \left(\frac{1}{2}\right)^n$ $n = 5.00$
This means that 5.00 half-lives have occurred over the 40.1 days, so the half-life will be found using the half-life rule.	$n = \frac{t}{t_{\frac{1}{2}}}$ $5 = \frac{40.1}{t_{\frac{1}{2}}}$ $t_{\frac{1}{2}} = \frac{40.1}{5}$ $= 8.02$ The half-life of iodine-131 is 8.02 days.

➤ Try yourself 3.4.3

HALF-LIFE EQUATION

A 8.9 g sample of magnesium-28 is weighed on Monday at 12 p.m. Only 0.556 g of magnesium-28 remains on the following Thursday at 11.36 p.m. If the mass of a single magnesium-28 nucleus is 4.645×10^{-25} kg, determine its half-life in hours.

Radioisotopes and radiometric dating

Carbon dating

Carbon dating is a technique used by archaeologists to determine the ages of fossils and ancient objects that were made from plant matter. This method involves measuring and comparing the proportions in the specimen of two isotopes of carbon, ^{12}C and ^{14}C.

Carbon-12 is a stable isotope but carbon-14 is radioactive. Carbon-14 only exists in trace amounts in nature. Carbon-12 atoms are about 1 000 000 000 000 (10^{12}) times more common than carbon-14 atoms.

Carbon-14 has a half-life of 5730 years and decays by beta negative emission to nitrogen-14. Its decay equation is:

$$^{14}_{6}C \rightarrow ^{14}_{7}N + ^{0}_{-1}\beta + ^{0}_{0}\overline{\nu}$$

Both carbon-12 and carbon-14 can combine with other atoms in the environment. For example, they both combine with oxygen to form carbon dioxide. Plants and animals take in carbon-based molecules from the air and food. This means that all living organisms contain the same percentage of carbon-14. In the environment, the production of carbon-14 is matched by its decay and so the proportion of carbon-14 atoms to carbon-12 remains constant.

After an organism dies, the amount of carbon-14 it contains will decrease as these atoms decay to form nitrogen-14 and are not replaced from the environment because the organism no longer needs nourishment. The number of atoms of carbon-12 does not change because carbon-12 is a stable atom. So, over time, the proportion of carbon-14 to carbon-12 atoms decreases.

The proportion of carbon-14 to carbon-12 in a dead organism can be compared with that found in living organisms and the approximate age of the specimen can be determined from the half-life of carbon-14.

In 1988, scientists used carbon-dating techniques to show that the Shroud of Turin was probably a medieval forgery. It had been claimed that Shroud of Turin was the piece of cloth that was the burial shroud of Jesus Christ (Figure 3.4.5). Carbon-dating tests on small samples of the cloth established that there was a high probability that it was made between 1260 and 1390, not around the time of Christ's death.

FIGURE 3.4.5 The Shroud of Turin

Radiocarbon dating is an important aid to anthropologists who are interested in finding out about the migration patterns of early people, including Indigenous Australians. This powerful technique can be applied to the remains of ancient campfires. It is accurate and reliable for samples up to about 60 000 years old.

Carbon dating cannot, however, be used to date dinosaur bones as they are more than 60 million years old, but it can be used to determine the age of more recently extinct animals from their fossils, like the extinct Australian marsupial *Diprotodon* shown in Figure 3.4.6.

FIGURE 3.4.6 The skull of a *Diprotodon* found in 1979 in northern New South Wales. Charcoal found buried near the skull was carbon-dated to be about 33 500 years old, giving an indication of when this animal lived.

Radioactive decay series dating of rocks

A method of determining the age of a rock sample is known as radiometric dating. This involves comparing the amount of uranium-235 to the amount of lead-207 in zircon crystals (zirconium silicate, $ZrSiO_4$) contained in the rock sample. The uranium-235 nuclei decay via a series to the stable isotope lead-207, with a half-life of 710 million years. It is assumed that all of the uranium, and none of the lead, found in the zircon crystals was present at the time the rock sample was formed, and that all of the lead was created as a result of the decay series of uranium-235.

Review

1 Explain why carbon dating cannot be used to determine the age of stone or metal-based archaeological artefacts.

2 The number of decays per second of a 1.0 g sample of carbon that has been extracted from an ancient wooden spear is 10.0 per second. A 1.0 g sample of carbon from a living piece of wood has a decay rate of 40.0 decays per second. Assuming that this was also the initial count rate of the spear, determine the age of the spear.

3 Explain why measurements of the isotope lead-207 are important in this method of dating rocks.

4 The oldest piece of the Earth's crust was found in the Jack Hills region of mid-Western Australia. In a zircon crystal (Figure 3.4.7) in a rock sample taken from this region, the ratio of the number of lead-207 nuclei to the remaining uranium-235 nuclei is 62.98. Use this number to determine the age of the rock sample.

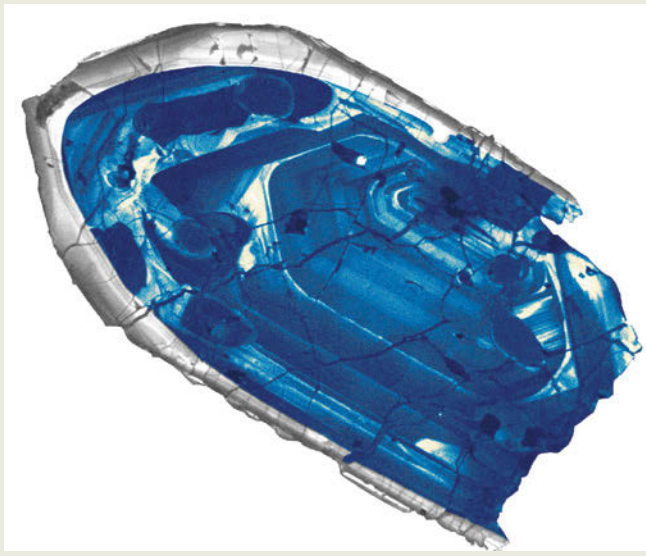


FIGURE 3.4.7 The oldest piece of the Earth's crust is this blue crystal of zircon found in mid-Western Australia.

3.4 Review

SUMMARY

- The rate of decay of a radioisotope is measured by its half-life, $t_{\frac{1}{2}}$. This is the time that it takes for half of the radioisotope to decay.
- The number of atoms of a radioisotope will decrease over time. Over one half-life, the number of atoms of a radioisotope will halve.
- The half-life equation can be used to calculate the number, N, of a radioisotope remaining after a number of half-lives, n, has passed: $N = N_o\left(\frac{1}{2}\right)^n$.
- A graph of the number of radioactive nuclei remaining is an exponential decay curve that decreases at a decreasing rate and can be used to determine the half-life of an isotope.

KEY QUESTIONS

Retrieval

1 Describe the shape of a graph of the number of radioactive nuclei remaining against time.

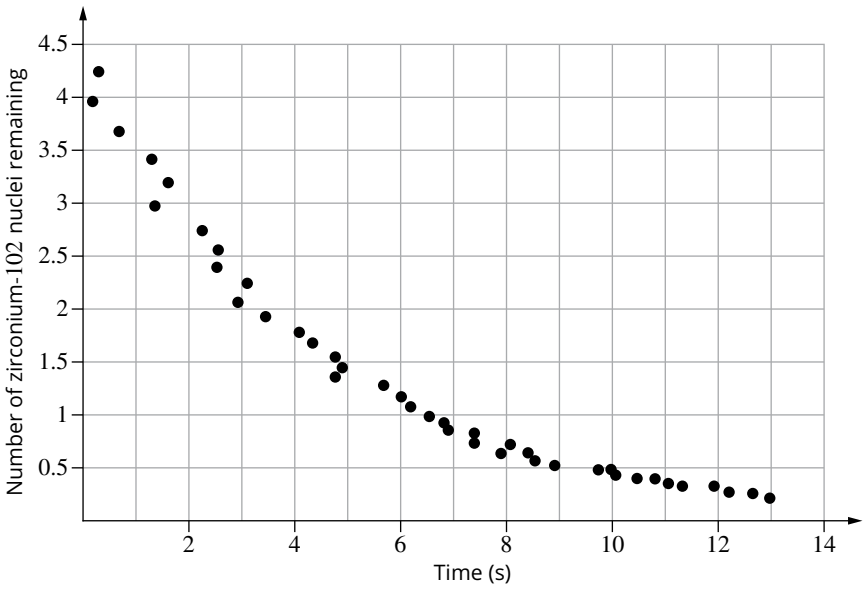
2 If a particular atom in a radioactive sample has not decayed during the previous half-life, identify the percentage chance that it will decay in the next half-life.

Comprehension

3 Explain why, after two half-lives, the number of nuclei of a sample of radioactive material has not completely disappeared.

4 The graph shows real data of the number of nuclei remaining of zirconium-102. Use it to determine the approximate half-life of the sample.

Number of zirconium-102 nuclei remaining against time



Analysis

5 Technetium-99m has a half-life of 6.0 hours. A sample of the radioisotope originally contains 8.0×10^{10} atoms. Determine how many technetium-99m nuclei remain after 6.0 hours.

6 A hospital in Alice Springs needs 12 µg of the radioisotope technetium-99m. The specimen has to be ordered from Sydney. The half-life of technetium-99m is 6 hours and the delivery takes 24 hours. Calculate how much must be produced in Sydney to satisfy the order for Alice Springs.

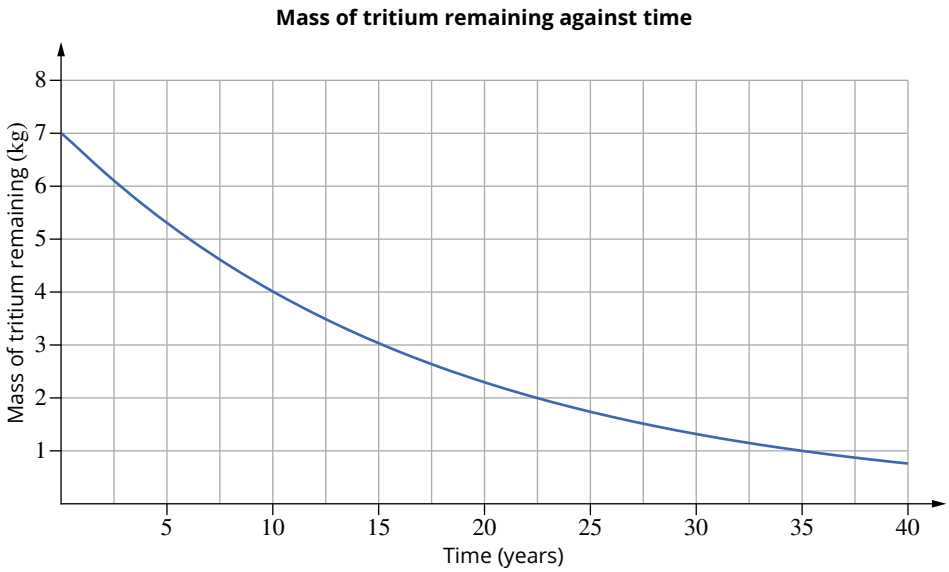
7 Radioactive materials are considered to be relatively safe when their activity has fallen below 0.1% of the initial value.

a Identify how many half-lives it takes for the activity of a material to fall below this level.

b Plutonium-239 is a by-product of nuclear reactors. Its half-life is 24 000 years. Calculate how long the plutonium-239 has to be stored as nuclear waste before it is considered safe to handle.

3.4 Review *continued*

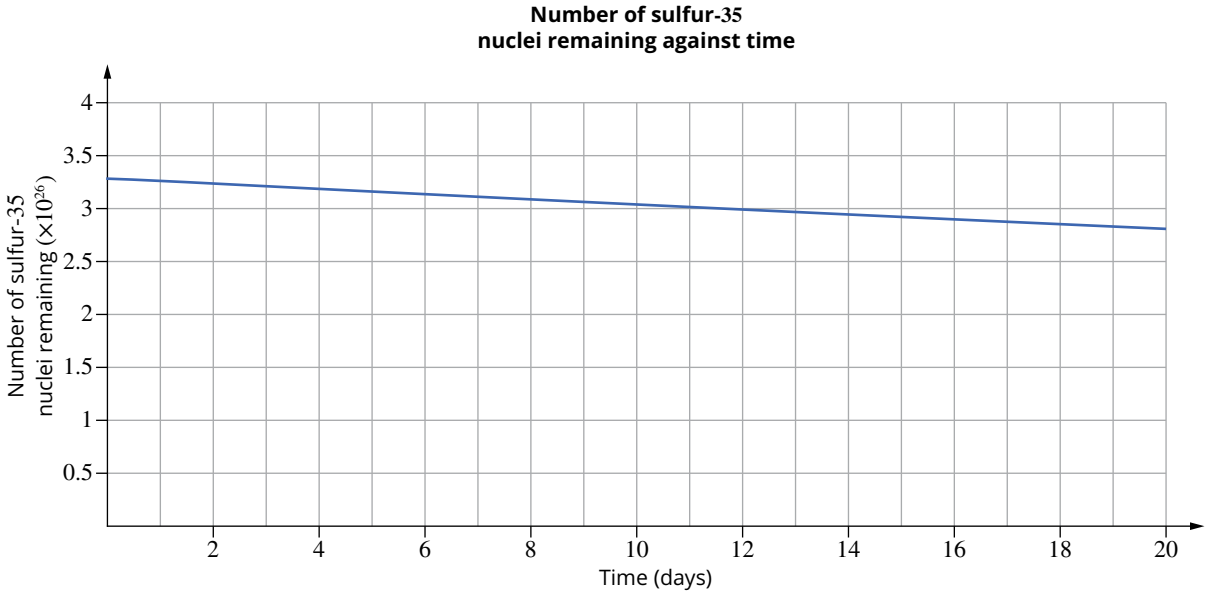
8 An amount of tritium (hydrogen-3) is weighed on New Year's Day each year for many years. The results of the experiment are shown in the graph.



Use the graph to answer the following questions:

a Identify how much tritium was present at the start of the observations.
b Determine how much tritium was present after 20 years.
c Determine how long it took the sample of tritium to reduce to 2.0 kg.
d Determine the half-life of tritium.
e Determine how much tritium would remain after 3 half-lives.
f Deduce how much tritium would remain after 5 half-lives.

9 The graph shown includes part of the decay curve of sulfur-35. Use the graph to help you answer the following questions.



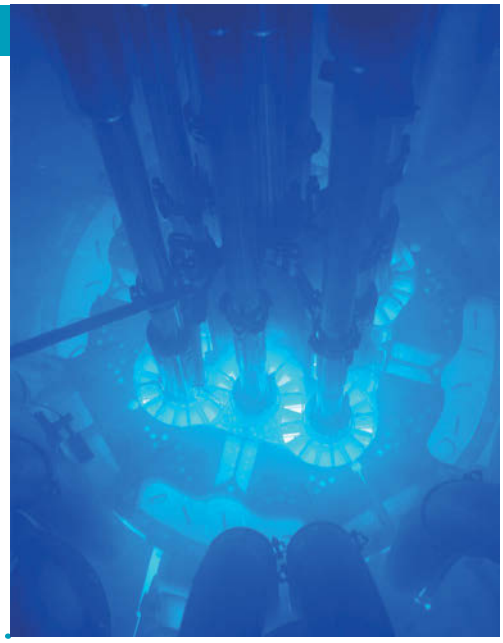
Sulfur-35 decays via beta negative radiation into the stable isotope chlorine-35.

a Determine how many chlorine-35 nuclei would exist via this decay reaction after 12 days.
b If the half-life of sulfur-35 is 87.5 days, determine how many chlorine-35 nuclei would exist after 262.5 days.

3.5 Mass–energy equivalence

BY THE END OF THIS MODULE, YOU SHOULD BE ABLE TO:

- use the electron volt (eV) as a unit of energy equal to 1.602×10^{-19} J
- recall that an isotope can be intentionally changed into another isotope by bombarding it with another particle in a process called artificial transmutation
- explain that, in any nuclear reaction, the sum of the masses of the reactants will not equal the sum of the masses of the products. This difference is known as the mass defect, Δm
- understand that a nuclear reaction will not proceed naturally if it requires energy; i.e. if the mass defect is a negative number
- recall that the energy required to break a nucleus completely into its constituent protons and neutrons is called the binding energy, ΔE
- calculate the binding energy, and binding energy per nucleon, using Einstein's mass–energy equivalence relationship: $E = mc^2$
- use the energy equivalence of one atomic mass unit of 931.6 MeV in calculations.



In every decay equation, energy is always produced as a result of the parent nucleus becoming more stable and creating a daughter nucleus. The amount of energy produced depends on the number of protons and neutrons, and on how tightly they are held together. In this module, you will explore the amount of energy released, not just by natural decay reactions, but also by a whole range of other natural and artificial reactions. It will also be shown that some of the mass of the nucleons is transformed into pure energy by the use of the most famous equation in science: $E = mc^2$.

THE ELECTRON VOLT

The energy released by a single decaying nucleus is very, very small, typically in the order of 2×10^{-11} joules (J). It is time-consuming and inconvenient to write nuclear energies in scientific notation, so physicists use a much smaller unit of energy called the **electron volt**, eV. Note that the electron volt shouldn't be confused with the unit 'volt', which will be used in the electricity chapters to follow.

An electron volt is the amount of work done in moving a single electron through a potential difference (i.e. voltage) of 1 volt, hence the name electron volt. You will learn more about this definition in Unit 3. One electron volt (1 eV) is equal to 1.602×10^{-19} J and 1 J is equal to 6.242×10^{18} eV.

In nuclear physics, most electron energies are described in keV (one thousand, 10^3, eV), MeV (one million, 10^6, eV), GeV (one billion, 10^9, eV) and TeV (one trillion, 10^{12}, eV).

Note that the eV is not an SI unit, which means that you will need to convert energy in eV to J before making any substitutions into formulas that use SI units.

$1\text{ eV} = 1.602 \times 10^{-19}\text{ J}$
$1\text{ J} = 6.242 \times 10^{18}\text{ eV}$

Table 3.5.1 and Figure 3.5.1 show the comparisons of various energetic processes in joules and in electron volts. This will give you an idea of how small 1 eV is.

TABLE 3.5.1 Energy processes and their equivalent energies

Energy process	Energy in joules	Energy in electron volts	Notes
highest-energy radio waves	2.0×10^{-22}	0.0012 eV (1.2 meV)	the least energetic form of electromagnetic radiation
red light	2.9×10^{-19}	1.8 eV	the lowest-energy light that our eyes can detect
violet light	5.0×10^{-19}	3.1 eV	the highest-energy light that our eyes can detect
typical exothermic chemical reaction such as combustion	1.6×10^{-18}	10 eV	energy released *per reaction*
typical energy per reaction in a nuclear reactor	3.2×10^{-11}	2×10^{8} eV (200 MeV)	this is as a result of nuclear fission reactions usually involving uranium isotopes
a snowflake hitting the ground	1×10^{-6}	6×10^{12} eV (6 TeV)	this is larger than all of the energy received by every radio telescope on Earth
proton collisions in the Large Hadron Collider	1.0×10^{-6}	6.5×10^{12} eV (6.5 TeV)	protons are collided at about 99.999 999% of the speed of light
highest-energy gamma rays	2×10^{-5}	1×10^{14} eV (100 TeV)	the most energetic form of electromagnetic radiation
a falling apple	1	6.2×10^{18} eV (6.2 EeV)	energy attained by an apple falling 1 metre on Earth.
500 kg car moving at 100 km h^{-1}	200 000	1.2×10^{24} eV (1.2 YeV)	one thousand million million million million times the energy of the lowest energy radio waves
most energetic single particle ever observed	50	3.1×10^{20} eV (310 EeV)	a cosmic-ray proton known as the 'Oh My God' particle observed from space in 1991 and thought to have travelled at 99.999 999 999 999 999 999 999 510% of the speed of light; its source remains unknown

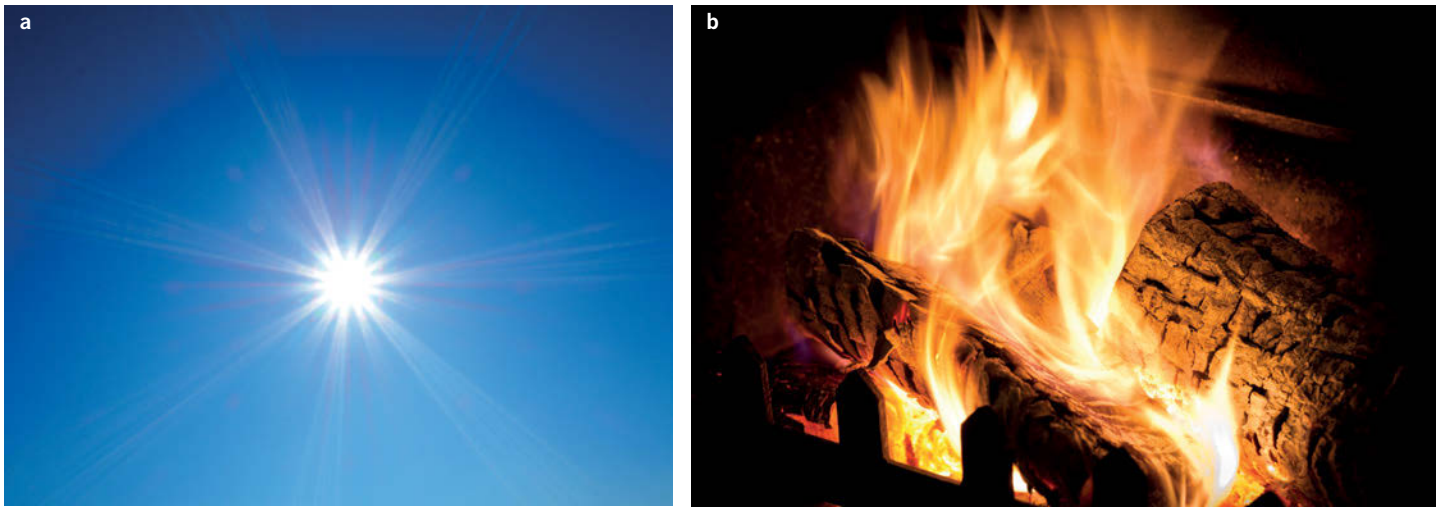


FIGURE 3.5.1 For the same amount of mass used, nuclear reactions occurring inside the Sun (a) produce about 20 million times more energy than that produced by burning wood (b).

Worked example 3.5.1

THE ELECTRON VOLT

Radium-226 is a radioisotope that decays into radon-222 via alpha radiation. The reaction is:

$$^{226}_{88}\text{Ra} \rightarrow {}^{222}_{86}\text{Rn} + {}^{4}_{2}\text{He} + \text{energy}$$

a If 4.934 MeV of energy is released from each radium-226 nucleus, state this in joules.

Thinking	Working
Convert 4.934 MeV into joules. First change 4.934 MeV into eV by multiplying by 10^6, which is the prefix mega.	4.934 MeV = 4.934×10^6 eV
To convert eV into J, multiply by 1.602×10^{-19}.	Energy $= 4.934 \times 10^6 \times 1.602 \times 10^{-19}$ $= 7.904 \times 10^{-13}$ J

b If 6.80×10^{24} nuclei of radium-226 nuclei decay, determine the amount of energy that would be released in eV and in joules.

Thinking	Working
Each reaction releases 4.934 MeV of energy, So, 6.80×10^{24} reactions will released $6.80 \times 10^{24} \times 4.934$ MeV of energy.	Total amount of energy $= 6.80 \times 10^{24} \times 4.934 \times 10^6$ eV $= 3.355 \times 10^{31}$ eV
Multiply 3.355×10^{31} by 1.602×10^{-19} to find the answer in joules.	Total amount of energy $= 3.355 \times 10^{31} \times 1.602 \times 10^{-19}$ $= 5.375 \times 10^{12}$ J = 5.38 TJ

➤ Try yourself 3.5.1

THE ELECTRON VOLT

The radioisotope technetium-99m becomes stable by emitting gamma radiation. If the energy of the gamma ray emitted by the parent nucleus is 2.26×10^{-14} J, determine how much energy this is in eV, keV and MeV.

ARTIFICIAL TRANSMUTATION

In the majority of decay reactions, the daughter nucleus is a different element to the parent nucleus. This is known as transmutation and is a naturally occurring process. Decay is one of the main natural methods by which an element is changed into another element, and is the reason why there are elements in the universe that are heavier than iron.

The most common *artificial* reaction in nuclear physics is nuclear bombardment. This involves firing a small particle (proton, neutron, alpha particle etc.) at a nucleus to analyse the particles and nuclei that emerge. The very first artificial nuclear bombardment experiment was carried out by Rutherford, as shown in Figure 3.5.2. In his famous experiment in 1919, Ernest Rutherford bombarded atoms of gaseous nitrogen with alpha particles emitted from a piece of radioactive ore, which led him to find small amounts of oxygen and hydrogen.

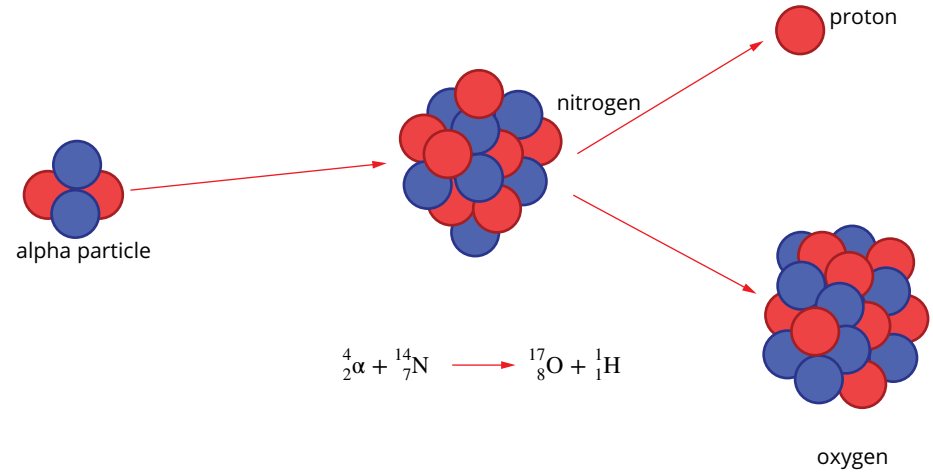


FIGURE 3.5.2 Artificial transmutation of a nitrogen nucleus into an oxygen nucleus and a proton

Rutherford fired an alpha particle at nitrogen-14 (the reactants) and created oxygen-17 with a proton (the products):

$$^{14}_{7}N + {}^{4}_{2}He \rightarrow {}^{17}_{8}O + {}^{1}_{1}H + \text{energy}$$

A nuclear reaction involves two or more particles colliding to produce new particles. It is the main technique of artificial transmutation.

This was also the first demonstration of a **nuclear reaction**, or transmutation, in which there is *more* than one reactant in the equation. Today, artificial transmutation occurs primarily in nuclear reactors and particle accelerators (Figure 3.5.3). In particle accelerators, increasingly heavier nuclei are fired at each other to try to synthesise heavier and heavier nuclei. An example of this was the creation in 2002 of four atoms of the heaviest element known, oganesson-294, with atomic number 118. In the core of a nuclear reactor, the production of energy via nuclear reactions produces nuclear waste as a by-product. These are typically isotopes of neptunium, americium and curium created by the beta decay of uranium or plutonium when they are bombarded with neutrons.

FIGURE 3.5.3 Part of the particle accelerator tunnel at the Joint Institute for Nuclear Research in Dubna, Russia. This facility is responsible for creating the first atoms of nobelium, nihonium, flerovium, moscovium, livermorium, tennessine and oganesson.

Worked example 3.5.2

ARTIFICIAL TRANSMUTATION

The stable isotope cobalt-59 is bombarded with a neutron to produce an unstable isotope that is used in nuclear medicine. The diagram below shows the particles involved in the creation of cobalt-60.

Write the full nuclear equation of this reaction and hence determine the nuclide produced.

Thinking	Working
The reactants of this reaction are cobalt-59 and a neutron, ${}^{1}_{0}n$. There is only one product of this reaction: ${}^{A}_{Z}X$. Cobalt has an atomic number of 27.	${}^{59}_{27}Co + {}^{1}_{0}n \rightarrow {}^{A}_{Z}X$
Mass number and atomic number must be conserved, so A and Z can be calculated.	$A = 59 + 1 = 60$ $Z = 27 + 0 = 27$
Therefore the nuclide produced is ${}^{60}_{27}Co$. Write the complete equation.	${}^{59}_{27}Co + {}^{1}_{0}n \rightarrow {}^{60}_{27}Co$ The nuclide produced is ${}^{60}_{27}Co$.

➤ Try yourself 3.5.2

ARTIFICIAL TRANSMUTATION

The first element heavier than plutonium to be created was curium, which was first made in 1944. The synthesis required the radioisotope plutonium-239 to be bombarded with a smaller particle to produce curium-242 and a single neutron.

Identify the smaller particle used for the bombardment reaction and write the full nuclear reaction.

ENERGY IN NUCLEAR REACTIONS

Burning 1 kg of coal typically produces 30 MJ of energy. Burning 1 kg of hydrogen can produce up to 140 MJ of energy, but 'burning' 1 kg of uranium-238 produces 80.6 TJ of energy, or more than 2 million times more energy than burning coal. Of course, the uranium-238 isn't actually burnt as it is in a chemical reaction, but instead it is involved in a nuclear reaction. All nuclear reactions give off millions of times more energy than chemical reactions, but why? The answer lies in the most famous science equation in history, first developed by Albert Einstein (Figure 3.5.4) in 1905.

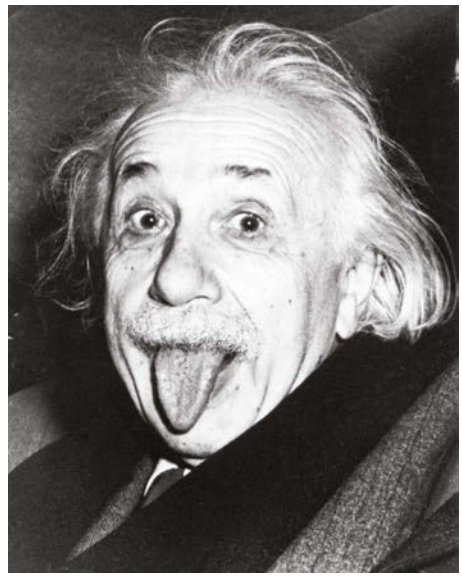


FIGURE 3.5.4 Albert Einstein on his 72nd birthday in 1951

The mass–energy equivalence

Einstein's equation is known as the mass–energy equivalence relationship and governs all energies in nuclear reactions.

$$E = mc^2$$

Einstein developed a mathematical rule that linked energy and matter, based on the fact that matter can be converted entirely into energy, and energy can be converted entirely into matter. In a chemical reaction the atoms are rearranged, and it is the breaking and reforming of the bonds between them that releases energy. In a nuclear reaction, it is the protons and neutrons themselves that are converted *directly* into energy.

Mass is not conserved in all nuclear reactions, which means that the sum of the masses of the reactants does not equal the sum of the masses of the products. This might seem to violate conservation laws, but because the missing mass has been converted into energy, the law of conservation of energy still applies.

The mass–energy equivalence relationship:

$E = mc^2$

where

ΔE is the energy content produced in a nuclear reaction (J)

Δm is the difference in mass before and after a nuclear reaction has taken place (kg)

c is the speed of light $2.99792 \times 10^8\,\text{m s}^{-1}$.

Worked example 3.5.3

THE MASS–ENERGY EQUIVALENCE

Determine how much energy, in J and MeV, is released if 5.0×10^{-28} kg of matter is converted into energy.

Thinking	Working
This is a direct application of Einstein's energy–mass equivalence rule: $E = mc^2$	$\Delta m = 5.0 \times 10^{-28}\,\text{kg}$ $c = 2.99792 \times 10^8\,\text{m s}^{-1}$
Substitute in for Δm and c to find the energy in joules (using kg for Δm).	$E = mc^2$ $= 5.0 \times 10^{-28} \times (2.99792 \times 10^8)^2$ $= 4.5 \times 10^{-11}\,\text{J}$
Convert to eV by dividing by 1.602×10^{-19}.	$= 2.8 \times 10^8\,\text{eV}$
Convert to MeV by dividing by 10^6.	$= 280\,\text{MeV}$

➤ Try yourself 3.5.3

THE MASS–ENERGY EQUIVALENCE

The nuclear bomb dropped on Hiroshima in 1945 converted a 'mere' 0.6 g of uranium into energy. Calculate the amount of energy, in J, that was released in that explosion.

The unified atomic mass unit

The masses of protons and neutrons are very small, so the continual use of the kg unit becomes inconvenient (just like the energy unit, joule). Physicists and chemists have come up with a more convenient unit of expressing particle masses. This is known as the unified atomic mass unit (u). One unified atomic mass unit (1 u) is defined as $\frac{1}{12}$ of the mass of a carbon-12 atom (6 protons, 6 neutrons and 6 electrons), which is $1.660\,54 \times 10^{-27}$ kg. Figure 3.5.5 and Table 3.5.2 outline how to convert between u and kg.

The atomic mass unit, u, is the unit of mass in which nucleons and nuclei are measured.

$1\,\text{u} = 1.660\,54 \times 10^{-27}\,\text{kg}$

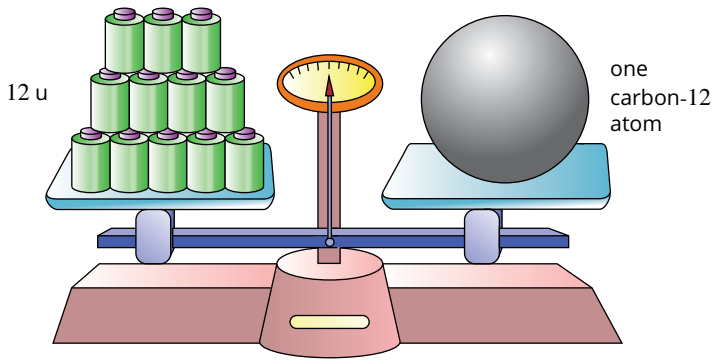


FIGURE 3.5.5 The atomic mass unit (u) is exactly equal to $\frac{1}{12}$ the mass of a carbon-12 atom.

TABLE 3.5.2 Converting to and from kg and u

To convert...	Do this	To check
kg into u	Divide the mass in kg by 1.66054×10^{-27}.	Your number should be much larger than before.
u to kg	Multiply the mass in u by 1.66054×10^{-27}.	Your number should be much smaller than before.

Using this conversion factor, Table 3.5.3 lists some particles and isotopes and their masses. Note that the mass of the isotopes given includes their orbiting electrons, which is why hydrogen-1 has a slightly heavier mass than a proton. Orbiting electrons do not participate in any common nuclear reactions, so they will not form part of the Δm value in the mass–energy rule. When Δm is calculated in a nuclear reaction, the masses of the orbiting electrons will cancel out.

TABLE 3.5.3 Selected particles and isotopes and their masses in kg and u

Particle or isotope	Mass in kg	Mass in u
electron and positron	$9.109\,384 \times 10^{-31}$	0.000 548 6
proton	$1.672\,622 \times 10^{-27}$	1.007 276
hydrogen-1	$1.673\,534 \times 10^{-27}$	1.007 825
neutron	$1.674\,927 \times 10^{-27}$	1.008 665
alpha particle (*nucleus* of helium-4)	$6.644\,661 \times 10^{-27}$	4.001 506
carbon-12	$1.992\,65 \times 10^{-27}$	12 exactly
uranium-238	$3.952\,929 \times 10^{-25}$	238.050 788 2

The masses of all particles and isotopes are known to a very high precision, so a large number of significant figures can be written during calculations. Therefore, it is important to keep track of as many significant figures as possible. It is very useful to know how much energy is released if exactly 1 u is converted into energy. Using the mass–energy rule for 1 u:

$$\begin{aligned} E &= mc^2 \\ &= 1\text{ u} \times \left(2.997\,92 \times 10^{8}\right)^2 \\ &= 1.660\,54 \times 10^{-27} \times 8.987\,52 \times 10^{16} \\ &= 1.492\,41 \times 10^{-10}\text{ J} \\ &= \frac{1.492\,41 \times 10^{-10}}{1.602 \times 10^{-19}} = 9.3159 \times 10^{8}\text{ eV} \\ &= 931.6\text{ MeV} \end{aligned}$$

This means that 1 u of matter is equivalent to 931.6 MeV of energy.

1 u of mass has an energy equivalent of 931.6 MeV.

This relationship is a very useful short-cut to performing energy calculations using the mass–energy rule. Simply calculate the change in mass of the reaction (u) and multiply this by 931.6 MeV to find the energy released. For example, from Table 3.5.3, an electron has a mass of $9.109\,384 \times 10^{-31}$ kg or 0.000 548 6 u.

$$\begin{aligned} E &= mc^2 \\ &= 5.486 \times 10^{-4} \times 931.6 \\ &= 0.5111 \text{ MeV} \end{aligned}$$

An electron has an energy equivalence of 0.511 MeV.

Worked example 3.5.4

THE UNIFIED ATOMIC MASS UNIT

The radioisotope iron-52 has a mass of 51.948 114 u.	
a Write this mass in kg.	
Thinking	**Working**
To convert from u to kg multiply the mass by $1.660\,54 \times 10^{-27}$.	$51.948\,114 \times 1.660\,54 \times 10^{-27}$ $= 8.626\,19 \times 10^{-26}$ kg
b Calculate the mass of the $^{52}_{26}$Fe nuclide in kg and u.	
Thinking	**Working**
The mass of the iron-52 isotope is given. Iron has an atomic number of 26 so this mass includes 26 electrons.	Mass of isotope = mass of nucleus + mass of orbiting electrons
Subtract the mass of the 26 electrons from the mass of the isotope to get the mass of the nucleus only. Calculate the mass of the nucleus in u first.	Mass of nucleus = mass of isotope – mass of 26 electrons $= 51.948\,114 - 26 \times 0.000\,548\,6$ u $= 51.948\,114 - 0.014\,263\,6$ u $= 51.933\,850$ u
To find mass in kg, multiply by $1.660\,54 \times 10^{-27}$. Note that this part could also be calculated in kg, and then converted to u.	$= 51.933\,850 \times 1.660\,54 \times 10^{-27}$ kg $= 8.623\,82 \times 19^{-26}$ kg

➤ Try yourself 3.5.4

THE UNIFIED ATOMIC MASS UNIT

Calculate the amount of energy (in MeV) that would be released if the nucleus of the lithium-5 radioisotope (m = 5.012 54 u) were to be completely converted into energy.

Mass defect and binding energy

If the products of a nuclear reaction are weighed accurately and compared with the mass of the reactants, then there is always a difference. Some mass is lost during the nuclear reaction, and that lost mass is converted into energy.

If a given, intact nucleus could be disassembled into its individual protons and neutrons, then the sum of the masses of the individual protons and neutrons would be slightly higher than the mass of the nucleus itself. The difference between the mass of the nucleus as a whole and the sum of the individual nucleons is called the **mass defect**, Δm. The energy equivalent of the mass defect is called the **binding energy**, ΔE, and is the work or energy needed to break apart a given nucleus into its individual parts. Another way of describing this is that some of the mass of the individual protons and neutrons that make up the nucleus is converted into energy that keeps the nucleus together when it is formed. Therefore, you can say that to construct a nucleus releases energy, and to fully break apart a nucleus requires energy.

The mass defect is the difference between the mass of the intact nucleus and the sum of the masses of the individual nucleons that make up the nucleus.

The binding energy is how much energy is needed to completely break up an intact nucleus into its individual protons and neutrons.

The mass defect (in u) is calculated as:

m = total mass of reactants – total mass of products

or

m = mass of nucleus – total mass of individual protons and neutrons

In terms of binding energy, the general equation is:

nucleus + binding energy → number of protons + number of neutrons

Binding energy is shown diagrammatically in Figure 3.5.6.

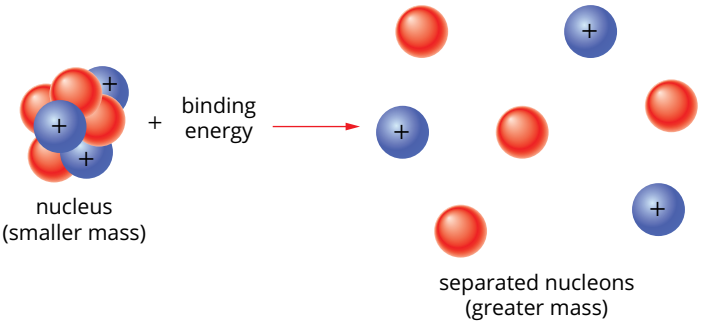


FIGURE 3.5.6 Energy, called the binding energy, must be supplied to a nucleus to completely separate its individual protons and neutrons.

The binding energy is calculated using the conversion factor of 931.6 MeV per u:

$$E = 931.6 \times \quad m$$

For example, the mass defect and binding energy of the isotope fluorine-19 can be calculated as follows.

Fluorine-19 has a nuclear mass of 18.993 465 82 u (and is the only stable isotope of fluorine).

Fluorine has an atomic number of 9 and its mass number of 19, so there are 10 neutrons in its nucleus.

Remember from Table 3.5.3 that: proton mass is 1.007 276 u and neutron mass is 1.008 665 u.

The nuclear reaction to completely break apart fluorine-19 into its 9 protons and 10 neutrons is:

$$^{19}_{9}\mathrm{F} \rightarrow 9\,^{1}_{1}\mathrm{H} + 10\,^{1}_{0}\mathrm{n}$$

The mass defect of fluorine-19 is therefore:

m = mass of fluorine -19 nucleus – (mass of 9 protons + mass of 10 neutrons)

= 18.99346582 – (9 × 1.007276 + 10 × 1.008665)

= 18.99346582 – (9.065484 + 10.08665)

= 18.99346582 – 19.152134

= –0.15866818 u

The negative result indicates that the sum of the masses of the 19 nucleons is greater than the mass of the fluorine-19 nucleus, as illustrated in Figure 3.5.7.

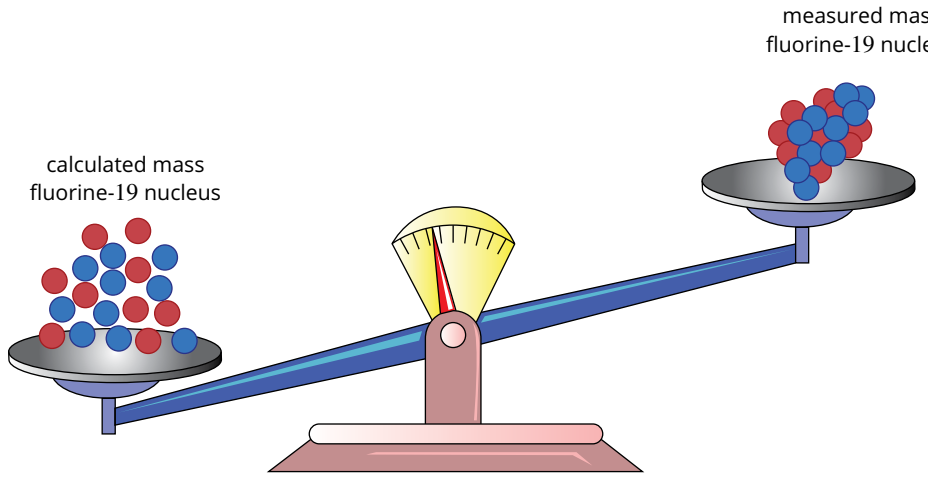


FIGURE 3.5.7 The sum of the masses of the 9 protons and 10 neutrons is larger than the mass of the fluorine-19 nucleus, indicating that mass has been converted into binding energy.

Note that the negative sign indicates that energy must be supplied for this reaction to occur, and so will not proceed naturally. The binding energy required to disassemble the fluorine-19 nucleus, ignoring the negative sign for the binding energy, is therefore:

$$E = 931.6 \times 0.158\,66818$$
$$= 147.8\,\text{MeV}$$

This means that 147.8 MeV of energy is needed to break apart the fluorine-19 nucleus into 9 protons and 10 neutrons. You can now write the complete nuclear reaction of the disassembly of fluorine-19 into its individual protons and neutrons:

$$^{19}_{9}\text{F} + 147.8\,\text{MeV} \rightarrow 9\,^{1}_{1}\text{H} + 10\,^{1}_{0}\text{n}$$

As the number of nucleons in a nucleus increases, so does the nuclear mass of the nucleus, and the binding energy of the nucleus. In order to compare the binding energies of nuclei, the binding energy is divided by the mass number. This is known as the **binding energy per nucleon** and it is an indication of how strongly a nucleus is held together. Nuclei with high binding energies per nucleon are held more tightly than nuclei with lower binding energies per nucleon because it takes more energy to completely separate them.

The binding energy per nucleon for fluorine-19 is:

$$E = \frac{147.8}{19}$$
$$= 7.779\ \text{MeV per nucleon}$$

Most stable isotopes have a binding energy per nucleon of about 8 MeV per nucleon.

The binding energy per nucleon is equal to the binding energy of a nucleus divided by the number of nucleons in the nucleus. It can be used to determine the stability of a nucleus.

Worked example 3.5.5

BINDING ENERGY PER NUCLEON

Calculate the binding energy per nucleon of the isotope nickel-62. Its nuclear mass is 61.912 99 u.
Comment on the stability of this isotope.

Thinking	Working
To calculate the binding energy per nucleon, find the binding energy. To do that, the mass defect is also needed. So, write the nuclear reaction for the total break-up of a nickel-62 nucleus into its parts.	Atomic number of nickel-62 is 28. Mass number of nickel-62 is 62. Neutron number of nickel-62 is 62 – 28 = 34 $^{62}_{28}\text{Ni} \rightarrow 28\,^{1}_{1}\text{H} + 34\,^{1}_{0}\text{n}$
The mass defect is the mass of the nucleus minus the mass of the 28 protons and the mass of the 34 neutrons. Remember from Table 3.5.3: proton mass is 1.007 276 u and neutron mass is 1.008 665 u. The negative mass indicates that this reaction will not proceed naturally.	m = 61.912 99 – (28 × 1.007 276 + 34 × 1.008 665) = 61.912 99 – (28.203 728 + 34.294 61) = 61.912 99 – 62.498 338 = –0.585 348 u
The binding energy equivalent of the mass defect is found by multiplying the mass defect by 931.6 MeV per u.	ΔE = 0.585 348 × 931.6 = 545.3 MeV
To find the binding energy per nucleon, divide by 62 (mass number).	ΔE per nucleon = 8.795 MeV per nucleon
Stable nuclei have a binding energy per nucleon of about 8, so nickel-62 should be a very stable isotope because its binding energy per nucleon is more than 8 MeV per nucleon.	Nickel-62 is a very stable isotope because its binding energy per nucleon is more than 8 MeV per nucleon.

➤ Try yourself 3.5.5

BINDING ENERGY PER NUCLEON

Calculate the binding energy per nucleon of the radioisotope uranium-235. Its nuclear mass is 234.993 51 u.

ENERGY IN DECAY

Einstein's mass–energy equivalence relationship can also be used to determine how much energy is released in natural radioactive decay. In any decay reaction, the sum of the masses of the products (daughter nuclei and other particles) will be lower than the mass of the reactants (the parent nucleus). This difference in mass will therefore be equivalent to the energy released by the decay process.

Alpha decay energy

In alpha decay, the mass difference, and therefore the energy released, will be given by:

Mass difference in alpha decay

= mass of parent nucleus – mass of daughter nucleus – mass of $^{4}_{2}\text{He}$

Energy released

= mass difference × 931.6 MeV

Note that the masses of the isotopes can be used instead of the masses of the nuclei, because the masses of the electrons are the same on each side of the equation and they will simply cancel out. The mass of helium-4 (alpha particle and two electrons) is 4.002 604 u.

The energy released in any alpha decay reaction is equal to:

$$\text{Energy} = \left(m_{\text{parent isotope}} - m_{\text{daughter isotope}} - 4.002604\right) \times 931.6 \text{ MeV}$$

Worked example 3.5.6

ALPHA DECAY ENERGY

Radium-226 was once used in paint on the dials of watches and clocks in the first half of the 20th century. It decays via alpha radiation with a visible glow when ultraviolet light is shone onto it. The hands of this clock from the 1950s glow brightly under UV light because the radium used in the paint gives off alpha radiation.

Write the decay equation for this process and use it to determine how much energy is released.

The isotopic masses of each particle in this decay reaction are:

Mass of radium-226 = 226.025 4 u

Mass of helium-4 = 4.002 604 u

Mass of daughter isotope = 222.017 5 u

Thinking	Working
This is an alpha decay reaction, so there will be an alpha particle, $^{4}_{2}\text{He}$, emitted, and a daughter nucleus, $^{A}_{Z}\text{X}$. Note that the isotopic masses are used here rather than the nuclear masses, because the number of electrons on each side of the reaction balances.	$^{226}_{88}\text{Ra} \rightarrow {}^{4}_{2}\text{He} + {}^{A}_{Z}\text{X}$
To find $^{A}_{Z}\text{X}$, use the conservation of mass number and conservation of atomic number.	$226 = 4 + A$, so $A = 226 - 4 = 222$ $88 = 2 + Z$, so $Z = 88 - 2 = 86$
The daughter nuclei have an atomic number of 86, which is radon. Now write the full alpha decay reaction.	$^{226}_{88}\text{Ra} \rightarrow {}^{4}_{2}\text{He} + {}^{222}_{86}\text{Rn}$
To find the energy given off by the alpha radiation, calculate the difference in mass between the reactants and products. Note that this reaction will proceed naturally because the mass difference is a positive number.	Δm = mass of $^{226}_{88}\text{Ra}$ – mass of $^{222}_{86}\text{Rn}$ – mass of $^{4}_{2}\text{He}$ = 226.025 4 – 222.017 5 – 4.002 604 = 0.005 296 u
Therefore the energy released by the alpha decay is the mass difference multiplied by 931.6 MeV per u.	Energy released = 0.005 296 × 931.6 = 4.934 MeV

➤ Try yourself 3.5.6

ALPHA DECAY ENERGY

Write the nuclear equation for the alpha decay of uranium-238 and use it to determine how much energy is released.

The isotopic masses of each particle in this decay reaction are:

Mass of uranium-238 = 238.050 788 2 u

Mass of helium-4 = 4.002 604 u

Mass of daughter isotope = 234.043 596 u

Beta decay energies

The energy released in beta decay reactions is about ten times less than that in alpha decay reactions.

In beta negative decay, the mass of the electron produced is already accounted for if the masses of the parent and daughter *isotopes* are used (i.e. the mass of the nuclei *and* the orbiting electrons), rather than the *nuclear* masses. The mass difference is simply the difference between the parent and daughter isotope masses:

Mass difference in beta negative decay = mass of parent isotope – mass of daughter isotope

Energy released = mass difference × 931.6 MeV

The energy released in any beta negative decay reaction is equal to:

$$\text{Energy} = \left(m_{\text{parent isotope}} - m_{\text{daughter isotope}}\right) \times 931.6 \text{ MeV}$$

Worked example 3.5.7

BETA NEGATIVE DECAY ENERGY

Thallium-204 decays via beta negative radiation. Write the decay equation for this process and use it to determine how much energy is released.

The isotopic masses of each particle in this decay reaction are:

Mass of thallium-204 = 203.973 863 5 u

Mass of electron = 0.000 548 6 u

Mass of daughter isotope = 203.973 043 6 u

Mass of antineutrino = 0 u

Thinking	Working
This is a beta negative decay reaction, so there will be an electron, ${}^{0}_{-1}\beta$, and an antineutrino, ${}^{0}_{0}\overline{\nu}$, emitted, with a daughter nucleus, ${}^{A}_{Z}X$, remaining.	${}^{204}_{81}Tl \rightarrow {}^{0}_{-1}\beta + {}^{0}_{0}\overline{\nu}_e + {}^{A}_{Z}X$
To find ${}^{A}_{Z}X$, use the conservation of mass number and conservation of atomic number.	$204 = 0 + 0 + A$, so $A = 204$ $81 = -1 + 0 + Z$, so $Z = 81 + 1 = 82$
The daughter nuclei have an atomic number of 82, which is lead. Now write the full beta negative decay reaction.	${}^{204}_{81}Tl \rightarrow {}^{0}_{-1}\beta + {}^{0}_{0}\overline{\nu}_e + {}^{204}_{82}Pb$
To find the energy given off by the beta negative decay, the difference in mass between the parent and daughter isotopes only is needed. The mass of the electron is *not* needed in this type of decay calculation. The mass of the neutrino is virtually zero, so this particle does not contribute to the mass difference. Note that this reaction will proceed naturally because the mass difference is a positive number.	Δm = mass of ${}^{204}_{81}Tl$ – mass of ${}^{204}_{82}Pb$ = 203.973 863 5 – 203.973 043 6 = 0.000 819 9 u
Therefore the energy released by the beta negative decay is the mass difference multiplied by 931.6 MeV per u.	Energy released = 0.000 819 9 × 931.6 = 0.763 8 MeV

➤ Try yourself 3.5.7

BETA NEGATIVE DECAY ENERGY

Write the nuclear equation for the beta negative decay of tritium (hydrogen-3) and use it to determine how much energy is released per reaction.

The isotopic masses of each particle in this decay reaction are:

Mass of hydrogen-3 = 3.016 049 277 9 u

Mass of daughter isotope = 3.016 029 3 u

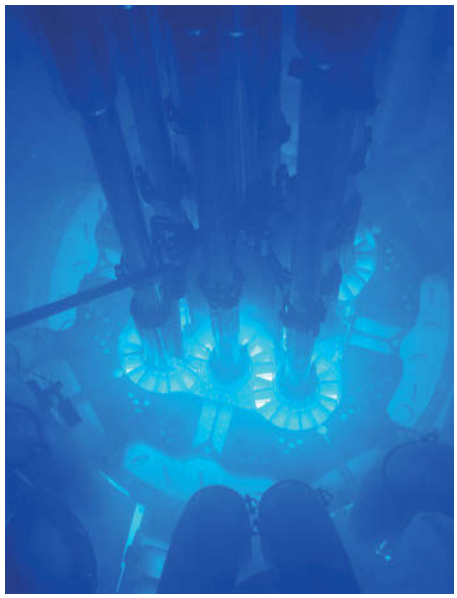


FIGURE 3.5.8 The blue 'Cerenkov radiation' glow around this submerged nuclear reactor core is due to beta decay particles travelling faster than the speed of light in water.

The situation is different in beta positive decay because a positron is produced, rather than an electron. Positrons do not make up ordinary matter and are therefore not accounted for in the isotope masses. The daughter isotope has one fewer proton than the parent nucleus, so the daughter isotope will also have one fewer electron than the parent isotope. To find the mass difference, you must subtract the mass of the daughter isotope, as well as *twice* the mass of an electron, from the parent isotope. This extra mass difference comes from the mass of the positron and the one fewer electrons in the daughter isotope.

Mass difference in beta positive decay

= mass of parent isotope – mass of daughter isotope – 2 × mass of electron

Energy released = mass difference × 931.6 MeV

The energy released in any beta positive decay reaction is equal to:

$$\text{Energy} = \left(m_{\text{parent isotope}} - m_{\text{daughter isotope}} - 0.0010972\right) \times 931.6 \text{ MeV}$$

The energy given off during any beta decay reaction is most commonly seen as an eerie blue glow around the core of a nuclear reactor (Figure 3.5.8). This is known as Cerenkov radiation, and results when the electrons or positrons produced actually travel faster than the speed of light in the water medium surrounding the reactor.

Worked example 3.5.8

BETA POSITIVE DECAY ENERGY

Fluorine-18 decays via beta positive radiation and is used extensively in positron emission tomography (PET) scans. Write the decay equation for this process and use it to determine how much energy is released.

The isotopic masses of each particle in this decay reaction are:

Mass of fluorine-18 = 18.000 938 0 u

Mass of positron = 0.000 548 6 u

Mass of daughter isotope = 17.999 161 0 u

Mass of neutrino = 0 u

Thinking	Working
This is a beta positive decay reaction, so there will be a positron, ${}^{0}_{1}\beta$, and a neutrino, ${}^{0}_{0}\nu_e$, emitted, with a daughter nucleus, ${}^{A}_{Z}\text{X}$, remaining.	${}^{18}_{9}\text{F} \rightarrow {}^{0}_{1}\beta + {}^{0}_{0}\nu_e + {}^{A}_{Z}\text{X}$
To find ${}^{A}_{Z}\text{X}$, use the conservation of mass number and conservation of atomic number.	$18 = 0 + 0 + A$, so $A = 18$ $9 = 1 + 0 + Z$, so $Z = 9 - 1 = 8$
The daughter nuclei have an atomic number of 8, which is oxygen. Now write the full beta positive decay reaction.	${}^{18}_{9}\text{F} \rightarrow {}^{0}_{1}\beta + {}^{0}_{0}\nu_e + {}^{18}_{8}\text{O}$
To find the energy given off by the beta positive decay, the difference in mass is needed. This is found by subtracting the mass of oxygen-18 and two positrons from the mass of the fluorine-18 isotope. This is because oxygen-18 has one fewer electrons (same mass as the positron) than fluorine-18, and the positron created also takes away some mass from the fluorine-18 nucleus. The mass of the neutrino is virtually zero so this particle contributes nothing to the mass difference. Note that this reaction will proceed naturally because the mass difference is a positive number.	Δm = mass of ${}^{18}_{9}\text{F}$ – mass of ${}^{18}_{8}\text{O}$ – 2 × mass of ${}^{0}_{1}\beta$ = 18.000 938 0 – 17.999 161 0 – 2 × 0.000 548 6 = 0.000 679 8 u
Therefore the energy released by the beta positive decay is the mass difference multiplied by 931.6 MeV per u.	Energy released = 0.000 067 98 × 931.6 = 0.6333 MeV or 633.3 keV

➤ Try yourself 3.5.8

BETA POSITIVE DECAY ENERGY

Write the nuclear equation for the beta positive decay of mercury-189 and use it to determine how much energy is released per reaction.

Isotopic masses needed are:

Mass of mercury-189 = 188.968 19 u

Mass of positron = 0.000 548 6 u

Mass of daughter isotope = 188.963 948 u

Gamma decay energy

There is no change in the mass number, atomic number or actual mass of the nucleus undergoing gamma decay, so there will be no mass difference between the parent and daughter nuclei. The parent nucleus loses energy because it is in a higher 'state' of energy. This is similar to a pot plant on a high shelf having a higher 'state' of energy than a pot plant on a lower shelf. When the parent nucleus falls to a lower 'state' it gives off energy as a gamma ray, as the nucleus reorganises its nucleons to a more stable arrangement. Gamma decay usually occurs after beta or alpha decay because those processes physically change the mass or the number of nucleons in the parent nucleus, leaving the daughter nucleus with an unstable arrangement of nucleons.

The gamma decay reaction for technetium-99m (also called *metastable* technetium-99) is:

$$^{99m}_{43}\text{Tc} \rightarrow {}^{99}_{43}\text{Tc} + {}^{0}_{0}\gamma + 140 \text{ keV}$$

The technetium-99 nucleus reorganises itself into a more stable configuration after the 140 keV gamma ray has been emitted, and it has the same atomic and mass numbers as the technetium-99m nucleus.

THE BINDING ENERGY PER NUCLEON CURVE

The higher the binding energy per nucleon of a nucleus, the more stable the nucleus is. Figure 3.5.9 is a graph of binding energy per nucleon against mass number for every known isotope.

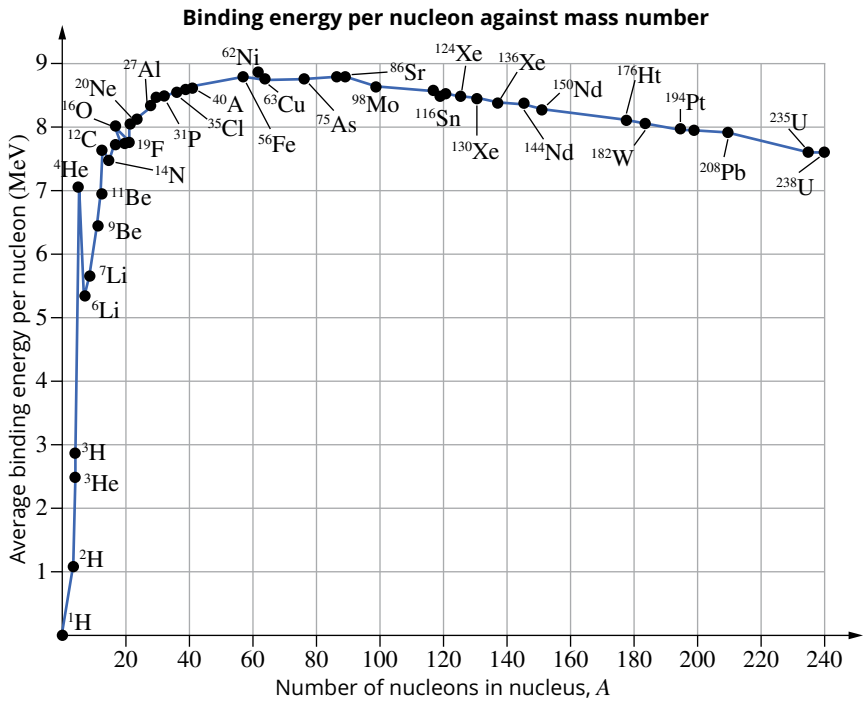


FIGURE 3.5.9 Graph of binding energy per nucleon for nuclei with mass numbers up to 240

A graph of the binding energy per nucleon against mass number has a rapid rise to a peak at nickel-62, then a gentler decline

There are several important features to note:

- There is a peak in binding energy per nucleon at nickel-62 (atomic number 28).
- Nuclei with low mass numbers tend to have low binding energy per nucleon, although $^4_2$He (an alpha particle) doesn't follow this trend.
- There is a rapid rise in binding energy per nucleon from a mass number of 2 to nickel-62.
- There is a more gentle decrease in binding energy per nucleon for nuclei with mass number greater than 62.

Nickel-62 has the highest binding energy per nucleon of all known isotopes. It is located very near to the isotopes iron-58 (atomic number 26) and iron-56, which are the second and third most tightly bound nuclei known. Isotopes heavier than nickel-62 are less stable because the diameter of their nuclei is too large for the attractive strong nuclear force to overcome the repulsive electrostatic force.

This curve will be used extensively in the final module of this chapter when you look at two specific types of nuclear reaction: fission and fusion.

Worked example 3.5.9

BINDING ENERGY PER NUCLEON CURVE

Use the graph in Figure 3.5.9 to compare the nuclear stability of oxygen-16 and beryllium-9.	
Thinking	**Working**
The approximate binding energy per nucleon for oxygen-16 and beryllium-9 can be read directly from the graph.	Binding energy per nucleon of oxygen-16 is approximately 8 MeV per nucleon. Binding energy per nucleon of beryllium-9 is approximately 6.5 MeV per nucleon.
The higher the binding energy per nucleon, the more tightly the nucleus is bound and the more stable it is.	8 MeV > 6.5 MeV So the nucleus of oxygen-16 is held together more tightly than a nucleus of beryllium-9.

➤ Try yourself 3.5.9

BINDING ENERGY PER NUCLEON CURVE

WS 1.2.3

Use the graph in Figure 3.5.9 to calculate the approximate binding energy of carbon-12.

3.5 Review

SUMMARY

- The electron volt (eV) is a unit of energy equal to 1.602×10^{-19} J. It is a non-SI unit, but is preferred for use in nuclear physics as it is more convenient than joules.
- An isotope can be intentionally changed into another isotope by bombarding it with another particle in a process called artificial transmutation.
- Artificial transmutation is different from natural radioactive decay, because decay is a naturally occurring process while artificial transmutation requires the input of energy, usually in a nuclear reactor or particle accelerator.
- The atomic mass unit (u) is a unit of mass used to measure the masses of nuclei and subatomic particles. It is equivalent to $1.660\,54 \times 10^{-27}$ kg.
- In most nuclear reactions, the sum of the masses of the reactants will not equal the sum of the masses of the products. This difference is known as the mass defect, Δm.
- A nuclear reaction will not proceed naturally if the mass defect is a negative number, because that reaction requires energy, rather than releases it.
- The energy required to break a nucleus completely into its constituent protons and neutrons is called the binding energy, ΔE.
- The binding energy can be calculated by using Einstein's famous mass–energy equivalence relationship:

$$E = mc^2$$

- One atomic mass unit (u) is equivalent to an energy of 931.6 MeV.
- The binding energy per nucleus is equal to the binding energy of a nucleus divided by the number of nucleons in that nucleus. It is a way of measuring the stability of a nucleus.
- A graph of binding energy per nucleon against mass number shows a curve with a peak at nickel-62. The higher a nuclei appears on the curve the more stable it is.

KEY QUESTIONS

Retrieval

1 Identify 5.0 MeV in terms of joules.

2 Identify 6.0×10^{-15} J in terms of eV and MeV.

3 Recall how many kg there are in each atomic mass unit.

4 Identify the isotope that has the highest binding energy per nucleon.

Comprehension

5 Explain how artificial transmutation is different from radioactive decay.

6 Explain why a nuclear reaction will not proceed if the mass defect is negative.

7 Identify the particle X in each of the following reactions.

a ${}^{9}_{4}\text{Be} + {}^{4}_{2}\text{He} \rightarrow {}^{12}_{6}\text{C} + \text{X}$

b ${}^{14}_{7}\text{N} + \text{X} \rightarrow {}^{14}_{6}\text{C} + {}^{1}_{1}\text{H}$

c ${}^{235}_{92}\text{U} + {}^{1}_{0}\text{n} \rightarrow {}^{92}_{36}\text{Kr} + \text{X} + 3\,{}^{1}_{0}\text{n}$

8 The artificial transmutation of cobalt-59 takes place in the core of a nuclear reactor. To create the new radioisotope cobalt-60, describe what the parent nucleus is bombarded with.

Analysis

9 Consider the following nuclear reaction:

$${}^{23}_{11}\text{Na} \rightarrow {}^{19}_{9}\text{F} + {}^{4}_{2}\text{He}$$

The following data could be useful:
Mass of sodium-23 = 22.9897 u
Mass of fluorine-19 = 18.9984 u
Mass of helium-4 = 4.002 604 u

a Determine the mass defect for the reaction.

b Deduce whether this reaction will proceed naturally.

10 Apply your knowledge to show that the energy equivalent of a single electron is 0.511 MeV.

11 The power output of the Sun is 3.83×10^{26} W (J s^{-1}). Determine how much matter is converted into energy each second to account for this amount of power.

12 Beryllium-8 (mass = 8.005 305 10 u) is radioactive and undergoes alpha decay.

a Recall the full nuclear equation for this decay.

b Determine how much energy is released by this decay in keV.

3.5 Review *continued*

13 Phosphorus-32 (mass = 31.973 907 27 u) is a radioactive isotope and beta negative decays to give the daughter isotope sulfur-32 (mass = 31.972 071 00 u).

a Recall the full nuclear equation for this decay.

b Determine how much energy is released by this decay in MeV.

14 Copper-64 (mass = 63.929 764 2 u) is also radioactive and beta positive decays to nickel-64 (mass = 63.927 966 0 u).

a Recall the full nuclear equation for this decay.

b Determine how much energy is released in this decay in keV.

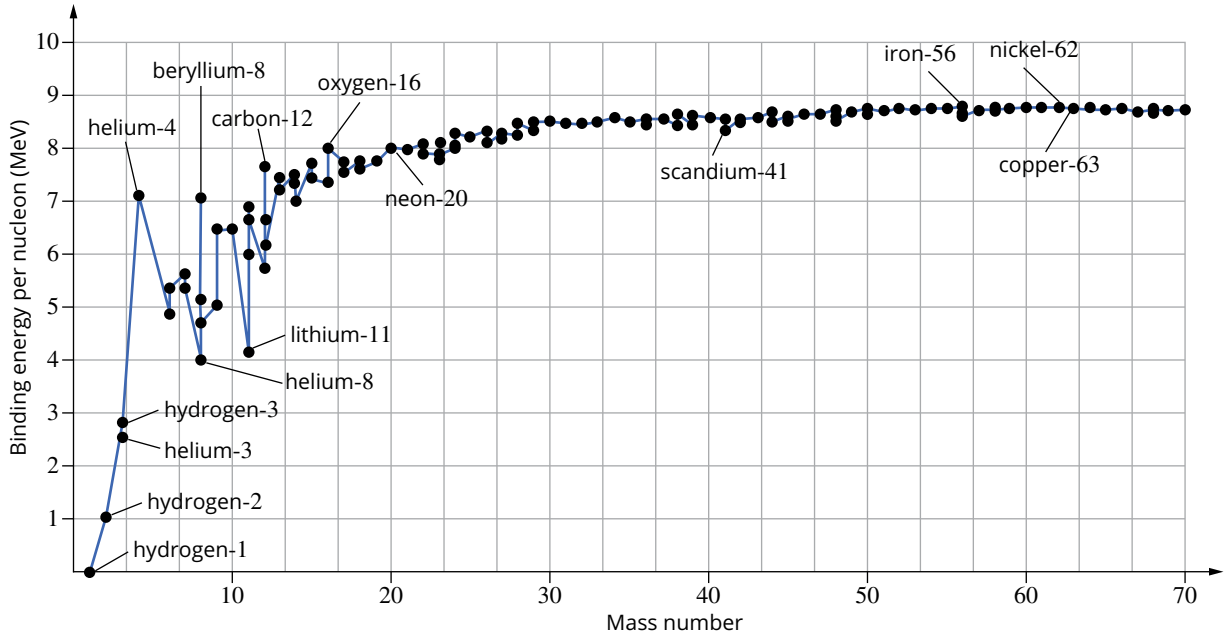
15 The graph below shows the binding energy for selected isotopes.

a Identify the isotope that is the most stable: oxygen-16, helium-8 or iron-56.

b Determine the binding energy of a nucleus of scandium-41.

c Use the binding energy per nucleon of carbon-12 to approximately determine its nuclear mass and isotope mass.

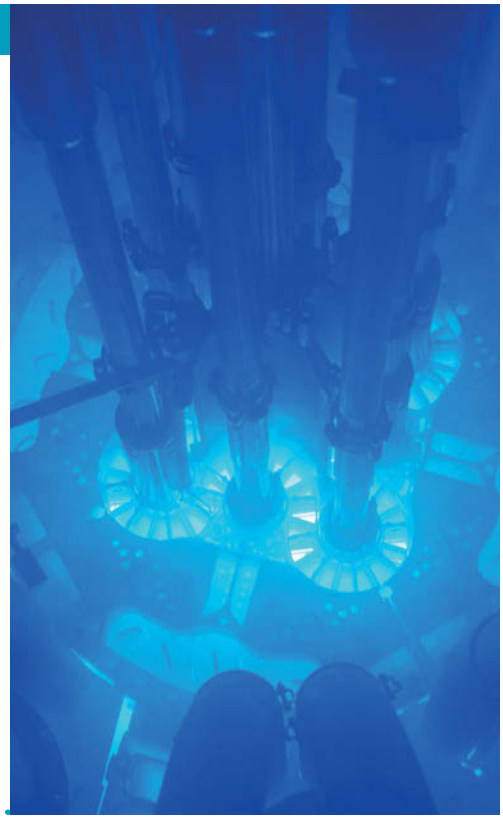
Binding energy per nucleon for selected isotopes with mass numbers from 1 to 70



3.6 Fission and fusion

BY THE END OF THIS MODULE, YOU SHOULD BE ABLE TO:

- recall that nuclear fission occurs when a nucleus is made to split and release a number of neutrons along with a large amount of energy
- recall that nuclear fission can be induced by bombarding a fissile nucleus with a neutron
- understand that a fissile nucleus is one that can absorb a neutron and undergo nuclear fission
- understand that at least one neutron per fission reaction is produced and that a chain reaction occurs when the free neutrons collide with further fissile nuclei, resulting in an exponential increase in the number of fission reactions and energy released
- understand that when a large nucleus such as uranium splits into two fragments, the binding energy per nucleus increases; this is the energy released during fission
- understand that nuclear fusion is the combining of light nuclei to form heavier nuclei. Extremely high temperatures and pressures are needed for fusion to occur
- explain that the amount of energy released per nucleon is greater for fusion than for fission reactions
- recall that as nucleons fuse together, the binding energy per nucleon increases; this is the energy released during fusion.



Einstein's mass–energy equivalence equation, $E = mc^2$, can be used to find the amount of energy produced in nuclear decay, and binding and bombardment reactions. This equation calculates the amount of energy released when a unit mass is completely converted into energy. There are two more classes of nuclear reactions that also release large amounts of energy. One of these, nuclear fission, is a source of power for a large number of countries around the world, and the other, nuclear fusion, is the most common reaction of any sort in the universe.

NUCLEAR FISSION

Just before World War II broke out, four German physicists, Otto Hahn, Lise Meitner, Fritz Strassmann and Otto Robert Frisch, discovered **nuclear fission** of a uranium isotope. Nuclear fission is a process in which a heavy and unstable nucleus is forced to split into lighter nuclei. As it splits it releases a large amount of energy and smaller particles, as shown in Figure 3.6.1.

Most daughter nuclei of fission reactions are radioactive themselves, and will decay, but usually at a slower rate. Fission is primarily used in the production of electricity in a nuclear reactor, and in nuclear weapons. Note that nuclear fission is not the same as natural radioactive decay.

The most common example of a radioisotope that can undergo fission is uranium-235. This fission reaction starts with the bombardment of the uranium-235 nucleus with a single, relatively slow-moving neutron to produce uranium-236. The extra neutron is absorbed into the uranium-235 nucleus.

Nuclear fission is the process in which a large nucleus is forced to split into at least two approximately equal-sized fragments with the release of neutrons and energy.

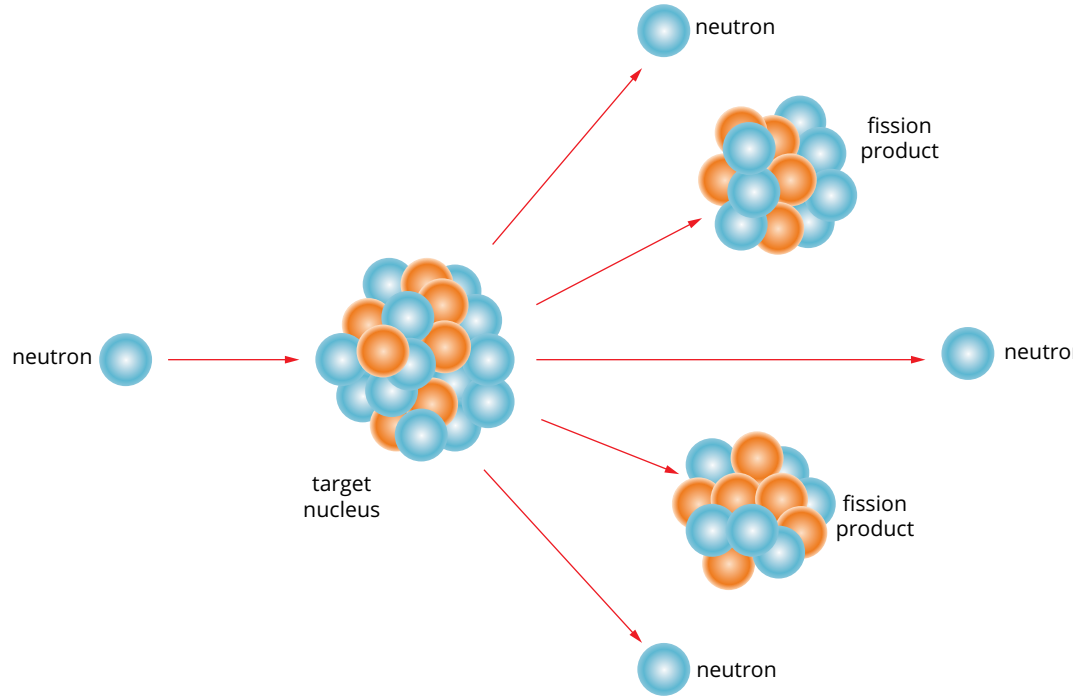


FIGURE 3.6.1 The nuclear fission reaction in which a target is bombarded with a smaller particle (usually a neutron) that causes the target to split into two approximately equal-sized pieces with more neutrons produced.

The strong nuclear force cannot overcome the electrostatic forces within this nucleus, so the uranium-236 nucleus breaks apart into at least two similar-sized nuclei along with a few neutrons and a large amount of energy.

These nuclear fission reactions are summarised below:

$$^{235}_{92}\text{U} + ^{1}_{0}\text{n} \rightarrow ^{236}_{92}\text{U}$$

$$^{236}_{92}\text{U} \rightarrow ^{141}_{56}\text{Ba} + ^{92}_{36}\text{Kr} + 3\,^{1}_{0}\text{n}$$

Note that the uranium-236 is not decaying into barium-141 and krypton-92, but creating **fission fragments** of these daughter isotopes. The fission fragments are usually very radioactive and therefore dangerous to living tissue.

The above reaction is just one combination of the ways uranium-236 can be fragmented. Other examples include:

$$^{235}_{92}\text{U} + ^{1}_{0}\text{n} \rightarrow ^{236}_{92}\text{U} \rightarrow ^{143}_{55}\text{Cs} + ^{90}_{37}\text{Rb} + 3\,^{1}_{0}\text{n}$$

or

$$^{235}_{92}\text{U} + ^{1}_{0}\text{n} \rightarrow ^{236}_{92}\text{U} \rightarrow ^{90}_{38}\text{Sr} + ^{143}_{54}\text{Xe} + 3\,^{1}_{0}\text{n}$$

As long as the atomic numbers and mass numbers are conserved, there are many other fragment pairs that can result from this fission reaction. The fragments usually range from germanium (Z = 32) to samarium (Z = 62). The general fission of uranium-235 is shown in Figure 3.6.2.

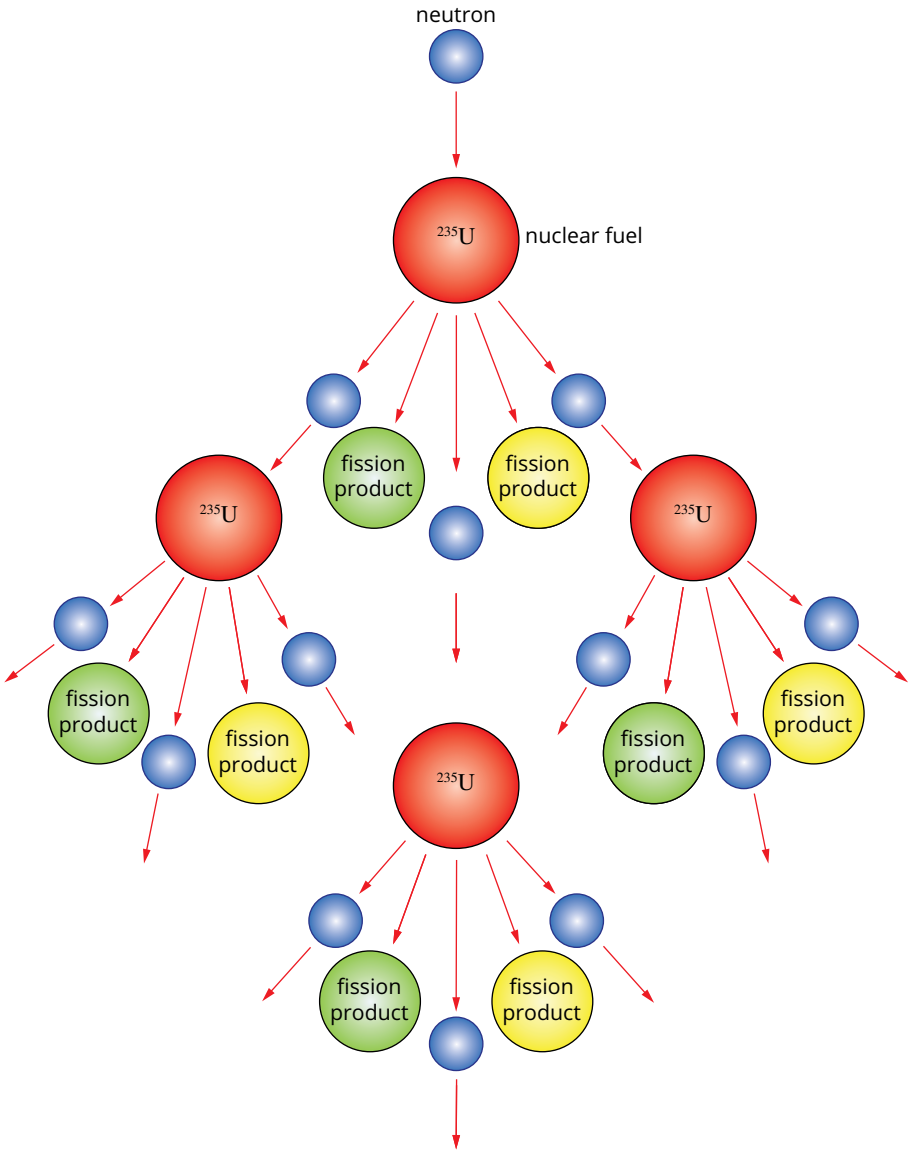


FIGURE 3.6.2 The general nuclear fission reaction of uranium-235 creates fission fragments and three neutrons.

Typically, the percentage of mass of the original heavy isotope that is converted into energy is around 0.1%, and the amount of energy created in a nuclear fission reaction is often more than 100 times that produced in natural radioactive decay. To calculate the amount of energy released in a single nuclear fission reaction, you apply the same reasoning as to calculating the mass difference in alpha decay.

$$\text{Mass difference} = \text{mass of reactants} - \text{mass of products}$$

$$\text{Energy} = \text{mass difference} \times 931.6 \text{ MeV per u}$$

The energy released by nuclear fission is calculated in the same way as decay reactions, in which the mass defect is multiplied by 931.6 MeV.

Worked example 3.6.1

ENERGY FROM NUCLEAR FISSION

When a uranium-235 nucleus is bombarded with a single neutron, it fragments into three neutrons, caesium-137 and rubidium-96.

a Write the equation for this nuclear fission reaction and calculate the energy released.

Thinking	Working
This is a nuclear fission reaction so there are two reactants: uranium-235 and a neutron. There are five products: caesium-137; rubidium-96 and three neutrons. The number of electrons is conserved in fission reactions, so the masses of the isotopes can be used instead of the nuclear masses.	$^{235}_{92}\text{U} + {}^{1}_{0}\text{n} \rightarrow {}^{137}_{55}\text{Cs} + {}^{96}_{37}\text{Rb} + 3\,{}^{1}_{0}\text{n}$

b Determine the percentage of the original mass of the uranium-235 that was converted into energy.
The required masses are:
Mass of neutron = 1.008 665 u
Mass of uranium-235 = 235.043 929 9 u
Mass of caesium-137 = 136.907 089 5 u
Mass of rubidium-96 = 95.934 27 u

Thinking	Working
Find the energy released by the reaction by first finding the difference in the masses of reactants and products. Mass difference = mass of reactants – mass of products Note that the mass difference is a positive value, so the nuclear fission reaction will proceed, but it would not proceed if the neutron were not bombarded at the uranium-235 nucleus initially.	Mass of reactants = 235.043 929 9 + 1.008 665 = 236.052 594 9 u Mass of products = 136.907 089 5 + 95.934 27 + 3 × 1.008 665 = 235.867 354 5 u Mass difference = 236.052 594 9 – 235.867 354 5 = 0.185 240 4 u
Now, find the amount of energy equivalent to the mass difference by multiplying the mass difference by 931.6 MeV per u.	Amount of energy released = 0.185 240 4 × 931.6 = 172.6 MeV
The percentage of mass lost from uranium-235 is found by dividing the mass difference by the mass of the uranium-235 and multiplying by 100.	Percentage of mass lost $= \frac{0.185\,240\,4}{235.043\,929\,9} \times 100$ = 0.079%

➤ Try yourself 3.6.1

ENERGY FROM NUCLEAR FISSION

A plutonium-239 nucleus is bombarded with a single neutron and fragments into xenon-134 and zirconium-103, with the release of three neutrons.

a Write the nuclear fission reaction for this process.

b Calculate the percentage of the original mass of the plutonium-239 that is converted into energy.
The required masses are:
Mass of neutron = 1.008 665 u
Mass of plutonium-239 = 239.052 163 4 u
Mass of xenon-134 = 133.905 394 5 u
Mass of zirconium-103 = 102.926 60 u

An important feature of nuclear fission is the production of extra neutrons, which can go on to react with other fissile nuclei to trigger more fission reactions. If three neutrons are released in a single fission reaction, then those neutrons can trigger three more fission reactions by bombarding more fissile material. Each of those fission reactions then produces three more neutrons, releasing 9, then 27, then 81 neutrons, and so on. This exponential cascade of more neutrons initiating more fission reactions is called a **chain reaction**, as shown in Figure 3.6.3.

A chain reaction occurs when a single nuclear reaction causes a dramatic increase in the number of successive nuclear reactions.

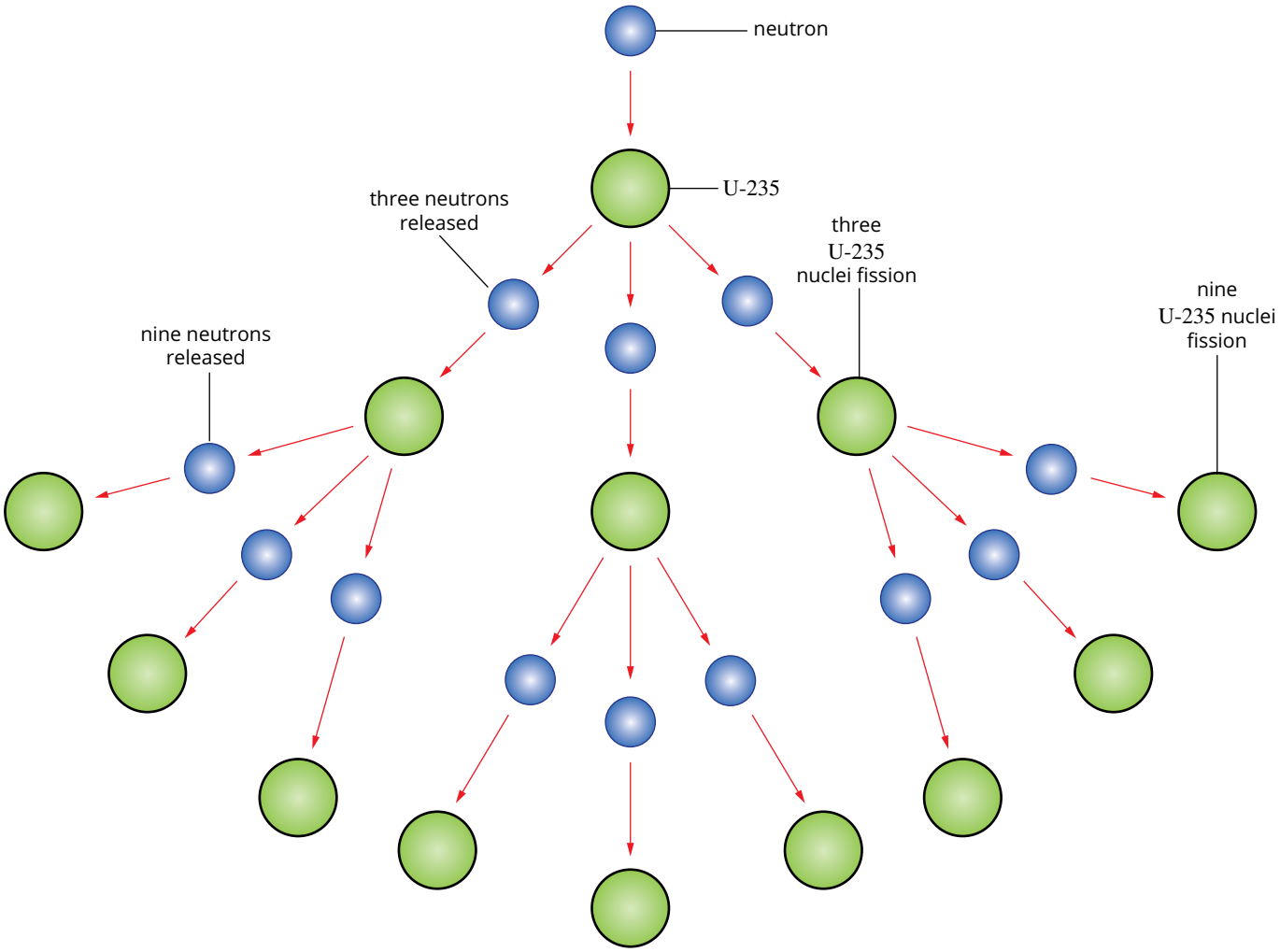


FIGURE 3.6.3 The start of a chain reaction involving uranium-235. Each fission reaction produces three neutrons, which then go on to react with three other uranium-235 nuclei to create nine new neutrons, and so on, in a runaway series of reactions producing very large amounts of energy.

After only 13 series of reactions there will be over one million neutrons available to trigger that many fission reactions. The number of fission reactions occurring at one given time during a chain reaction is increasing, so the amount of energy produced also increases.

Chain reactions continue for as long as there is enough material available. The amount of material needed to sustain a chain reaction is known as the critical mass. Inside nuclear reactors the amount of fissile material is controlled and a chain reaction is usually not possible. However, in a nuclear weapon there is enough material to sustain a chain reaction and Figure 3.6.4 is the result.

FIGURE 3.6.4 The unmistakable mushroom cloud formed by an unregulated chain reaction of uranium-235 or plutonium-239 in a nuclear bomb. This photograph was taken in 1971 by the French army when they conducted nuclear weapons testing at Moruroa Atoll in the Pacific Ocean.

NUCLEAR FUSION

Nuclear fission is the result of a heavy nucleus splitting into two or more smaller nuclei with the release of energy and particles. The opposite type of reaction in which two smaller nuclei combine to produce a heavier nucleus and energy is known as **nuclear fusion**. Fusion occurs when two light nuclei (usually isotopes of hydrogen or helium) join together to make a heavier and more stable nucleus. The mass of the new nucleus is lighter than the sum of the nuclei that fused to form it, so energy will be released in this process.

Nuclear fusion is the process whereby two smaller nuclei join, or fuse, together to create a larger nucleus with the creation of energy.

Fusion reactions, specifically the reaction of two protons joining to make helium, are, by far, the most common type of nuclear or chemical reaction in the universe. They produce the second highest amount of energy per kilogram of matter, only behind matter–antimatter annihilation reactions.

In order for fusion to occur, two conditions must be met.

1 The smaller nuclei must be travelling very fast. To achieve this the particles must have a very high temperature of about 10 million kelvin.
2 There need to be enough nuclei available to sustain a fusion reaction. This occurs under high pressure.

Both conditions of high speed and high pressure are easily met in the cores of stars, and a long time ago at the Big Bang. Currently, no nuclear fusion reactor on Earth can sustain a fusion reaction with a net output of energy, but research continues in the USA, Asia and Europe (Figure 3.6.5).

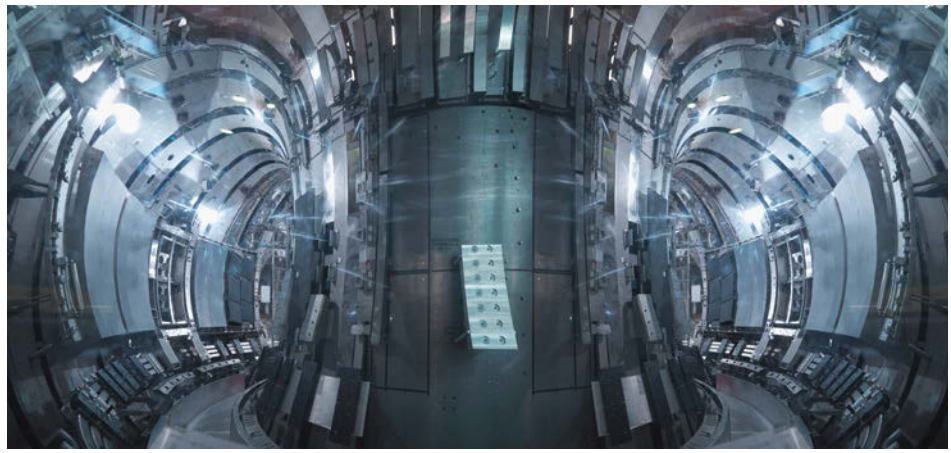


FIGURE 3.6.5 The inside of a nuclear fusion reactor design called a tokamak at the Joint European Torus in England

A very common nuclear fusion reaction that occurs inside the cores of stars the size of the Sun is the fusion of ${}^{2}_{1}\mathrm{H}$ (the nucleus of deuterium, or hydrogen-2) with a proton, ${}^{1}_{1}\mathrm{H}$. This reaction produces ${}^{3}_{2}\mathrm{He}$ and energy in the form of a gamma ray. The reaction is written as:

$$ {}^{1}_{1}\mathrm{H} + {}^{2}_{1}\mathrm{H} \rightarrow {}^{3}_{2}\mathrm{He} + {}^{0}_{0}\gamma $$

Note that even though this reaction produces a gamma ray, it is not the same as gamma decay.

As in nuclear fission, some of the products of a fusion reaction are smaller particles. An example of a fusion reaction that occurred about one minute after the Big Bang is the reaction of the nucleus of deuterium with the nucleus of tritium (Figure 3.6.6).

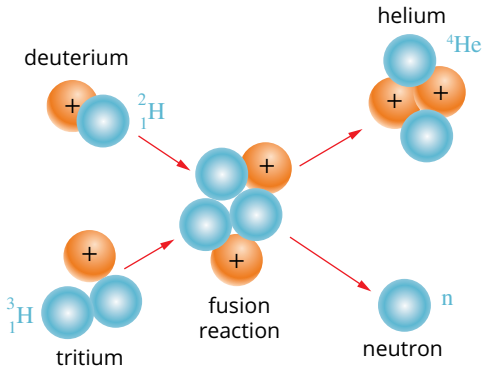


FIGURE 3.6.6 The fusion reaction of ${}^{2}_{1}\mathrm{H}$ with ${}^{3}_{1}\mathrm{H}$ produces an alpha particle, a neutron and energy.

This produces an alpha particle, a free neutron and energy:

$$ {}^{2}_{1}\mathrm{H} + {}^{3}_{1}\mathrm{H} \rightarrow {}^{4}_{2}\mathrm{He} + {}^{1}_{0}\mathrm{n} + \text{energy} $$

Inside the cores of the largest stars, fusion reactions of an alpha particle with heavier nuclides can take place that produce nuclides up to ${}^{56}_{28}\mathrm{Ni}$. The heaviest nuclide that can fuse with an alpha particle is, therefore, ${}^{52}_{26}\mathrm{Fe}$, because it produces ${}^{56}_{28}\mathrm{Ni}$ in the following reaction:

$$ {}^{52}_{26}\mathrm{Fe} + {}^{4}_{2}\mathrm{He} \rightarrow {}^{56}_{28}\mathrm{Ni} + \text{energy} $$

Fusion of nuclides heavier than ${}^{56}_{28}\mathrm{Ni}$ actually *require* energy rather than *produce* energy and so will not proceed.

The amount of energy created in a nuclear fusion reaction is usually lower than that produced in a nuclear fission reaction, but the energy per mass of reactants is much higher, around 0.5% of the fusing particles. Again, to calculate the amount of energy released in a nuclear fusion reaction, you apply the same reasoning as used in nuclear fission reactions:

$$ \text{Mass difference} = \text{mass of reactants} - \text{mass of products} $$

$$ \text{Energy} = \text{mass difference} \times 931.6\ \text{MeV per u} $$

The energy released by nuclear fusion reactions is calculated in the same way as for decay reactions, in which the mass defect is multiplied by 931.6 MeV.

Worked example 3.6.2

ENERGY FROM NUCLEAR FUSION

A deuterium (hydrogen-2) nucleus fuses with a tritium (hydrogen-3) nucleus to produce an alpha particle and a neutron.

a Write the equation for the nuclear fusion reaction.

Thinking	Working
This is a nuclear fusion reaction so there are two reactants: a deuterium nucleus and a tritium nucleus. There are two products: an alpha particle and a neutron.	${}^{2}_{1}\text{H} + {}^{3}_{1}\text{H} \rightarrow {}^{4}_{2}\text{He} + {}^{1}_{0}\text{n}$

b Calculate the energy released by the process and, hence, the percentage of the mass of the reactants that has been converted into energy.

The required masses are:
Mass of neutron = 1.008 665 u
Mass of deuterium atom = 2.014 101 78 u
Mass of tritium atom = 3.016 049 2 u
Mass of an alpha particle = 4.001 506 u

Thinking	Working
To find the energy released by the reaction, the difference in mass of the reactants and products is needed. Note that because the masses of the deuterium and tritium isotopes, and the mass of the alpha particle (without any electrons) are given, the masses of two electrons will need to be subtracted from the reactants to keep everything in terms of nuclear masses. Also note that the nuclear fusion reaction will proceed because the mass difference is a positive value.	Mass of deuterium nucleus = mass of deuterium isotope – mass of electron = 2.014 101 78 – 0.000 548 6 = 2.013 553 18 u Mass of tritium nucleus = mass of tritium isotope – mass of electron = 3.016 049 2 – 0.000 548 6 = 3.015 500 6 u Mass of reactants = 2.013 553 18 + 3.015 500 6 = 5.029 053 78 u Mass of products = 4.001 506 + 1.008 665 = 5.010 171 u Mass difference = 5.029 053 78 – 5.010 171 = 0.018 882 78 u
Now find the amount of energy this is equivalent to by using 931.6 MeV per u.	Amount of energy released = 0.018 882 78 × 931.6 = 17.59 MeV
The percentage of the masses of the reactants that has been converted into energy is found by dividing the mass difference by the sum of the masses of the reactants and then multiplying by 100.	Percentage of reactants mass lost as energy $= \frac{0.1888278}{5.029053789 \times 100}$ = 0.38%

➤ Try yourself 3.6.2

ENERGY FROM NUCLEAR FUSION

An important nuclear fusion reaction that occurs inside stars heavier than the Sun is the combining of a carbon-12 nucleus with an alpha particle to create a heavier nucleus and energy in the form of a gamma ray.

The required masses are:

Mass of carbon-12 atom = 12.000 000 0 u

Mass of daughter isotope = 15.994 914 619 56 u

Mass of alpha particle (nucleus only) = 4.001 506 u

a Write the nuclear fusion reaction for this process.

b Determine the nuclide created in this reaction.

c Calculate the energy released from this reaction.

d Calculate the percentage of the mass of reactants that has been converted into energy.

FISSION, FUSION AND THE BINDING ENERGY PER NUCLEON CURVE

Nuclear fission reactions produce energy when heavy nuclei split into two or more lighter nuclei. Nuclear fusion reactions produce energy when two lighter nuclei combine to produce a heavier nucleus.

Fusion reactions produce energy up to the creation of mass number 62, which is nickel-62. Fission reactions produce energy for products down to nickel-62. This is seen more clearly in the binding energy per nucleon graph in Figure 3.6.7.

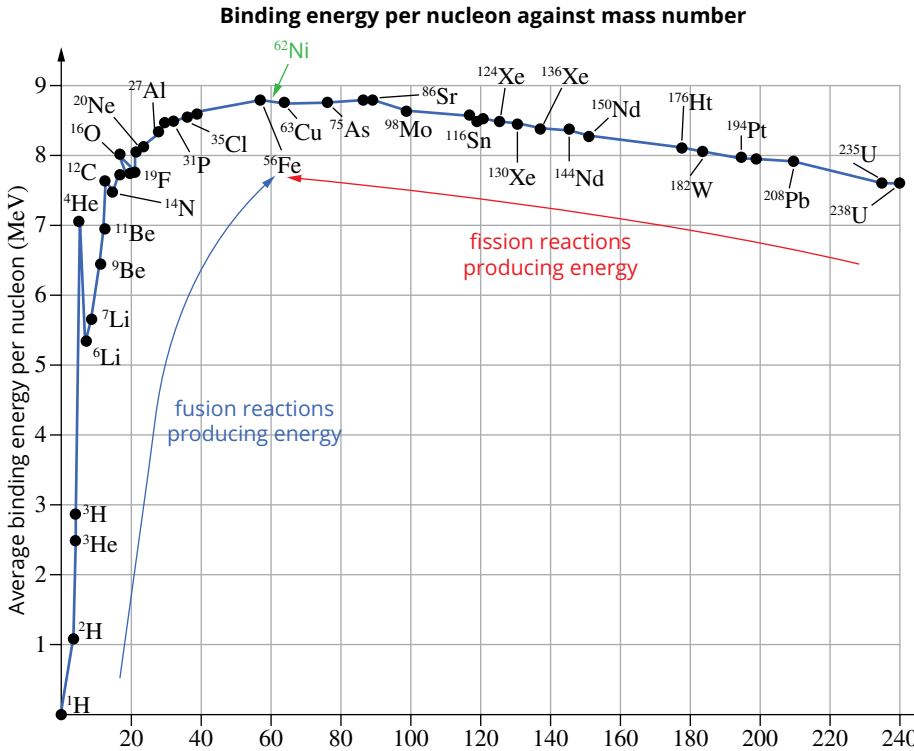


FIGURE 3.6.7 Fusion reactions produce energy when the product is lighter than nickel-62, and fission reactions produce energy when the product is heavier than nickel-62.

There are other important features of this graph:

- Fusion reactions produce energy when their products are higher on the graph (i.e. have a greater binding energy per nucleon) than their reactants. This is especially important when fusion of nuclides such as helium-4 is occurring because of the local peak in the graph at this nuclide.
- Similarly, fission reactions will produce energy when their products are higher on the graph than their reactants.
- Fusion reactions do not occur if their products are heavier than nickel-62, because those reactions require energy to proceed.
- Fission reactions do not occur if their products are lighter than nickel-62, because those reactions also require energy to proceed.
- The fusion part of the graph is steeper. This means that a small change in mass number for low-mass nuclei produce more energy than a similar change in mass number for high-mass nuclei. Another way to say this is that a higher percentage of mass is being converted into energy in fusion than occurs in fission, or that there is more energy released per nucleon in fusion than in fission.

Nuclear *fission* reactions produce energy if the products are heavier than nickel-62 (have a mass number larger than 62).

Most nuclear *fusion* reactions produce energy if the products are lighter than nickel-62 (have a mass number smaller than 62).

Harnessing nuclear power

The use of nuclear power and the replacement of fossil fuels have long been debated all over the world. Currently, more than thirty countries use some form of nuclear fission reaction to produce electricity or heating and, worldwide, about 10% of electricity is generated by nuclear fission. France leads the world in nuclear power generation with almost three-quarters of its electricity production produced by nuclear fission reactors. Australia only has one nuclear reactor in Lucas Heights in Sydney, but this reactor is used to produce radionuclides for use in medicine and research.

Fossil fuels dominate Australia's production of electricity and are the leading cause of enhanced global warming from the production of carbon dioxide. Nuclear fission, however, produces almost no carbon dioxide so, in that aspect, nuclear fission will not harm the environment. Fission power is also much more efficient than the burning of fossil fuels: 1 kg of uranium-235 fuel in a nuclear reactor produces millions of times more energy than the same mass of coal, oil or natural gas.

Figure 3.6.8 shows the uranium hexafluoride pellets used as nuclear fuel in fission reactors around the world. The pellets are cylinders 1 cm in diameter by 1.5 cm high with a mass of 6 g and each pellet can produce 480 GJ of energy.

FIGURE 3.6.8 The uranium hexafluoride fuel pellets used in many nuclear power stations around the world

The risks involved in harnessing nuclear power are the major reasons why many countries have not adapted nuclear fission as a source of energy. Some of these factors are discussed.

Waste products

Fission reactions produce many isotopes and some of these are very radioactive and have long half-lives. There is a continuing debate as to what to do with this waste, such as dump it in the ocean, bury it, or even launch it into the Sun.

Security

Countries that use fission require uranium as a fuel, but they may have to import uranium from another country. This creates security issues with transportation: a third party might intercept shipments, as fuel used in nuclear reactors can be modified to produce fuel for nuclear weapons.

Risk of accidents

Nuclear fission is generally safe, but when accidents occur, the consequences are disastrous and can last for centuries. There have been three major nuclear reactor incidents (Three Mile Island in the USA in 1979, Chernobyl in the Ukraine in 1986, and Fukushima in Japan in 2011) in which the cooling systems of the reactor failed, causing the nuclear fuel to melt down into the floor (Figure 3.6.9). This caused the fission reactions to become uncontrolled to a point where explosions release a large amount of radioactive material into the environment.

FIGURE 3.6.9 Solidified radioactive 'lava' made of concrete, this structure known as the 'Elephant's Foot' is a result of the Chernobyl disaster.

Review

1. Identify the country that generates the highest percentage of its electricity using nuclear power.
2. State what Australia's only nuclear reactor produces.
3. When a 6 g piece of coal is burnt, it will produce about 180 kJ of energy. Determine how many times less energy the coal produces than a 6 g uranium hexafluoride pellet.
4. Explain why nuclear fission produces no carbon dioxide.
5. Of the risk factors mentioned above, deduce which one would have the most drastic consequences in terms of economic loss and loss of human life. Explain your answer.

3.6 Review

SUMMARY

- Nuclear fission occurs when a nucleus is made to split and release a number of neutrons along with a large amount of energy.
- Nuclear fission can be induced by bombarding a fissile nucleus with a neutron.
- A fissile nucleus is one that can absorb a neutron and undergo nuclear fission.
- If a large nucleus such as uranium splits into two fragments, the binding energy per nucleon also increases. This is the energy released during fission.
- When fission occurs, the mass of the fission fragments is always less than the mass of the original particles. This decrease in mass is proportional to energy, as given by $\Delta E = \Delta mc^2$.
- In a fission reaction, at least one neutron per fission is produced. A chain reaction occurs when the free neutrons collide with further fissile neuclei, resulting in an exponential increase in the number of fission reactions and energy released.
- Nuclear fusion is the combining of light nuclei to form heavier nuclei. Extremely high temperatures and pressues are needed for fusion to occur.
- A small amount of mass is lost during a fusion reaction. This mass is related to the energy produced according to $\Delta E = \Delta mc^2$.
- Nuclei are positively charged and so repel each other due to electrostatic forces. Approaching nuclei must have enough speed and pressure to overcome the electrostatic forces and get close enough for the strong nuclear force to take effect.
- The amount of energy released per nucleon is greater for fusion than for fission reactions.
- As nucleons fuse together, the binding energy per nucleon increases. This is the energy released during fusion.

KEY QUESTIONS

Retrieval

1 List an example of a nuclide that will undergo nuclear fission.

2 List an example of a nuclide that will undergo fusion.

3 Define the terms 'fissile' and 'chain reaction'.

Comprehension

4 Explain how nuclear fission differs from radioactive decay.

5 Explain why nuclear fission is generally considered to be a non-natural process.

6 Explain why slow-moving neutrons are needed for fission to occur, but very fast-moving particles are needed for fusion to occur.

7 Explain why fusion require enormous temperatures and pressures.

Analysis

8 Differentiate between nuclear fission and nuclear fusion.

9 Plutonium-239 is a fissile material. When a plutonium-239 nucleus is struck by, and absorbs, a neutron, it can fragment in many different ways.

Consider the example of a nucleus of plutonium-239 that splits into barium-145 and strontium-93 and releases some neutrons.

a Determine the number of neutrons.

b Recall the full fission reaction for this process.

c Calculate how much energy is released in this reaction by determining the mass difference for the following masses of isotopes:
Plutonium-239 mass = 239.052 163 4 u
Neutron mass = 1.008 665 u
Barium-145 mass = 144.927 63 u
Strontium-93 mass = 92.914 026 u

d Determine the percentage of the original plutonium-239 isotope that was converted into energy.

10 The following fusion reaction is taking place inside the core of the Sun:

$$^{3}_{2}\text{He} + \text{X} \rightarrow {}^{4}_{2}\text{He} + {}^{1}_{1}\text{H} + {}^{1}_{1}\text{H}$$

During each reaction, 23.0 MeV of energy is released.

a Determine the atomic and mass numbers and symbol of particle X.

b Calculate how much energy is released per reaction in joules.

c Determine the mass defect for this fusion reaction.

Chapter review

WS 1.2.5 WS 1.2.6 TR 1.2

03

KEY TERMS

alpha particle
alpha radiation
antineutrino
artificial transmutation
atomic number
beta negative radiation
beta particle
beta positive radiation
binding energy
binding energy per nucleon
chain reaction
coulomb
coulomb force
daughter nucleus
decay
decay series
electromagnetic wave
electron
electron volt
electrostatic force
fission fragments
gamma radiation
gamma ray
half-life
ionisation
ionising radiation
isotope
mass defect
mass number
neutral
neutrino
neutron number
nuclear fission
nuclear fusion
nuclear reaction
nuclear reactor
nuclear transmutation
nucleon
nuclide
parent nucleus
particle accelerator
penetrating ability
positron
proton
radiation
radioactive
radioactivity
radioisotope
radionuclide
Segre plot
strong nuclear force
subatomic
transmutation
unified atomic mass unit

KEY QUESTIONS

Retrieval

1 Identify the collective term used for protons and neutrons:
- **A** isotopes
- **B** nuclides
- **C** neurons
- **D** nucleons

2 Identify the number of protons in the $^{145}_{61}$Pm nuclide:
- **A** 145
- **B** 61
- **C** 84
- **D** 206

3 Identify the isotope(s) that have seven neutrons in their nucleus:
- **A** carbon-12
- **B** carbon-13
- **C** carbon-14
- **D** nitrogen-14

4 Identify how many protons and neutrons there are in the $^{45}_{20}$Ca nuclide.

5 Use the periodic table (Figure 3.2.2, page 54) to determine the number of protons, neutrons and nucleons in cobalt-60.

6 Determine the nature of the unknown, X, for the following transmutation:

$$^{60m}_{27}\text{Co} \rightarrow {}^{60}_{27}\text{Co} + \text{X}$$

(60m means the nuclide is metastable and has a higher level of stability than very short-lived isotopes. The mass number is still 60.)

7 Identify each of these particles or radiation types:
- **a** $^{0}_{-1}$A
- **b** $^{1}_{1}$B
- **c** $^{4}_{2}$C
- **d** $^{1}_{0}$D
- **e** $^{0}_{0}$E
- **f** $^{0}_{1}$F

Comprehension

Questions 8–10 refer to equations I–IV below:

I $^{64}_{29}\text{Cu} \rightarrow {}^{64}_{28}\text{Ni} + {}^{0}_{1}\beta + {}^{0}_{0}\nu$

II $^{20}_{10}\text{Ne} + {}^{4}_{2}\text{He} \rightarrow {}^{24}_{12}\text{Mg} + {}^{0}_{0}\gamma$

III $^{256}_{102}\text{No} \rightarrow {}^{252}_{100}\text{Fm} + {}^{4}_{2}\text{He}$

IV $^{64}_{29}\text{Cu} \rightarrow {}^{64}_{30}\text{Zn} + {}^{0}_{-1}\beta + {}^{0}_{0}\bar{\nu}$

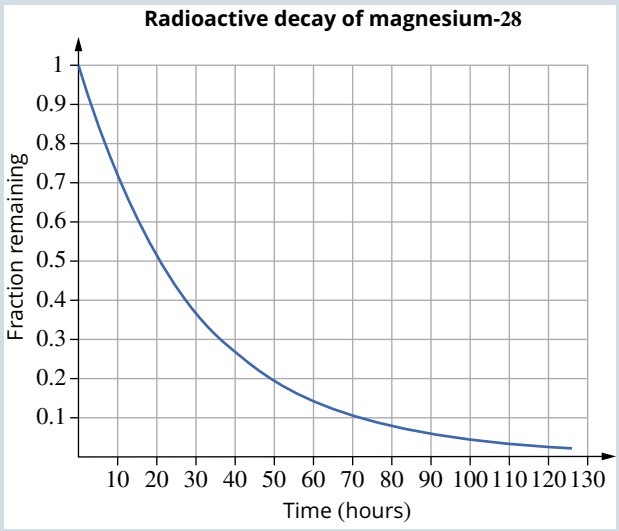
8 Identify the equation or equations that show an example of a reaction that releases energy.
- **A** I, III and IV
- **B** III only
- **C** I and IV
- **D** I, II, III and IV

9 Identify the equation or equations that show an example of a type of beta decay.
- **A** I, III and IV
- **B** III only
- **C** I and IV
- **D** I, II, III and IV

10 Identify the equation or equations that show an example of alpha decay.

A I, III and IV
B III only
C I and IV
D I, II, III and IV

11 Identify the information that can be obtained about magnesium-28 from the graph below.



A decay mode
B activity after a given time
C number of nuclei remaining after a given time
D half-life

12 State, and explain, the type of decay that the following hypothetical nuclides will undergo:

a $^{100}_{5}B$
b $^{31}_{30}Zn$
c $^{156m}_{72}Hf$

13 Molybdenum-99 is a beta emitter with a half-life of 67 hours. It decays to form metastable technetium-99m, which has a half-life of 6 hours. This, in turn, decays to form technetium-99, which has a half-life of about 250 000 years.

a Identify the most stable of the three isotopes. Explain your choice.
b Identify the the least stable of the three isotopes. Explain your choice.

14 Explain how the amount of energy released during a single nuclear fission reaction compares to the amount of energy released for a single fusion reaction.

15 The half-life of uranium-236 is 23.4 million years. Explain how a single individual nucleus of uranium-236 can spontaneously decay at any time.

Analysis

16 Determine what percentage of the original material of a substance remains after 4 half-lives.

A 25%
B 12.5%
C 6.25%
D 0%

17 The binding energy of the $^{147}_{62}Sm$ nuclide is 1217 MeV. Determine the binding energy per nucleon of $^{147}_{62}Sm$.

A 1217 MeV per nucleon
B 8.28 MeV per nucleon
C 19.6 MeV per nucleon
D 14.3 MeV per nucleon

Questions 18 and 19 refer to the following nuclear reaction:

$$^{249}_{98}Cf + ^{48}_{20}Ca \rightarrow ^{294}_{118}Og + 3\,^{1}_{0}n$$

18 Identify the correct method of calculating the mass defect.

A mass of Cf-249 + mass of Ca-48 – mass of Og-294 – 3 × mass of neutron
B mass of Og-294 + 3 × mass of neutron × mass of Cf-249 – mass of Ca-48
C binding energy of products – binding energy of reactants
D binding energy of reactants – binding energy of products

19 Identify the type of reaction this is an example of:

A nuclear fusion
B beta negative decay
C alpha decay
D nuclear bombardment

20 Iodine-131 has a half-life of 8 days. A sample of the radioisotope initially contains 2.4×10^{12} iodine-131 nuclei. Determine how many iodine-131 nuclei remain after 24 days.

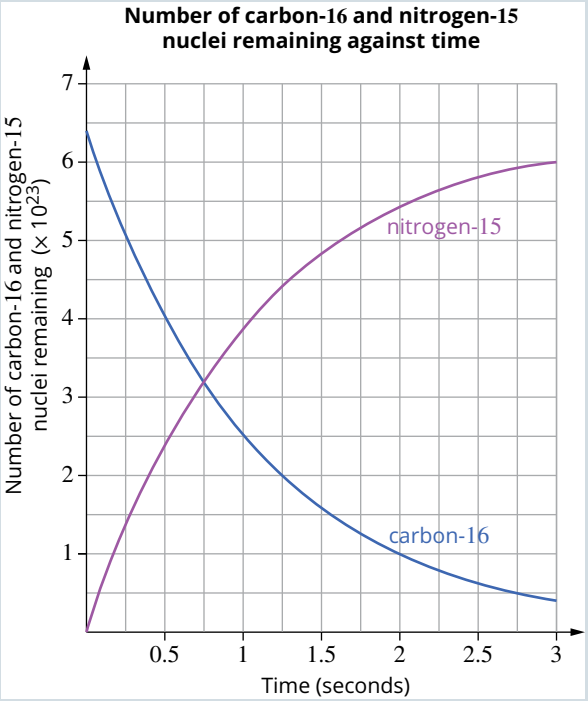
21 Calculate how much mass is converted to energy if 774 keV of energy is released during a particular decay reaction.

22 Calculate the binding energy and binding energy per nucleon for the following nuclides. The isotopic mass of each appears in brackets.

a $^{181}_{76}Os$ (180.95324 u)
b $^{40}_{19}K$ (39.963998 48 u)

23 Calculate the percentage of the mass of the separate protons and neutrons that is converted into energy to form the $^{56}_{26}Fe$ nuclide. Iron-56 has a mass of 55.934 936 3 u.

Knowledge utilisation



24 The graph shows the decay curve of the radioisotope carbon-16, which decays via beta negative radiation into the radioisotope nitrogen-16. It then emits a single neutron to become the stable isotope nitrogen-15. The graph shows the number of carbon-16 nuclei remaining in blue, and the number of nitrogen-15 nuclei created in purple.

- **a** Explain why the number of nitrogen-15 nuclei starts at zero.
- **b** Determine the half-life of carbon-16.
- **c** Explain why the curve of number of nitrogen-15 nuclei is increasing.
- **d** Discuss the meaning of the point of intersection of the number of carbon-16 and nitrogen-15 nuclei remaining.
- **e** Determine the a conclusion that can be reached about the total of the number of carbon-16 plus nitrogen-15 nuclei remaining.
- **f** Argue, presenting two different reasons, why you cannot determine the half-life of nitrogen-15 from this curve.

25 A free neutron (i.e. one that is not inside the nucleus of an atom) has a half-life of about 15 minutes.

- **a** Identify the type of decay will it undergo.
- **b** Determine the full nuclear equation for this decay.
- **c** Determine how much energy is released when it decays.
- **d** Calculate the energy released (in J) in total if 500.0 g of plutonium-239 undergoes a typical nuclear fission reaction that produces 200.0 MeV. One atom of plutonium-239 has a mass of 239.0521634 u.

26 Max performed an experiment to find the half-life of a sample of solid, crystal, radioactive iodine-131 in a laboratory. The sample was weighed at the start of the observations and was found to be 436 g. Max then weighed the remaining sample at various times and these were recorded in the table below.

Time after first observation	Remaining mass of sample (± 1 g)
0	436
1 minute	436
1 hour	424
12 hours	411
1 day	395
2 days	360
5 days	291
10 days	166
15 days	131
20 days	77

- **a** Draw a graph of the data above, showing how the mass of the iodine-131 changes over time. Include a line of best fit on your graph.
- **b** Use the graph to determine the half-life of iodine-131.
- **c** Hypothesise why Max recorded the mass of the sample at irregular times after the first observation until 5 days into the experiment.
- **d** Iodine-131 decays via beta negative emission into gaseous xenon-131. Devise two safety precautions Max had to take when he made mass measurements.
- **e** Max realises that the mass of the sample is probably more than the actual mass of the remaining iodine-131. Draw a conclusion as to why he thought this. Suggest an experiment he could carry out to make sure that the measured mass is the actual mass of the remaining iodine-131 and nothing else.

CHAPTER

04 Electrical physics

Every object around you is made up of charged particles. When these particles move relative to one another, you experience a phenomenon known as 'electricity'. This chapter looks at the fundamental concepts such as current and voltage that scientists have developed to explain electrical phenomena. This will provide the foundation for studying practical electrical circuits in the following chapter.

WS 1.3.1

Syllabus subject matter

Topic 3 • Electrical circuits

CURRENT, POTENTIAL DIFFERENCE AND ENERGY FLOW

- recall that electric charge can be positive or negative
- recall that electric current is carried by discrete electric charge carriers
- recall the law of conservation of electric charge
- define *electric current*, *electrical potential difference* in a circuit, and *power*
- solve problems involving electric current, electric charge and time
- recall that the energy available to electric charges moving in an electrical circuit is measured using electrical potential difference
- solve problems involving electrical potential difference
- explain why electric charge separation produces an electrical potential difference (no calculations required to demonstrate this)
- solve problems involving power.

RESISTANCE

- define *resistance*
- recall and solve problems using Ohm's law
- compare and contrast ohmic and non-ohmic resistors
- interpret graphical representations of electrical potential difference versus electric current data to find resistance using the gradient and its uncertainty.

MANDATORY PRACTICAL

- Conduct an experiment that measures electric current through, and electrical potential difference across an ohmic resistor in order to find resistance.

SCIENCE AS A HUMAN ENDEAVOUR

- Electrical energy in the home

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4.1 Charge and the atom

BY THE END OF THIS MODULE, YOU SHOULD BE ABLE TO:

- recall charges of subatomic particles
- define electric charge
- recall that charge is measured in coulombs
- recall that electric charge can be either positive or negative
- describe how an insulator can be charged
- explain how to charge by friction, induction and conduction
- recall the law of conservation of charge
- describe insulators as charge carriers.

All matter in the universe is made of tiny particles. These particles have a property called charge that can be positive, negative or neutral. Usually, the numbers of positive and negative charges balance out perfectly and you are unaware of them. However, when significant numbers of these charged particles become separated or move relative to each other, it results in **electricity**. In order to understand electricity, it is important to first understand the way charged particles interact with each other.

ELECTRIC CHARGE

Electric **charge** is a fundamental property of many subatomic particles. Electric charge can either be positive or negative. The size of the charge determines the force with which a particle can attract or repel other charged particles when close together. Charge is a characteristic of matter that refers to the *extent* to which a particle has fewer or more electrons than protons.

Charge carriers

The tiny particles that make up all matter are called **atoms**. Every atom contains a nucleus at its centre. Recall that a nucleus is made up of positively charged particles called protons and neutral particles called neutrons. The nucleus, which is positively charged due to the protons, is surrounded by negatively charged particles called electrons. A model of an atom is shown in Figure 4.1.1.

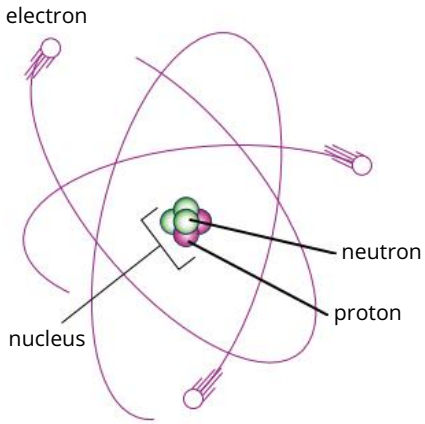


FIGURE 4.1.1 A simple model of the atom

Simple models of the atom, often called planetary models, show the electrons orbiting the nucleus much like planets orbiting the Sun (Figure 4.1.1). This is because particles with like charges repel each other, but particles with opposite charges attract each other. In an atom, the negatively charged electrons are attracted to the positively charged nucleus.

This is an important rule to remember when thinking about the interaction of charged particles. The attraction of charged particles is summarised in Table 4.1.1.

TABLE 4.1.1 Attraction and repulsion of charged particles

Charge	Positive	Negative
positive	repel	attract
negative	attract	repel

In neutral atoms, the number of electrons is exactly the same as the number of protons. This means that their charges balance each other out, leaving the atom electrically neutral.

It is difficult to remove a proton from the nucleus of an atom. In comparison, electrons are loosely held to their respective atoms and are relatively easy to remove.

When electrons move from one object to another, each object is said to have gained a **net charge**. The object that loses the electrons will gain a net positive charge, because it will now have more positive protons than negative electrons. The object that gains electrons will gain a net negative charge. When an atom has gained or lost electrons and the number of positive and negative charges is no longer balanced, the atom has become **ionised** or has become an **ion**.

The movement of charged particles (electrons and ions) from one area to another through a medium is commonly known as electricity.

The understanding that the movement of electrons, rather than protons, creates electrical effects is a relatively new discovery. So be aware that many of the rules and conventions used when talking about electricity refer to electric **current** as the movement of positive charge carriers.

> **i** An excess of electrons causes an object to be negatively charged, and a deficit of electrons will mean the object is positively charged.

Measuring charge

To measure the actual amount of charge of an object, a 'natural' unit would be the magnitude (size) of the charge carried by one electron or one proton. This fundamental constant of charge is often referred to as the **elementary charge** and is given the symbol e. A proton therefore has a charge of $+e$ and an electron has a charge of $-e$.

The size of the elementary charge is very small. For most practical situations, it is more convenient to use a larger unit to measure charge. The SI (standard) unit of charge is known as the **coulomb** (symbol C). It is named after Charles-Augustin de Coulomb (1736–1806), who was the first scientist to measure the forces of attraction and repulsion between charges.

A coulomb is quite a large unit of charge: +1 coulomb (1 C) is equivalent to the combined charge of 6.2×10^{18} protons. Therefore, the charge on a single proton is $+1.6 \times 10^{-19}$ C. Similarly, −1 C is equivalent to the combined charge of 6.2×10^{18} electrons, meaning that the charge on a single electron is -1.6×10^{-19} C.

The amount of charge, q, is equal to the number of electrons, n_e, multiplied by the charge on one electron, $-e$ (-1.6×10^{-19} C).

> **i** The elementary charge, $+e$, of a proton is equal to 1.6×10^{-19} C.
>
> The elementary charge, $-e$, of an electron is equal to -1.6×10^{-19} C.

> **i** $q = n_e \times -e$
>
> where
>
> q is the amount of charge in coulomb (C)
>
> n_e is the number of electrons
>
> $-e$ is the charge on one electron (-1.6×10^{-19} C).

Worked example 4.1.1

THE AMOUNT OF CHARGE ON A GROUP OF ELECTRONS

Calculate the charge, in coulombs, carried by 6.0 billion electrons.

Thinking	Working
Express 6.0 billion in scientific notation.	1.0 billion = 10^9 6.0 billion = 6.0×10^9
Calculate the charge, q, in coulombs by multiplying the number of electrons by the charge on one electron (-1.6×10^{-19} C).	$q = n_e \times -e$ $= (6.0 \times 10^9) \times (-e)$ $= (6.0 \times 10^9) \times (-1.6 \times 10^{-19}\text{ C})$ $= -9.6 \times 10^{-10}$ C

➤ Try yourself 4.1.1

THE AMOUNT OF CHARGE ON A GROUP OF ELECTRONS

Calculate the charge, in coulombs, carried by 4.0 million electrons.

Worked example 4.1.2

THE NUMBER OF ELECTRONS IN A GIVEN AMOUNT OF CHARGE

The net charge on an object is –3.0 μC. Calculate the number of extra electrons on the object.
(1 μC = 1 microcoulomb = 10^{-6} C)

Thinking	Working
Express –3.0 μC in scientific notation.	$q = -3.0\,\mu C$ $= -3.0 \times 10^{-6}\,C$
Find the number of electrons by dividing the charge on the object by the charge on an electron (-1.6×10^{-19} C).	$q = n_e \times -e$ $n_e = \frac{q}{-e}$ $= \frac{-3.0 \times 10^{-6}\,C}{-1.6 \times 10^{-19}\,C}$ $= 1.9 \times 10^{13}$ electrons

➤ Try yourself 4.1.2

THE NUMBER OF ELECTRONS IN A GIVEN AMOUNT OF CHARGE

The net charge on an object is –4.8 μC. Calculate the number of extra electrons on the object.
(1 μC = 1 microcoulomb = 10^{-6} C).

ELECTRICAL CONDUCTORS AND INSULATORS

Electrons are much easier to move than protons. Electrons also move more freely in some materials than in others.

In **metals**, the electrons are only very slightly attracted to their respective nuclei. Metals are good **conductors** of electricity. In conductors, loosely held electrons can effectively 'jump' from one atom to another and move freely throughout the material. This can be seen in Figure 4.1.2.

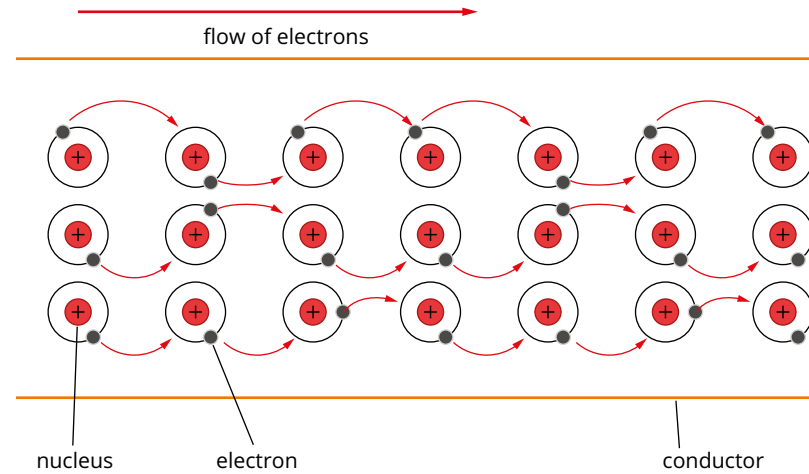


FIGURE 4.1.2 Electrons moving through a conductor. The electrons are free to move throughout the lattice of positive ions.

Copper is an example of a metal that is a good conductor. For this reason it is used in telecommunications and electrical and electronic products (Figure 4.1.3).

In comparison, the electrons in **non-metals** are very tightly bound to their respective nuclei and cannot readily move from one atom to another. Non-metals do not conduct electricity very well and are known as **insulators**. A list of common conductors and insulators is provided in Table 4.1.2.

FIGURE 4.1.3 These copper wires conduct electricity by allowing the movement of charged particles.

TABLE 4.1.2 Some common conductors and insulators

Conductors		Insulators	
Good conductors	**Moderate conductors**	**Good insulators**	**Moderate insulators**
• all metals, especially silver, gold, copper, and aluminium • any ionic solution	• water • earth • semiconductors such as silicon, germanium	• plastics • polystyrene • dry air • glass • porcelain • cloth (dry)	• wood • paper • damp air • ice • snow

Semiconductors

Some materials, such as silicon, are known as semimetals or metalloids. Their properties are somewhere between those of metals and non-metals. For example, the electrons in a silicon atom are not as tightly bound to the nucleus as those of a non-metal; however, they do not move as easily as the electrons in a metal. Therefore, silicon and similar elements are known as semiconductors.

Silicon's ability to conduct electricity can be adjusted by adding small amounts of other elements such as boron, phosphorus, gallium or arsenic in a process known as doping. Adding another substance contributes free electrons that can greatly increase the conductivity of silicon within electronic devices. This makes silicon very useful in the construction of computer chips (Figure 4.1.4).

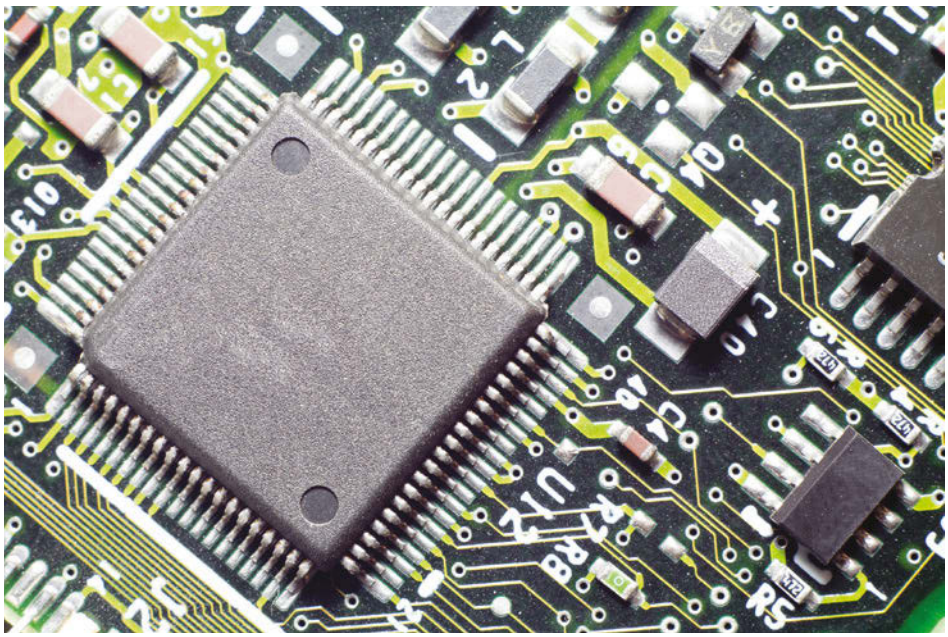


FIGURE 4.1.4 Silicon has been used in the construction of computer chips since the late 1950s.

Much of the convenience of our modern lifestyle is based on the unique conductive properties of silicon and it has many electronic applications.

CHARGING AN INSULATOR

Sometimes insulators can undergo a phenomenon in which they can become electrically charged. Charge does not build in materials that conduct electricity, as electrons are free to move around the material. However, when charge is transferred to an insulating material, the excess charge will remain in the initial location of charging, because insulating materials impede the free flow of electrons. As a result, charge is not evenly distributed across the object. Insulating materials become charged because of electrostatic forces of attraction and repulsion.

- **Electrostatic attraction** occurs when unlike charged particles attract (e.g. a positively charge proton is attracted to a negatively charged electron).
- **Electrostatic repulsion** occurs when two particles with the same charge repel each other (e.g. positive repels positive).

It is important to understand this phenomenon when explaining how charge can build in different insulating materials.

- Charging by friction occurs when two insulating materials become charged when rubbed together. During this process, atoms are forced close together. Because of this, electrons in one object interact closely with the nuclei of atoms in the other object. The object with the greater pull on electrons gains electrons and becomes more negatively charged. The other object loses electrons and becomes more positively charged.

  You can easily demonstrate this by rubbing a balloon on your hair. As you rub the balloon on your head, electrons will transfer from your hair to the balloon, making the balloon more negatively charged and your hair more positively charged. You will soon notice that the opposite charges between the balloon and your hair will cause them to attract each other!
- Charging by **induction** is a method of charging two insulating materials without any contact between the objects. When you place a charged object near a neutral object, a charge can be induced. For example, if you place a negatively charged balloon near a neutrally charged wall, some of the electrons in the wall will be repelled by the overall negative charge of the balloon (Figure 4.1.5). Conversely, the positively charged protons will be attracted to the negative charge of the balloon. This causes the surface of the wall to become more positively charged, attracting the balloon to its surface. When the balloon is moved away, the electrons will eventually redistribute throughout the wall, which will return to a neutral state.
- Charging by conduction occurs when a charged object (positive or negative) touches a neutral object and transfers its charge to that object. It is sometimes referred to as charging by 'contact'. In insulators, only the specific area that was touched would become charged. In conductors, charge can easily be transferred and distributed across the entire object.

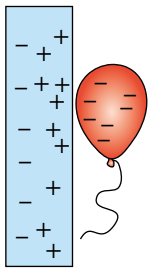


FIGURE 4.1.5 Positive charges in the wall are induced to move towards the balloon, whereas like charges are repelled to the back of the wall.

FIGURE 4.1.6 Lightning bolts over a city skyline.

Conservation of charge

Electric charge cannot be created or destroyed. This means that if an object gains electric charge from another object, then the other object must lose charge. This is known as the law of conservation of charge. For example, if you gain +10 μC of charge rubbing a balloon on your head, then that balloon must acquire a net −10 μC of charge.

Lightning

Lightning is one of nature's greatest spectacles (Figure 4.1.6). In the 18th century, Benjamin Franklin (1706–1790) showed that lightning is basically the same sort of electrical phenomenon that can be achieved by rubbing a glass rod with wool, or rubbing a balloon on your hair.

A typical lightning bolt transfers 10 or more coulombs of negative charge (more than 60 billion billion electrons) in approximately one thousandth of a second.

During a thunderstorm, It is thought that charge is transferred in collisions between the tiny ice crystals that form as a result of the cooling of upwards-flowing moist air and the larger, falling hailstones. As a result of small temperature differences between the crystals and hailstones, the crystals become positively charged and the hailstones become negatively charged. The crystals carry their positive charge to the top of the cloud while the negative charge accumulates in the lower region. There is normally also a second, smaller positively charged region at the bottom because of positive charges that are attracted up from the ground towards the negative region (Figure 4.1.7).

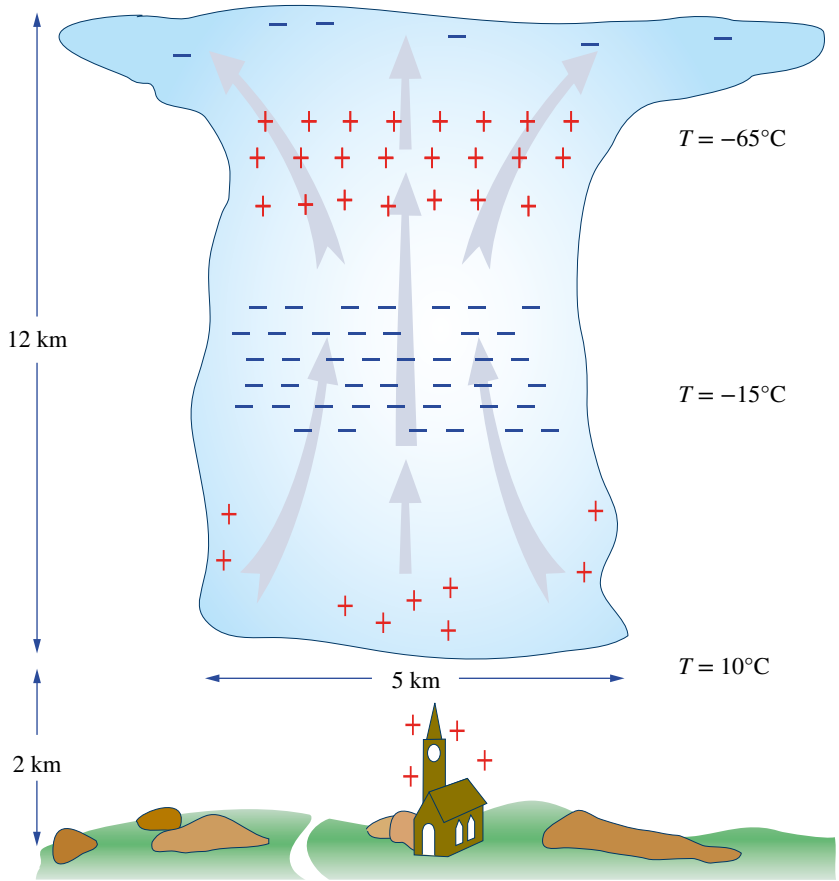


FIGURE 4.1.7 A thundercloud can be several kilometres wide and well over 10 km high. Strong updrafts drive the electrical processes that lead to the separation of charge.

The strong negative charge of the lower region of the cloud will induce positive charges on tall objects on the ground. This may lead to a discharge, which can form a conductive path for lightning. Strong electric fields will develop between these regions of opposite charge. If they become sufficiently strong, electrons can be stripped from the air molecules (which become ionised). The electric field will cause the free electrons and ions to gain kinetic energy and collide with more molecules, starting an 'avalanche of charges'. This is the lightning flash seen either within the cloud or between the Earth and the cloud. Most flashes are within the cloud; only a relatively small number actually strike the ground.

WS 1.3.2 PA 1.3.1

4.1 Review

SUMMARY

- Electric charge is a fundamental property of matter. Charge can be positive or negative.
- Like charges repel; unlike charges attract.
- When an object loses electrons, it develops a positive net charge; when it gains electrons, it develops a negative net charge.
- The letter q is used to represent the amount of charge. The SI unit of charge is the coulomb (C).
- The elementary charge e, the charge on a proton, is equal to 1.6×10^{-19} C. The elementary charge $-e$, the charge on an electron, is -1.6×10^{-19} C.
- The law of conservation of charges states that electric charge cannot be created or destroyed and is always conserved. If an object gains charge from another object, the other object must lose an equal amount of charge.
- Electrons move easily through conductors, but not through insulators. This is because the electrons in materials that are good conductors are weakly attracted to the nucleus, but electrons in insulators are more strongly attracted to the nucleus.
- An object can be charged by friction, induction or conduction.

KEY QUESTIONS

Retrieval

1 State the unit of measurement of charge.

2 State the law of conservation of charge.

Comprehension

3 Use a visual representation to demonstrate the movement of electrons in a conductor.

4 Explain how you can charge an object by:
- **a** friction
- **b** induction
- **c** conduction.

5 Explain why electrical circuits often consist of wires that are made from copper and are coated in protective rubber.

Analysis

6 Plastic strip A, when rubbed, is found to attract plastic strip B. Strip C is found to repel strip B. Determine what will happen when strip A and strip C are brought close together.

7 Calculate how many electrons make up a charge of –5.0 C.

8 Calculate the charge, in coulombs, of 4.2×10^{19} protons.

9 Calculate the number of extra electrons on an object, for each of the following net charges.
- **a** –6.0 μC
- **b** –8.3 C
- **c** –1.6 μC

10 A scientist charges two identical metal spheres. Sphere A has a net charge of $+10q$. Sphere B has an overall net charge of $-4q$. The scientist then brings the spheres together so that they touch before being separated again. Determine the new net charge on each sphere.

4.2 Potential difference

BY THE END OF THIS MODULE, YOU SHOULD BE ABLE TO:

- define 'potential difference' in a circuit
- recall that the energy available to charges moving in an electrical circuit is measured using potential difference
- describe flow of current due to electrical potential difference between two points on a conductor
- recall that potential difference is measured in volts
- explain why charge separation produces an electrical potential difference
- recall that voltage is measured using an voltmeter
- describe potential difference (voltage) as work done per unit charge: $1\,V = 1\,JC^{-1}$
- recall the formula for calculating potential difference
- calculate potential difference
- calculate the work done by a circuit.

Electrons won't move around a circuit unless they are given energy. In an electrical circuit, this energy is given by the battery (Figure 4.2.1). This is because chemical reactions are taking place inside every battery. The chemical reactions provide potential energy to the electrons inside it. When a circuit connects two ends of the battery, the potential energy of the electrons is converted into electrical energy and the electrons move through the wire. This then enables the electrons to deliver electrical energy from the battery to a component, such as a bulb, which is then transferred into other forms of energy such as light or heat energy.

Chemical reactions in a battery drive electrons towards the positive terminal of the battery. This is because the electrons at the negative terminal repel each other. This repulsion moves the electrons into the wire. At the positive terminal, electrons in the wire are attracted to the positive charges created by the deficiency of electrons. This attraction causes them to move into the battery. The net effect of electrons flowing into the wire at one end and out of it at the other end produces an electric current that flows through the wire.

ENERGY IN CIRCUITS

Chemical energy stored inside a battery is **transformed** (changed or converted) into **electrical potential energy**. This potential energy is stored as a separation of charge between the two terminals of the battery. This can be visualised as a 'concentration' of charge at either end of the battery. One terminal (the negative terminal) has a concentration of negative charges; the other terminal (the positive terminal) has a concentration of positive charges. When the battery is connected within a device, chemical reactions will maintain this difference in charge between the two terminals for some time.

The difference in charge between the two terminals of a battery can be quantified (given a numerical value) as a difference in the electrical potential energy per unit charge. This is commonly called **potential difference**, V, and is measured in volts (V).

It is this potential difference between the terminals of the battery that provides the energy to a circuit. The energy is then **transferred** to different components in the circuit. At each component, the energy is transformed into a different type of energy. For example, a light bulb transforms energy into heat and light, and a fan transforms energy into motion (kinetic energy) and heat and sound.

FIGURE 4.2.1 Chemical energy is stored within batteries.

Electromotive force (EMF) describes the amount of electrical energy per unit of charge produced inside an electrical source such as a battery. The unit for measuring EMF is the volt; however, EMF is not to be confused with potential difference. Although both are a measure of energy per unit charge, potential difference describes the amount of energy per unit charge being transformed from electrical energy into another form (e.g. heat and light in a light bulb).

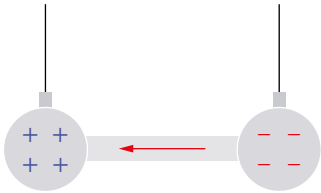


FIGURE 4.2.2 An electrical potential difference exists between these two objects due to the difference in charge concentration. Electrons flow from the negative object to the positive object, as shown by the arrow, until the potential difference is zero.

If you use a conductor to link two separate bodies with a potential difference, charges will flow through the conductor until the potential difference is equal to zero (Figure 4.2.2). For the same reasons, when a conductor is charged, charges will move through it until the potential difference between any two points in the conductor is equal to zero.

Cells and batteries

A single cell generates electricity by converting chemical energy to electrical potential energy. If a series of cells is added together, it is called a battery. Often a series of cells is packaged in a way that makes it look like a single device, but inside is a battery of cells connected together (Figure 4.2.3). The terms 'battery' and 'cell' can be used interchangeably as the term 'battery' is frequently used in common language to describe a cell.

FIGURE 4.2.3 A mobile-phone battery. The term 'battery' actually refers to a group of electric cells connected together.

Energy transfers and transformations in a torch

A torch is a simple example of how energy is transformed and transferred within a circuit. In a torch, chemical energy in the battery is transformed to electrical potential energy. There are two batteries connected, so a bigger potential difference is available (Figure 4.2.4). Energy can be transferred to the light bulb when the end terminals of the batteries are connected to the torch's circuit and the torch is switched on.

The electrical potential difference between the battery's terminals causes electrons within the circuit to move. The electrons flow through the wires of the torch. These electrons collide with the atoms in the small wire (filament) in the torch's light bulb and transfer kinetic energy to them. This transfer of kinetic energy means that the particles inside the filament move faster and faster and the filament gets very hot. When hot, the filament emits visible light.

The energy changes can be summarised as:

chemical energy $\xrightarrow{\text{transformed}}$ electrical potential energy

electrical potential energy $\xrightarrow{\text{transformed}}$ kinetic energy (electrons)

kinetic energy (electrons) $\xrightarrow{\text{transferred}}$ kinetic energy (filament atoms)

kinetic energy (filament atoms) $\xrightarrow{\text{transformed}}$ thermal energy + light

Eventually, when most of the chemicals within the battery have reacted, the battery is no longer able to provide enough potential difference to power the torch. This is because the chemical reaction has slowed and electrons are not being driven to the negative terminal. The torch stops working and the batteries are said to have gone flat.

Similar energy transfers and transformations take place every time electrical energy is used.

FIGURE 4.2.4 An X-ray image of the internal structure of a torch. The bulb and two batteries are clearly visible.

POTENTIAL DIFFERENCE

When charges are separated in a battery, each charge gains electrical potential energy. In a similar way, if a mass is lifted above the ground it gains gravitational potential energy. The change in electrical potential energy of each charge is known as the potential difference (V).

As you can see in Figure 4.2.5, when you lift an object to some height (B) above the ground (A), you have done some work and have placed it at a height where it has it has more gravitational potential energy (E_g): $E_g\text{B} > E_g\text{A}$.

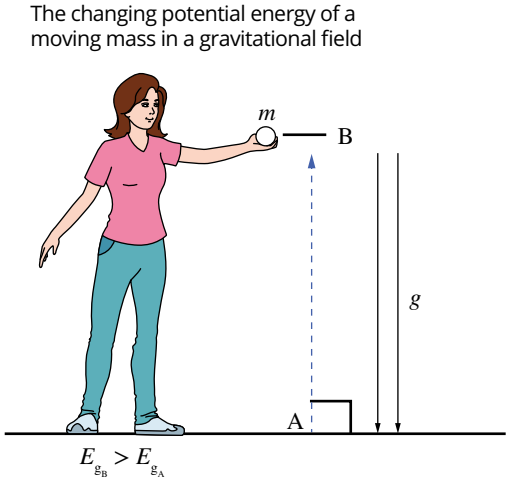


FIGURE 4.2.5 Lifting a mass above ground level increases its gravitational potential energy just as moving an electron to the negative terminal of an electric cell gives it electrical potential energy.

Volts and voltage

Somewhat confusingly, scientists use the symbol V for both the quantity potential difference *and* its unit of measurement, the volt. The context usually makes it clear which meaning is intended.

- For the potential difference variable, use italics: V.
- For the unit volts, do not use italics: V.

For this reason, potential difference is often referred to as 'voltage'.

Birds on a wire

Birds can sit on power lines and not get electrocuted even though the wires are not insulated (Figure 4.2.6). For a current to flow through a bird on a wire, there would have to be a potential difference between its two feet. The bird has both feet touching the same wire, which might be at a very high potential (voltage), so there is no potential difference between the bird's feet. If the bird could stand on the wire and touch any other object such as the ground or another wire, then it would get a big electric shock. This is because there would be a potential difference between the wire and the other object and current would flow.

FIGURE 4.2.6 There is no potential difference between each bird's feet.

MEASURING POTENTIAL DIFFERENCE: VOLTAGE

A potential difference of 1 J C^{-1} is equal to 1 V.

When a battery is labelled 9 V, this means that the battery provides 9 J of energy to each coulomb of charge.

As with other forms of energy, it is useful to measure the amount of potential difference in a given situation. Potential difference, V, is formally defined as the amount of electrical potential energy, W, given to each coulomb of charge, q. As an equation, it is:

$$V = \frac{W}{q}$$

Energy is measured in joules and charge in coulombs, so the potential difference is measured in joules per coulomb (J C^{-1}). This quantity has been assigned a unit, the **volt** (V).

Worked example 4.2.1

DEFINITION OF POTENTIAL DIFFERENCE

Calculate the electrical potential energy that is carried by 5.0 C of charge at a potential difference of 10.0 V.	
Thinking	**Working**
Recall the definition of potential difference.	$V = \frac{W}{q}$
Rearrange this to make energy the subject.	$W = Vq$
Substitute in the appropriate values and solve.	$= 10.0 \times 5.0$ $= 50$ J

➤ Try yourself 4.2.1

DEFINITION OF POTENTIAL DIFFERENCE

A car battery can provide 3600 C charge at 12 V. Calculate the electrical potential energy that is stored in the battery.

Measuring voltage: the voltmeter

Voltage is usually measured by a device called a **voltmeter**. Voltmeters measure the change in voltage (potential difference) as current passes through a particular component. This means that one wire of the voltmeter is connected to the circuit before the component and the other wire is connected to the circuit after the component. This is called connecting the voltmeter 'in parallel', making a parallel circuit. Voltmeters and parallel circuits are discussed in further detail in Chapter 5.

QUANTIFYING ELECTRICAL ENERGY

Work done by a circuit

In electrical circuits, electrical potential energy is converted into other forms of energy. Work is done when energy is changed from one form to another. (Work is covered in more detail in Chapter 8.) The amount of energy provided by a circuit can be calculated using the definition for potential difference:

$$V = \frac{W}{q}$$

Rearranging the definition of voltage gives:

$$W = Vq$$

Using the definition of current:

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

$$q = It$$

Therefore:

$$W = VIt$$

This gives us a practical way to calculate the energy used in a circuit from measurements you can make.

$W = VIt$

where

W is the energy provided by the current, which is the same as the work done (J)

V is the potential difference (V)

I is the current (A)

t is the time (s).

Worked example 4.2.2

USING $W = VIt$

A potential difference of 12 V is used to generate a current of 750 mA to heat water for 5.0 minutes. Calculate the energy transferred to the water in that time.	
Thinking	**Working**
Convert the quantities to SI units.	$\frac{750\text{ mA}}{1000} = 0.750\text{ A}$ $5.0\text{ min} \times 60\text{ s} = 300\text{ s}$
Substitute values into the equation and calculate the amount of energy in joules.	$W = VIt$ $= 12 \times 0.750 \times 300$ $= 2700\text{ J}$ $= 2.7\text{ kJ}$

➤ Try yourself 4.2.2

USING $W = VIt$

A potential difference of 12 V is used to generate a current of 1750 mA to heat water for 7.5 minutes. Calculate the energy transferred to the water in that time.

4.2 Review

SUMMARY

- Electrical potential difference measures the electrical potential energy available per unit charge.
- Voltage is measured using a voltmeter.
- Potential difference (voltage) is work done per unit charge:

$$1\,V\,J\,C^{-1}$$

- Potential difference (voltage) is measured in volts (V), where 1 volt is the work done per unit charge; i.e. $1\,V = 1\,J\,C^{-1}$.
- Potential difference is measured using a voltmeter.
- Potential difference can be defined as the work done to move a charge against an electric field between two points, using the equation:

$$W = Vq \text{ or } V = \frac{W}{q}$$

- In a circuit, the energy required for charge separation is provided by a cell or battery. The chemical energy within the cell is transformed into electrical potential energy.
- The energy dissipated in a circuit, W, or the work done by a circuit, is given by the equation $W = VIt$, where V is the potential difference, I is the current and t is time.

KEY QUESTIONS

Retrieval

1 Define 'potential difference'.

2 Describe the energy transfers that occur in a torch.

3 State the formula for calculating potential difference in terms of charge and electrical potential energy.

4 Name the piece of equipment used to measure potential difference.

5 State the formula for energy provided by a circuit in terms of charge, time and potential difference.

Comprehension

6 Explain the difference between a cell and a battery.

7 Explain why birds do not get electrocuted when they perch on overhead power lines.

Analysis

8 Determine the conditions under which charge will flow between two bodies linked by a rod.

9 Calculate the amount of electrical potential energy carried by 10.0 C of charge at a potential of 20.0 V.

10 Determine the energy provided by a 12 V battery that gives a charge of 10.0 C.

11 A charge of 5.0 C flows from a battery through an electric water heater and delivers 100.0 J of heat to the water. Determine the potential difference of the battery.

12 Determine how much charge must have flowed through a 12.0 V car battery if 2.00 kJ of energy was delivered to the starter motor.

13 An electric water heater is connected to a 9.0 V power supply and draws a current of 500.0 mA for 10.0 minutes. Calculate the amount of energy that is transferred to the water in this time.

14 A light bulb that is connected to 240 V uses 3.6 kJ of electrical potential energy in exactly one minute.

a Identify the type(s) of energy that the electrical energy has been transformed into.

b Calculate the current flowing through the lamp.

15 An electrical heating element with a 20.0 V power supply draws a current of 500.0 mA and transfers 10.0 kJ of energy to the water. Calculate how long this takes, in minutes.

16 Consider the water model analogy for the electrical energy obtained from a battery. Analyse what the potential difference of the battery could be compared with.

4.3 Electric current

BY THE END OF THIS MODULE, YOU SHOULD BE ABLE TO:

- recall that electric current is carried by discrete charge carriers
- distinguish between electron flow and conventional current
- describe flow of current due to electrical potential difference between two points on a conductor
- describe the formula to calculate current
- solve problems involving current, charge and time.

A flow of electric charge is called electric **current**. Current can be carried by moving electrons in a wire or by ions in solution. This section explores current as it flows through wires in electrical circuits.

Electrical circuits are involved in much of the technology used every day and are responsible for many familiar sights, such as a city skyline at night (Figure 4.3.1).

FIGURE 4.3.1 Electrical circuits are responsible for lighting up whole cities.

ELECTRICAL CIRCUITS

An **electrical circuit** is a path made of conductive material through which charges can flow in a closed loop. This flow of charges is called electric current. The most common conductors used in circuits are metals, such as copper wire. The charges that flow around the circuit in the wire are negatively charged electrons. The movement of electrons in the wire is called electron flow.

A simple example of an electrical circuit is shown in Figure 4.3.2. The light bulb is in contact with the positive terminal (end) of the battery and a copper wire joins the negative terminal of the battery to one end of the filament in the light bulb. This arrangement forms a closed loop that allows electrons within the circuit to flow from the negative terminal towards the positive terminal of the battery. The battery is a source of energy. The light bulb transforms this energy into other forms of energy, such as heat and light, when the circuit is connected.

If a switch is added to the circuit in Figure 4.3.2, the light bulb can be turned off and on. A switch on a power point or an appliance allows you to break the circuit.

When the switch is closed, the circuit is complete. The current flows in a loop along a path made by the conductors and then returns to the battery.

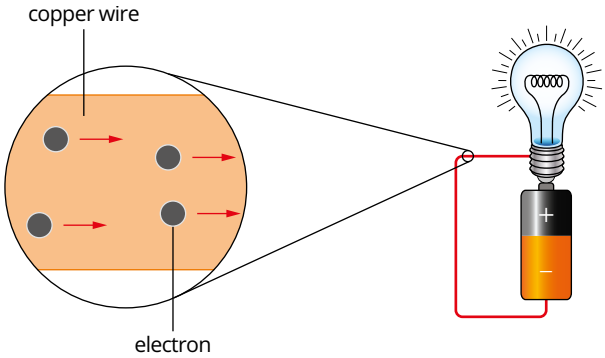


FIGURE 4.3.2 When there is a complete conduction path from the positive terminal of a battery to the negative terminal, a current flows.

When the switch is open, the circuit is broken and the current can no longer flow. This is what happens when you turn off the switch for a lamp or TV. A break in the circuit occurs when two conductors in the switch are no longer in contact. This stops the flow of current and the appliance will not work. A circuit with a broken conducting path is often called an open circuit.

Electrical circuits are discussed in more detail in Chapter 5.

Current will flow in a circuit only when the circuit forms a continuous (closed) loop from one terminal of a power supply to the other terminal.

Electron flow

In any piece of conducting material, such as copper wire, electrons are present throughout the material. If there is no current flowing, this means there is no net flow of electrons, but the electrons are still present.

When you connect a piece of conducting material to the negative terminal of a battery, the negative terminal tries to 'push' the electrons away. However, the electrons will not flow if the circuit is open. This is because the electrons at the open part of the circuit have effectively reached a dead end, like cars stopped at a road block. This prevents all the other electrons in the material from flowing, like a long traffic jam caused by the road block.

When you close the circuit, you create a clear pathway for the electrons to flow through. This means the electron closest to the negative terminal forces the next electron to move, and so on, all the way around the circuit. Therefore all electrons move almost simultaneously throughout the circuit so that electrical devices, such as light bulbs, seem to turn on immediately after you flick the switch.

Conventional current vs electron flow

When electric currents were first studied, it was (incorrectly) thought the charges that flowed in circuits were positive. Based on this, scientists traditionally talked about electric current as if current flowed from the positive terminal of the battery to the negative terminal. This convention is still used today, even though you know now that it is actually the negative charges (electrons) that flow around a circuit.

The direction of **conventional current** is opposite to the direction of electron flow, as shown in Figure 4.3.3. Conventional current (or current), I, flows from the positive terminal of a power supply to the negative terminal. Electron flow (or electron current) refers to the flow of electrons from the negative terminal to the positive terminal of a power supply.

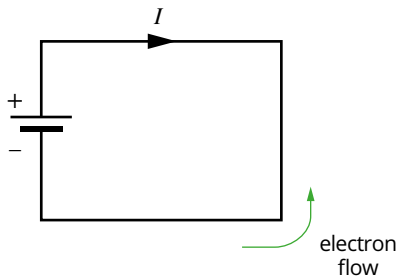


FIGURE 4.3.3 Conventional current (I) and electron flow are in opposite directions. The long terminal of the battery is positive.

Quantifying current

One common misconception about current is that charges are used up or lost when a current flows from one point to another. However, the charge carriers (electrons) are conserved at all points.

As current flows, electrons travel into the wire at the negative terminal of the battery. As electrons flow around a circuit, they remain within the metal conductor. They flow through the circuit and return to the battery at the positive terminal—they are not lost in between. In common electrical circuits, a current consists of electrons flowing within a copper wire (Figure 4.3.3). This current, I, can be defined as the amount of charge that passes through a point in the conductor per second.

MEASURING CURRENT

The number of electrons that pass through a point in a circuit per second gives a measure of electric current. Because the electrons do not leave the wire, current is conserved in all parts of a circuit. Current is measured in amperes, or amps (A). One ampere of current is equivalent to one coulomb per second ($\mathrm{C\,s^{-1}}$).

The current, I, is the amount of charge, q, that flows through a point in a circuit in time, t, seconds:

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

Current is a flow of electrons. It is equal to the number of electrons, n_e, that flow through a particular point in the circuit multiplied by the charge on one electron, q_e, divided by the time that has elapsed in seconds, t.

$$I = \frac{q}{t} = \frac{n_e q_e}{t}$$

Conventional current

Note that a flow of 1 C of *positive charge to the right* in one second is equivalent to a flow of 1 C of *negative charge to the left* in one second. That is, both situations represent a conventional current of 1 A to the right.

A typical current in a circuit powering a small DC motor would be about 50 mA. Even with this seemingly small current, approximately 3×10^{17} electrons flow past any point on the wire each second.

Electrons generally do not travel in straight lines through conductors, as they constantly collide with other particles in the medium; therefore, the average velocity at which particles travel through a conductor is used to measure current. This average is known as the **drift velocity**. The drift velocity for electrons in a copper wire is of the order of $10^{-5}\,\text{m s}^{-1}$.

> Current is a measure of how fast electrons move through a point in a circuit over time:
> $I = \frac{q}{t} = \frac{n_e q_e}{t}$
> where
> I is the current in amperes (A)
> q is the amount of charge in coulombs (C)
> n_e is the number of electrons
> q_e is the charge on an electron (-1.6×10^{-19} C)
> t is time in seconds (s).

Worked example 4.3.1

USING $I = \frac{q}{t}$

Calculate the number of electrons that flow past a particular point each second in a circuit that carries a current of 0.5 A.	
Thinking	**Working**
Rearrange the equation $I = \frac{q}{t}$ to make q the subject.	$q = I \times t$
Calculate the amount of charge that flows past the point in question by substituting the values given.	$q = 0.5 \times 1$ $= 0.5\,\text{C}$
Find the number of electrons by dividing the charge by the charge on an electron (1.6×10^{-19} C).	$n_e = \frac{q}{q_e}$ $= \frac{0.5}{1.6 \times 10^{-19}}$ $= 3 \times 10^{18}$ electrons

➤ Try yourself 4.3.1

USING $I = \frac{q}{t}$

Calculate the number of electrons that flow past a particular point each second in a circuit that carries a current of 0.75 A.

Measuring current: the ammeter

Current is commonly measured by a device called an **ammeter**.

An ammeter is connected along the same path taken by the current flowing through the light bulb. This is referred to as connecting the ammeter 'in series'. Ammeters and series circuits are covered in more detail in Chapter 5.

ANALOGIES FOR ELECTRIC CURRENT

You cannot see the movement of electrons in a wire, so it is sometimes helpful to use analogies or 'models' to visualise or explain the way an electric current behaves. It is important to remember that no analogy is perfect: it is only a representation, and there will be situations in which the electric current does not act as you would expect from the analogy.

Water model

A very common model is to think of electric charges as water being pumped around a pipe system, as shown in Figure 4.3.4. In this model, the battery pushes electrons through the wires just like a pump pushes water through the pipes. Water cannot be compressed, so the same amount of water flows in every part of a pipe, just as the electric current is the same in every part of a wire. The light bulb in an electrical circuit converts electrical energy into heat and light, just like the turbine converts the gravitational energy of the water into kinetic energy. The water that has flowed through the turbine flows back to the pump that provides the energy needed for it to keep flowing.

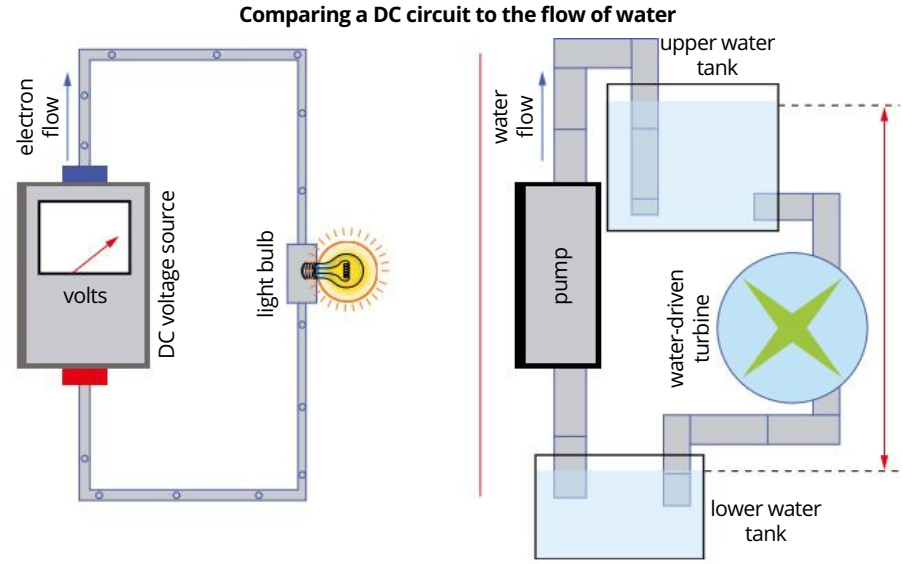


FIGURE 4.3.4 An electric current can be compared to water flowing through a pipe system.

This model reinforces the following characteristics of an electric current:

- The power supply transfers energy to the electrons and so the electrons gain potential energy.
- The energy of the electrons is converted into other forms of energy when the electrons pass through the components in the circuit.

One of the limitations of the water model is that you usually cannot see water moving through a pipe and so you have to imagine what is happening in the pipe and then compare it to the motion of electrons in the wires.

Bicycle-chain model

Although electrons move relatively slowly through a conductor, the effects are almost instantaneous. For example, the delay between flicking a light switch and the light coming on is too small to be noticed. One way of understanding this is to compare an electric current to a bicycle chain, as shown in Figure 4.3.5.

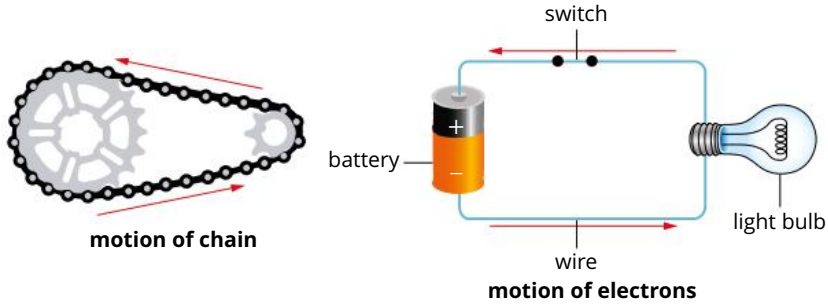


FIGURE 4.3.5 Electrons in a wire are like the links of a bicycle chain. Just like the links of a bicycle chain, electrons move together in a conductor.

A wire is full of electrons that all repel each other, so moving one electron affects all the others around it. An electric current is like a bicycle chain: even if the cyclist pedals slowly, the links in the chain mean that energy is instantly transferred from the pedals to the wheel. In this model, the pedals of the bicycle are like the battery of the electrical circuit: the pedals provide the energy that causes the chain to move.

This model reinforces the following characteristics of an electric current:

- Electric effects are nearly instantaneous, just as there is no delay between turning the pedals and the back wheel of the bicycle turning.
- Charges in an electric current are not 'consumed' or 'used up', just as links in the chain are not used up.
- The amount of energy provided by an electric current is not entirely dependent on the current. This is like when a cyclist changes gears to give the same amount of energy to the bicycle while pedalling at different rates.

Although the bicycle-chain model can be a helpful analogy, there are a number of important differences between a bicycle chain and an electrical circuit.

- The number of charges flowing in an electric current is much larger than the number of links in a bicycle chain.
- Electrons in a wire do not touch one another like the links in a chain.

Analogies for potential difference

The two models used for electric current can also be used to understand the concept of potential difference, which was covered in the Module 4.2.

In the water model shown in Figure 4.3.4, potential difference is similar to the water pressure in the pipe. If the water is pumped into a raised water tank, then the potential difference can also be compared to the gravitational potential energy given to each drop of water.

In the bicycle-chain model shown in Figure 4.3.5, potential difference is related to how hard the bicycle is being pedalled. If the cyclist is pedalling hard, this would correspond to a high voltage in which each link in the chain is carrying a larger amount of energy than if the cyclist was pedalling slowly.

In both analogies, the overall rate of energy output (power) is related to both the current and the potential difference. In the water model, the pressure in the pipe could be very high but the rate of energy transfer will depend on how quickly the water is flowing. Similarly, a cyclist can work at the same rate by pedalling hard with the chain moving slowly or pedalling more easily but with the chain moving more quickly.

4.3 Review

SUMMARY

- A flow of electric charge is called electric current. For example, in the wires of an electrical circuit, the charge is carried by electrons.
- Current will flow between two points on a conductor if there is an electrical potential difference between those points.
- Electric current is carried by discrete charge carriers.
- Current will flow in a circuit only when the circuit forms a continuous (closed) loop from one terminal of a power supply to the other terminal.
- When an electric current flows, electrons all around the circuit move towards the positive terminal, at the same time. This is called electron flow.
- Conventional current in a circuit flows from the positive terminal to the negative terminal.
- Current is dependent on the speed of charged particles, the number of charged particles that are moving and the charge being carried by the particles.
- Current, I, is defined as the amount of charge, q, that passes through a point in a conducting wire per second. It has the unit amperes or amps (A), which are equivalent to coulombs per second. The equation for this is:

$$I = \frac{q}{t} = \frac{n_e q_e}{t}$$

- Current is measured with an ammeter connected along the same path as the current flowing (that is, in series) within the circuit.

KEY QUESTIONS

Retrieval

1 State what the links in the bicycle chain can be compared with in the bicycle chain model for electric current.

2 State the formula for determining electric current.

3 Define 'drift velocity'.

4 Name a common conductor used in circuits.

Comprehension

5 Identify the requirements for current to flow in a circuit.

Analysis

6 Differentiate between conventional current and electron flow.

7 When a light bulb is connected in an electrical circuit, it uses electrical energy to produce heat and light. Explain whether this means that charges are used up as they flow through the circuit.

8 Compare and contrast current and potential difference.

9 Max connects a simple electrical circuit, and notices that when the switch is closed, the light bulb lights up immediately. He says this is because the electrons move around the circuit at the speed of light. Consider whether or not he is correct.

10 Find the current that flows in a light bulb through which a charge of 30.0 C flows in each of the following times.

a 10.0 seconds

b 1.0 minute

c 1.0 hour

11 A car headlight draws a current of 5.0 A. Determine how much charge will have flowed through it in each of the following times.

a 1.0 second

b 1.0 minute

c 1.0 hour

12 In a solution of salt water, a total positive charge of +15 C moved past a point to the right in 5.0 s, and in the same time a total negative charge of –30.0 C moved to the left.

a Determine the current through the solution during this time.

b Some time later it was found that in 5.0 s a total of +5.0 C had moved to the right while –15 C had moved to the left. Determine the current this time.

13 Determine the amount of charge that would flow through each of the following:

a pocket calculator in 10.0 minutes, if it draws a current of 5.0 mA

b car starter motor in 5.0 seconds, if it draws a current of 200.0 A

c light bulb in 1.0 hour, if it draws a current of 400.0 mA.

14 Exactly 10^{20} electrons flow past a point in 4.0 seconds.

a Calculate the amount of charge, in coulombs, that moves past a point in this time.

b Determine the current, in amps.

15 3.2 C flows past a point in 10.0 seconds.

a Calculate the number of electrons that move past a point in this time.

b Determine the current, in amps.

4.4 Resistance

BY THE END OF THIS MODULE, YOU SHOULD BE ABLE TO:

- define 'resistance'
- recall that resistance is measured in ohms
- describe the use of the colour-band system in resistors
- recall how resistance is dependent on the material of a conductor; proportional to length; inversely proportional to cross-sectional length.

Resistance is an important concept because it links the ideas of potential difference and current. **Resistance** is a measure of how hard it is for current to flow through a particular material. As conductors allow current to pass through easily, they are said to have low resistance. Insulators have a high resistance because they 'resist' or limit the flow of charges through them.

For a particular object or material, the amount of resistance can be quantified (given a numerical value). This means that the performance of electrical circuits can be studied and predicted with a high degree of confidence.

Resistance is a measure of how hard it is for current to flow through a particular material. Resistance is measured in ohms (Ω).

RESISTANCE TO THE FLOW OF CHARGE

Energy is required to create and maintain an electric current. For electrons to move from one place to another, they need to first be separated from their atoms and then given energy to move. In some materials (i.e. conductors), the amount of energy required for this is negligible (almost zero). In insulators, a much larger amount of energy is required.

When the electrons are moving through the material, energy is also required to keep them moving at a constant speed. Consider an electron travelling through a piece of copper wire. It is common to imagine the wire as an empty pipe or hose through which electrons flow. However, a piece of copper wire is not empty; it is full of copper ions. These ions are packed tightly together in a lattice arrangement. As an electron moves through the wire, it will 'bump' into the ions. The electron needs constant 'energy boosts' to keep it moving in the right direction. This is why an electrical device will stop working as soon as the energy source (e.g. battery) is disconnected.

Electron movement

Even when current is not flowing, free electrons tend to move around in a piece of metal due to thermal effects. The free electrons are rushing around at random with great speed. However, the net velocity of an electron through a wire—the drift velocity introduced in Module 4.3—is quite slow. Figure 4.4.1 compares the random motion of an electron when current is not flowing (AB) to the motion of the electron when current is flowing (AC). The difference between the two paths is only small. However, the combined effect of countless electrons moving together in this way represents a significant net movement of charge.

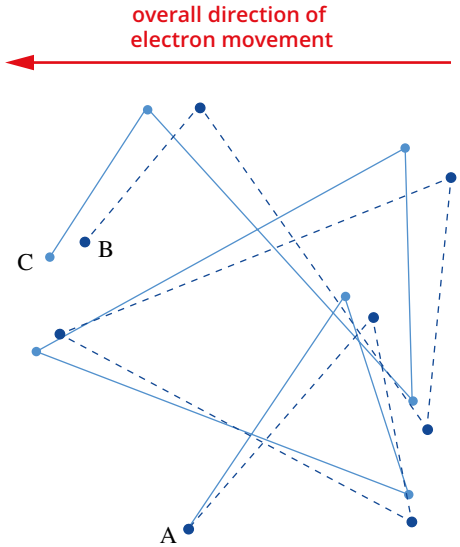


FIGURE 4.4.1 Path AB shows the random motion of an electron due to thermal effects. Path AC shows the path of the same electron when an electric current is flowing in the direction indicated.

VARIABLES THAT AFFECT RESISTANCE

Understanding the way electrons move through a wire can help us to make some predictions about the resistance of different objects.

Cross-sectional area and length

Consider electrons moving through two pieces of wire: one long and one short. In the longer piece of wire, the electrons bump into more ions along the way, so more energy would be needed for the electrons to travel from one end to the other. In other words, the longer piece of wire would provide greater 'resistance' to the flow of electric current.

Similarly, a thicker piece of wire allows more electrons to flow through it at the same time, much like a dual-lane highway allows faster traffic flow than a single lane. In practice, the cross-sectional area of the wire (its area when viewed end on) is important. The greater the cross-sectional area of the wire, the lower its resistance will be.

The relationship between the resistance of a conductor and its length and thickness follows a mathematical relationship. There is a direct relationship between resistance and length: doubling the length of the conductor doubles its resistance. There is an inverse relationship between resistance and the cross-sectional area of the conductor.

Temperature

Another factor that affects the resistance of a material is its temperature. The temperature of an object is a measure of the average kinetic energy of its particles. The temperature of a solid is an indication of how quickly its particles are vibrating.

Increasing the temperature of a piece of copper wire means that the copper ions will vibrate back and forth more quickly. This makes it more likely that an electron will collide with the ion as it moves past it. Therefore, increasing the temperature of the wire also increases the resistance of the wire.

Similarly, current passing through a conductor can cause it to heat up. Think again of an electron moving through a copper wire: when the electron collides with a copper ion, it transfers some of its kinetic energy to the ion. As a result of this collision, the copper ion gains kinetic energy, causing it to vibrate more quickly. An increase in the kinetic energy of the copper means that its temperature has increased, so the copper wire heats up.

This is one of the reasons why personal computers contain cooling fans, as shown in Figure 4.4.2. Electrical components are packed very tightly together on the computer motherboard. Cooling the components and the conductors that connect them prevents the computer from overheating. It also reduces the resistance of the components and helps them to run more efficiently.

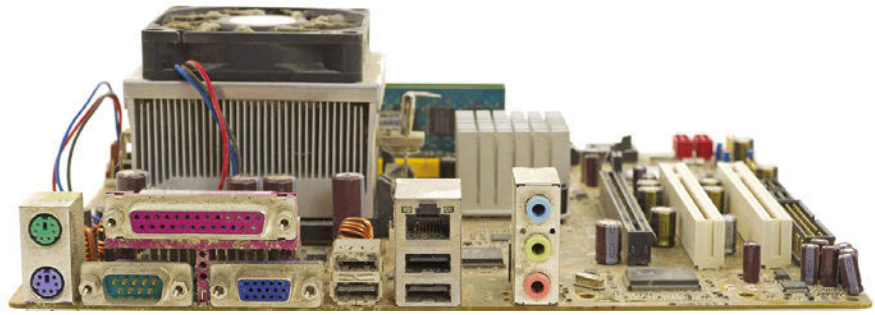


FIGURE 4.4.2 The cooling fan in this computer motherboard circulates air around the electrical components to cool them down.

RESISTORS IN SIMPLE CIRCUITS

Resistors are often used to control the amount of current in a particular circuit. Resistors can be manufactured to produce a relatively constant resistance over a range of temperatures. A colour-coding system is used on resistors to explain the amount of resistance they provide, including a percentage tolerance (precision). Figure 4.4.3 shows a resistor that uses the colour-coding system.

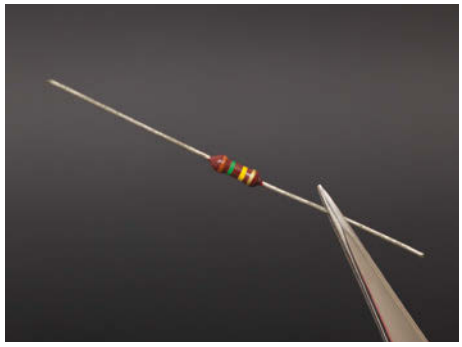


FIGURE 4.4.3 Common resistors are electrical devices with a known resistance. The coloured bands indicate the resistor's resistance and tolerance.

Colour-coded resistors

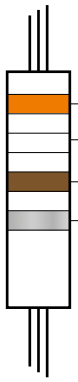
A resistor is typically a small piece of equipment that does not allow enough room to clearly print information about the resistor in the form of numbers. A colour-coding system is used on many resistors to convey detailed information in a small space about the resistance and tolerance of the resistor. Figure 4.4.4 below explains how to interpret the colour-coding system.

Resistor colour code

Band colour	Value
Black	0
Brown	1
Red	2
Orange	3
Yellow	4
Green	5
Blue	6
Purple	7
Grey	8
White	9
Gold	0.1
Silver	0.01

Tolerance colour code

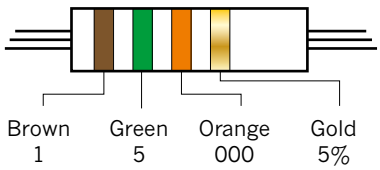
Band colour	±%
Brown	1
Red	2
Gold	5
Silver	10
None	20



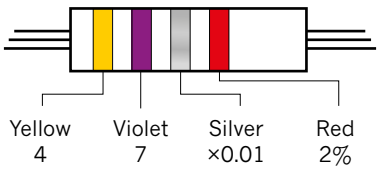
What this means

Band 1 First figure of value
Band 2 Second figure of value
Band 3 Number of zeros/multiplier
Band 4 Tolerance (±%) See below

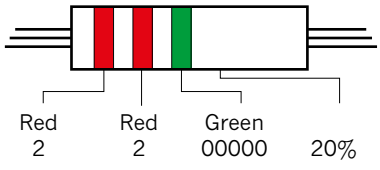
Note that the bands are closer to one end than the other.



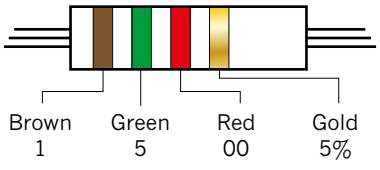
Resistor is 15 000 Ω or 15 kΩ ± 5%



Resistor is 47 × 0.01 Ω or 0.47 kΩ ± 2%



Resistor is 2 200 000 Ω or 2.2 MΩ ± 20%



Resistor is 1500 Ω or 1.5 kΩ ± 5%

FIGURE 4.4.4 Examples of resistor colour-coding. The tolerance gives a measure of the uncertainty in the resistance of the resistor.

4.4 Review

SUMMARY

- Resistance is a measure of how hard it is for current to flow through a particular material.
- Resistance is measured in ohms (Ω).
- The resistance of a material is proportional to its length and temperature, and is inversely proportional to its cross-sectional area.
- Colour-coding systems are used on many resistors to convey detailed information about their usage.

KEY QUESTIONS

Retrieval

1 Define 'resistance'.

2 State the unit of measurement for resistance.

3 State three variables that affect resistance in a wire.

Comprehension

4 Explain the purpose of a colour-coding system on resistors.

Analysis

5 **a** Judge whether its resistance would increase or decrease if the length of a piece of wire is increased.

b Judge whether its resistance would increase or decrease if the cross-sectional area of a piece of wire is increased.

c The resistance of a piece of wire is found to be 0.8Ω. Determine the resistance of a piece of the same wire twice as long.

6 Assess why the resistance of a wire would increase as it heats up.

4.5 Ohm's law

BY THE END OF THIS MODULE, YOU SHOULD BE ABLE TO:

- recall Ohm's law, $V = IR$
- solve problems using Ohm's law
- compare and contrast ohmic and non-ohmic conductors
- interpret graphical representations of potential difference and current data to find resistance using the gradient and its uncertainty
- investigate resistance across ohmic conductors.

As discussed in the previous module, the resistance of a component is a measure of how difficult it is for electric charge to flow through a component (such as a light bulb). This resistance is caused by collisions between charge carriers (electrons) and other charge carriers and the fixed positive metal ions in a circuit.

Georg Ohm (1789–1854) discovered that if the temperature of a metal wire was kept constant, the current flowing through it was directly proportional to the potential difference across it: $I \propto V$. This relationship would later be known as Ohm's law.

Ohm's law states that the potential difference across a metallic conductor, V, and the current flowing through it, I, are proportional at a given temperature. For example, if the potential difference across a wire is doubled, then the current flowing through the wire would also double. If the potential difference is tripled, then the current would also triple. In Ohm's law, R is the proportionality constant (resistance) in ohms (Ω).

$$V = IR \text{ or } \Delta V = IR$$

V is the potential difference in volts (V)

I is current in amps (A)

R is the constant of proportionality (resistance) in ohms (Ω)

This equation can be transposed to give a quantitative (mathematical) definition for resistance:

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

If an identical voltage produces two different-sized currents when separately connected to two light bulbs, then the resistance of the two light bulbs must differ. A higher current would mean a lower resistance of the light bulb, according to Ohm's law. This is because, when a conductor provides less resistance, more current can flow.

Ohm's law:

$V = IR$ (or $\Delta V = IR$)

where

V is the potential difference in volts (V)

I is current in amps (A)

R is the constant of proportionality (resistance) in ohms (Ω).

Worked example 4.5.1

USING OHM'S LAW TO CALCULATE RESISTANCE

When a potential difference of 3.0 V is applied across a piece of wire, 5.0 A of current flows through it. Calculate the resistance of the wire.

Thinking	Working
Ohm's law is used to calculate resistance.	$V = IR$
Rearrange the equation to find R.	$R = \frac{V}{I}$
Substitute in the values for this situation.	$R = \frac{3.0}{5.0}$ $= 0.60\,\Omega$

➤ Try yourself 4.5.1

USING OHM'S LAW TO CALCULATE RESISTANCE

An electric bar heater draws 10.0 A of current when connected to a 240.0 V power supply. Calculate the resistance of the element in the heater.

Ohm's law can also be used to determine the current flowing through a resistor when a particular potential difference is applied across it. Similarly, if the current and resistance are known, the potential difference across the resistor can be calculated.

Worked example 4.5.2

USING OHM'S LAW TO FIND CURRENT

A 100.0 Ω resistor is connected to a 12.0 V battery. Calculate the current (in mA) that would flow through the resistor.

Thinking	Working
Recall Ohm's law.	$V = IR$
Rearrange the equation to make I the subject.	$I = \frac{V}{R}$
Substitute in the values for this problem and solve.	$I = \frac{12}{100} = 0.12\,\text{A}$
Convert the answer to the required units.	$I = 0.12\,\text{A}$ $= 0.12 \times 10^3\,\text{mA}$ $= 120\,\text{mA}$

➤ Try yourself 4.5.2

USING OHM'S LAW TO FIND CURRENT

The element of a bar heater has a resistance of 25 Ω. Calculate the current (in mA) that would flow through this element if it is connected to a 240 V supply.

Worked example 4.5.3

USING OHM'S LAW TO FIND POTENTIAL DIFFERENCE

A current of 0.25 A flows through a 22 Ω resistor. Calculate the voltage across the resistor.

Thinking	Working
Recall Ohm's law.	$V = IR$
Substitute in the values for this problem and solve.	$V = 0.25 \times 22$ $= 5.5\,\text{V}$

➤ Try yourself 4.5.3

USING OHM'S LAW TO FIND POTENTIAL DIFFERENCE

The globe of a torch has a resistance of 5.7 Ω when it draws 700.0 mA of current. Calculate the potential difference across the globe.

OHMIC AND NON-OHMIC CONDUCTORS

Conductors that obey Ohm's law are known as **ohmic** conductors. Resistors are ohmic conductors because the current flowing through a resistor is usually proportional to the voltage across the resistor.

You can identify an ohmic conductor if you measure the current that flows through the conductor when different potential differences are applied across it.

Worked example 4.5.4

USING OHM'S LAW TO CALCULATE RESISTANCE, CURRENT AND POTENTIAL DIFFERENCE

The table below shows measurements for the potential difference and corresponding current for an ohmic conductor.

V (V)	0	2	4	V_2
I (A)	0	0.25	I_1	0.75

Determine I_1 and V_2.

Thinking	Working
Determine the factor by which potential difference has increased from the second column to the third column.	$\frac{4}{2} = 2$ The potential difference has doubled.
Apply the same factor increase to the current in the second column, to determine the current in the third column (I_1).	$I_1 = 2 \times 0.25$ $= 0.50\,\text{A}$
Determine the factor by which current has increased from the second column to the fourth column.	$\frac{0.75}{0.25} = 3$ The current has tripled.
Apply the same factor increase to the potential difference in the second column, to determine the potential difference in the fourth column (V_2).	$V_2 = 3 \times 2$ $= 6\,\text{V}$

➤ Try yourself 4.5.4

USING OHM'S LAW TO CALCULATE RESISTANCE, CURRENT AND POTENTIAL DIFFERENCE

The table below shows measurements for the potential difference and corresponding current for an ohmic conductor.

V (V)	0	3	9	V_2
I (A)	0	0.20	I_1	0.80

Determine I_1 and V_2.

The data from an experiment in which the current and potential difference are measured for a device is usually plotted on an *I*–*V* graph. If the conductor is ohmic, this graph will be a straight line passing through the origin (Figure 4.5.1).

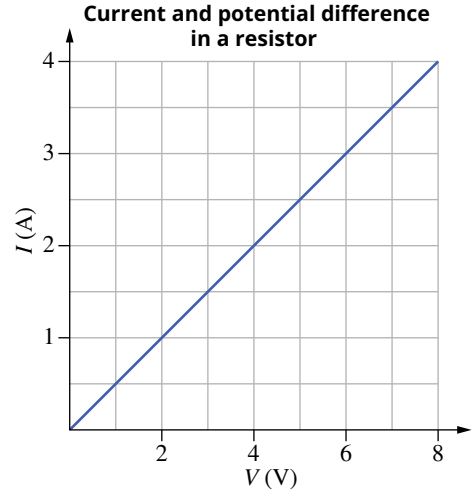


FIGURE 4.5.1 The resistance of an ohmic conductor is constant, so the *I*–*V* graph is a straight line that passes through the origin.

The resistance of the ohmic conductor (or resistor) can be found from the gradient of the *I*–*V* graph. Ohm recognised that the gradient was equal to the inverse of the resistance:

$$\frac{1}{R} = \frac{\text{rise}}{\text{run}} = \frac{4-1}{8-2} = \frac{3}{6}$$

$$\therefore R = \frac{6}{3} = 2$$

However, not all conductors are ohmic. The *I*–*V* graphs for **non-ohmic** conductors are not straight lines (Figure 4.5.2). Light bulbs and diodes are examples of non-ohmic conductors.

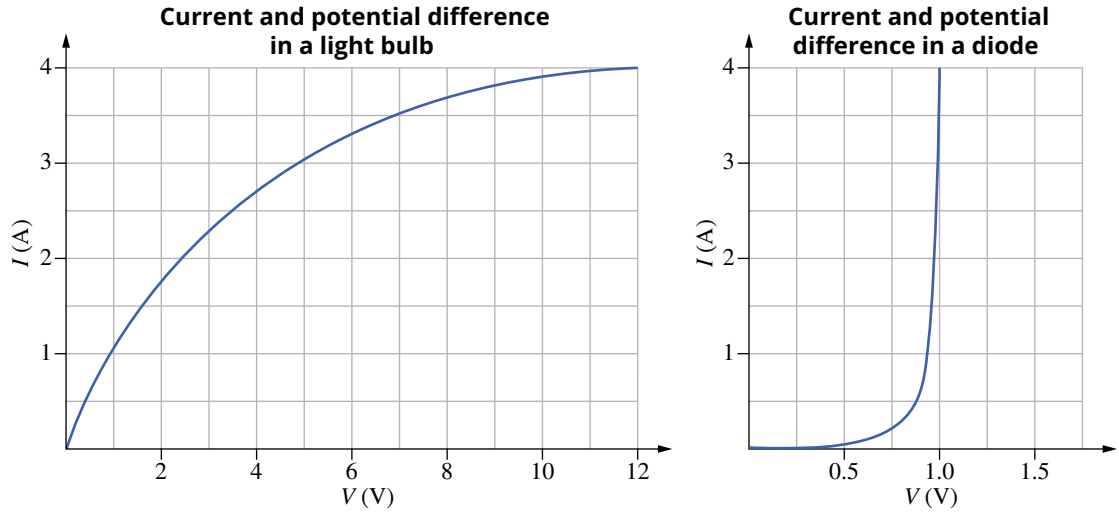


FIGURE 4.5.2 The *I*–*V* graph for a non-ohmic resistor is not a straight line.

USING *I*–*V* GRAPHS TO DETERMINE RESISTANCE

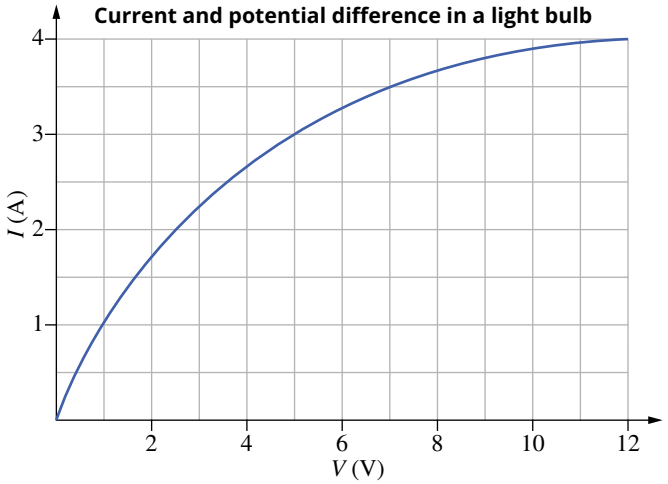
The inverse of resistance is defined as the ratio $\frac{I}{V}$. For an ohmic conductor, this value will be a constant regardless of the potential difference across the conductor. However, the resistance of a non-ohmic conductor will vary. The resistance of a non-ohmic conductor for a particular potential difference can be found by reading the value of the current from the *I*–*V* graph and using $R = \frac{V}{I}$. It is not necessary

(or correct) to find the gradient of the tangent to the curve, even though this is a common technique in other areas of physics.

Worked example 4.5.5

CALCULATING RESISTANCE FOR A NON-OHMIC CONDUCTOR

Calculate the resistance of the light bulb with the *I*–*V* graph below, when the potential difference is 5.0 V.

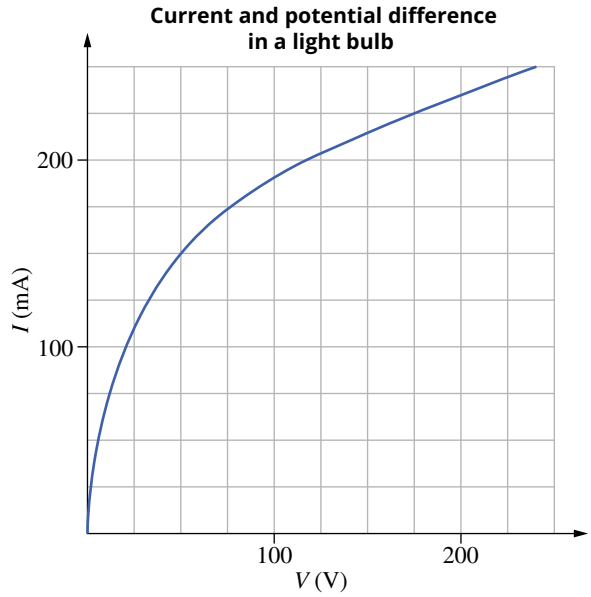


Thinking	Working
From the graph, determine the current at the required potential difference.	For $V = 5.0\,V$, $I = 3.0\,A$
Substitute these values into Ohm's law to find the resistance.	$R = \frac{V}{I} = \frac{5.0}{3.0} = 1.7$

➤ Try yourself 4.5.5

CALCULATING RESISTANCE FOR A NON-OHMIC CONDUCTOR

A 240 V, 60 W incandescent light bulb has *I*–*V* characteristics shown in the graph below. Calculate the resistance of the light bulb at 175 V.



4.5 Review

SUMMARY

- Ohm's law describes the relationship between current, potential difference and resistance:

$$V = IR$$

- Conductors that obey Ohm's law are known as ohmic conductors.
- Ohmic conductors have a constant resistance. The resistance of non-ohmic conductors varies for different potential differences.
- A graph of V–I can be used to find the resistance of an ohmic conductor by calculating the gradient of the line.

KEY QUESTIONS

Retrieval

1 State Ohm's law.

Comprehension

2 A student measures the current drawn by a resistor when different values of potential difference are applied. They plot their results on a graph. Describe the shape of the graph and how the student could find the resistance of the resistor from the graph if:

a the resistor is ohmic

b the resistor is non-ohmic.

3 Explain what Ohm's law is used to determine.

Analysis

4 A student finds that the current through a resistor is 3.5 A when a voltage of 2.5 V is applied to it.

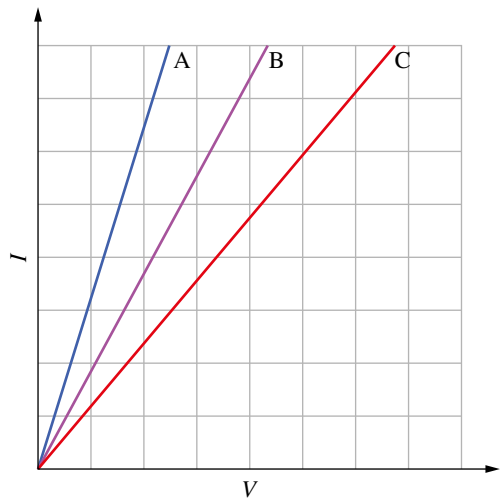
a Determine the resistance of the resistor.

b The voltage is then doubled and the current is found to increase to 7.0 A. Explain whether the resistor is ohmic or not.

5 Rose and Rachel are trying to find the resistance of an electrical device. They find that at 5.0 V it draws a current of 200.0 mA and at 10.0 V it draws a current of 500.0 mA. Rose says that the resistance is 25.0 Ω, but Rachel maintains that it is 20.0 Ω. Judge who is correct and provide reasons for your choice.

6 Nick has an ohmic resistor to which he has applied 5.0 V. He measures the current as 50.0 mA. He then increases the voltage to 8.0 V. Calculate the current he will find now.

7 An experiment is conducted to gather data about the relationship between current and potential difference for three ohmic devices, labelled A, B and C. The data is used to plot an I–V graph for each device, as shown in the graph.



a For a given potential difference, list the devices in order of highest current to lowest current.

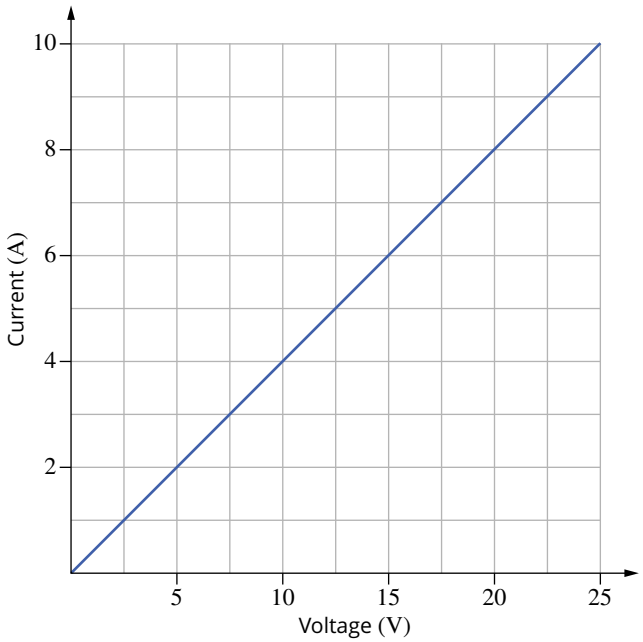
b Sort the devices in order of highest resistance to lowest resistance.

8 The table below shows measurements for the potential difference and corresponding current for an ohmic conductor.

V (V)	0	2	3	V_2
I (A)	0	0.25	I_1	0.60

Determine I_1 and V_2.

9 A student obtains a graph of the current–voltage characteristics of a piece of resistance wire, as shown in the diagram.

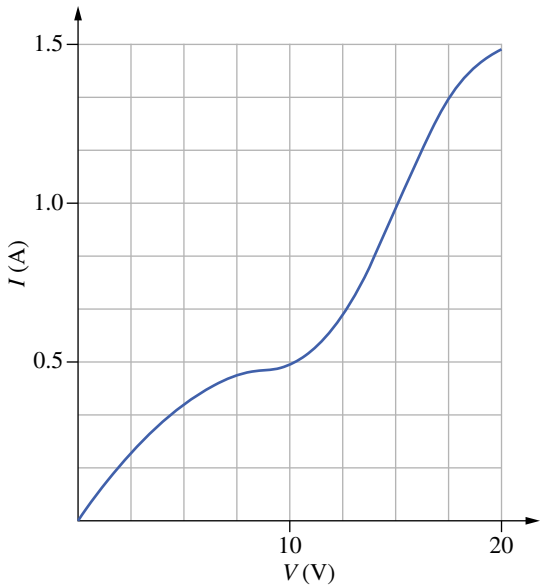


a Explain whether this piece of wire is ohmic or non-ohmic.

b Determine the current that flows in this wire at a voltage of 7.5V.

c Calculate the resistance of this wire.

10 A strange electrical device has the *I*–*V* characteristics shown on the graph.



a Identify whether the device is ohmic or non-ohmic and explain your answer.

b Determine the current that is drawn when a voltage of 10V is applied to the device.

c Calculate the voltage that is required to double the current drawn at 10V.

d Determine the resistance of the device for each of the following voltages.

i 10V

ii 20V

4.6 Power in a circuit

BY THE END OF THIS MODULE, YOU SHOULD BE ABLE TO:

- define power dissipation over resistors in a circuit
- recall the formula $P = VI$
- solve problems involving power
- model rearrangement of $P = VI$ to solve for $P = \frac{V^2}{R} = I^2R$.

If you wanted to buy a new phone charger, you might wonder how you could determine how quickly the charger will charge up the battery on your phone. Printed on all appliances is a rating for the **power** of that device. Power is a measure of how quickly energy is converted by the appliance. In other words, power is the rate at which energy is transferred or transformed by the components within the device.

POWER

Whenever energy is being transferred from one place to another, or transformed from one form to another, 'work' is being done. (Work is covered in more detail in Chapter 8.) Power, P, can be described as the rate at which work is done.

$$P = \frac{\text{energy transformed}}{\text{time}} = \frac{W}{t}$$

where

P is power in watts (W)

W is energy converted in joules (J)

t is time in seconds (s)

1 watt (W) = 1 joule per second (J s^{-1}).

The more powerful an appliance is, the faster it can do a given amount of work. In other words, an appliance that draws more power can do the same amount of work in a shorter amount of time. If you want something done quickly, then you need an appliance that has a higher power rating.

Recall the equation for work done in a circuit from Module 4.2:

$$W = VIt$$

Combine this with the power expression above:

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

This expression also enables you to calculate the energy transformations in a circuit by measuring voltage and current across circuit components.

Power is a measure of how much energy is converted in a unit of time in seconds (s).

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

where

P is power in watts (W)

W is energy converted in joules (J)

t is time in seconds (s)

1 watt (W) = 1 joule per second (J s^{-1}).

$P = VI$

where

P is power (W)

V is potential difference (V)

I is current (A).

Worked example 4.6.1

USING $P = VI$

An appliance connected to a 230 V power source draws a current of 4.0 A. Calculate the power used by this appliance.	
Thinking	**Working**
Identify the relationship needed to solve the problem.	$P = VI$
Identify the required values from the question, substitute and calculate the power used.	$P = VI$ $= 230 \times 4.0$ $= 920\ \text{W}$

➤ Try yourself 4.6.1

USING $P = VI$

An appliance connected to a 120 V power source draws a current of 6.0 A. Calculate the power used by this appliance.

POWER DISSIPATION IN A CIRCUIT

When designing electrical circuits, it is important to consider not only the components required to perform a specific task but also their ability to survive under normal operating conditions. Resistors are often used in circuits to dissipate electrical power by causing a voltage drop across it. This is done by converting electrical energy into unwanted energy, usually in the form of heat energy. Most resistors have a marked power rating to ensure that the user knows the maximum amount of power that can be dissipated by the resistor without burning it out.

In previous modules, you have developed the following equations:

$$P = VI \quad V = IR \quad I = \frac{V}{R}$$

From these equations, you can determine the amount of power dissipated by a resistor by substituting in the potential difference across a resistor.

$$\begin{aligned} P &= VI \\ &= V\,\frac{V}{R} \quad \left[I = \frac{V}{R}\right] \\ &= \frac{V^2}{R} \end{aligned} \qquad \begin{aligned} P &= VI \\ &= (IR) \times I \quad [V = IR] \\ &= I^2R \end{aligned}$$

The power dissipated, P, by a resistor, R, with a potential difference, V, can be found using the following equation:

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

The power dissipated, P, when a current, I, flows though a resistor, R, in a circuit can be found using the equation:

$$P = I^2R$$

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

where

- P is the power in joules per second ($J\,s^{-1}$)
- V is the potential difference in volts (V)
- I is current in amps (A)
- R is the resistance in ohms (Ω).

Worked example 4.6.2

USING $P = I^2R$

Calculate the power dissipated when a current of 10 mA flows through a 20 Ω resistor.

Thinking	Working
Identify the relationship needed to solve the problem.	$P = I^2R$
Identify the required values from the question, substitute and calculate.	$P = I^2R$ $= (10 \times 10^{-3})^2 \times 20$ $= 0.002\,W$ $= 2\,mW$

➤ Try yourself 4.6.2

USING $P = I^2R$

Calculate the power dissipated when a current of 20 mA flows through a 50 Ω resistor.

WS 1.3.5

Electrical energy in the home

Lighting can account for around 10% of energy use in the home, and concerns about sustainable energy usage and climate change have led to international research and development to improve the energy efficiency of electric lighting.

A traditional incandescent light bulb consists of a thin piece of curled or bent wire, called a filament, in a glass bulb (Figure 4.6.1). Often the bulb is evacuated (has the air removed) or filled with an inert (unreactive) gas so that the filament does not corrode. The wire is usually made of tungsten or another metal with a high melting point. When an electric current passes through the filament, it heats up. This in turn increases the resistance of the filament, causing it to heat up further. The filament quickly becomes so hot that it starts to glow, radiating heat and light.

FIGURE 4.6.1 An incandescent bulb produces light when its filament heats up.

This form of lighting is very inefficient. Only a small amount of the energy that goes into an incandescent light bulb is transformed into light; over 95% of the energy is lost as heat. This is useful if the desired output is heat, such as in a toaster or an electric heater. It is not so useful for lighting, especially in hot climates where extra heat is not wanted.

Energy-saving updates to the incandescent bulb, including compact fluorescent lamps (CFLs) and light-emitting diode (LED) bulbs, are much more efficient, typically using around 20% of the energy of incandescent bulbs. CFLs are the spiral-shaped light bulbs you may have in your home, and work on a similar principle to the longer fluorescent tubes used in schools and hospitals. Examples of LED bulbs and CFLs are shown in Figure 4.6.2.

Both types of bulb are more energy-efficient, but they also have disadvantages. CFLs contain small amounts of toxic mercury, so their disposal is a problem. LED bulbs can emit a more-directed light, so are good for spotlights, but can be less effective at general lighting in the home, and their quality can be variable. Since 2009, the Australian Government has been phasing out the use of incandescent bulbs, and is working to standardise and improve the efficiency of LED bulbs.

An exciting area of research is the use of organic light-emitting diodes (OLEDs). These contain an organic compound (e.g. carbon) and emit light when an electric current is applied. A traditional LED is a very bright point source, whereas OLEDs are commonly made into larger flat surfaces. OLEDs are already used in the screens of some mobile phones, TVs and laptops. Their design makes OLED screens much thinner than standard LED screens, and allows much more flexibility in how they are used. For example, they can be used as a coating on glass for windows that are transparent in the daytime and that light up at night, or on a flexible surface.

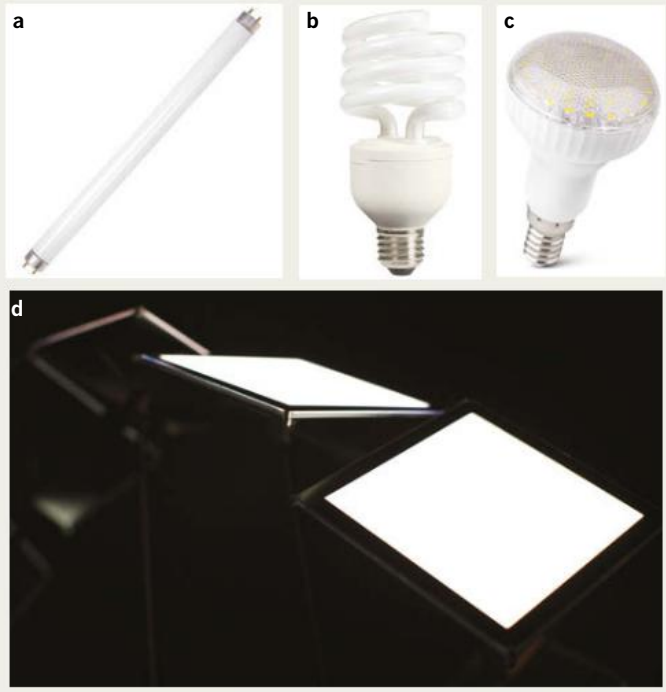


FIGURE 4.6.2 Alternatives to incandescent light bulbs include (a) fluorescent tubes, (b) fluorescent bulbs, (c) LED bulbs and (d) OLEDs.

A team at the University of Queensland, led by Dr Ebinazar Namdas, is working in partnership with scientists in India to develop the organic semiconductor technology used in OLEDs. Their aim is to reduce the cost and improve the efficiency of lighting in the home, and to provide highly energy-efficient lighting for remote communities that currently have no access to electric lighting.

Review

1. Recall the percentage of energy use in the home that is used for lighting.
2. Calculate the amount of energy used in an incandescent light bulb that is emitted as light.
3. List two potential advantages of OLEDs over LEDs.

4.6 Review

SUMMARY

- Power is the rate at which energy is transferred or transformed in a circuit component. It is defined and quantified by the relationships:

$$P = \frac{W}{t} = VI$$

- Power dissipation occurs when voltage is lost as current moves through components in a circuit. It is defined and quantified by the relationships:

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

KEY QUESTIONS

Retrieval

1 Define 'power'.

2 Give an equation for power, P, in terms of:

a energy transformed, W, and time, t

b potential difference, V, and current, I

c current, I, and resistance, R.

Comprehension

3 Explain how energy-efficient light bulbs can produce the same amount of light and do the same amount of work as incandescent light bulbs if they have a much lower power rating.

Analysis

4 A freezer has a power rating of 460 W and it is designed to be connected to 230 V.

a Calculate the work performed by the freezer in 5.0 minutes.

b Calculate the current flowing through the freezer.

5 A light bulb that is connected to 240 V uses 3.6 kJ of electrical potential energy in exactly one minute. Calculate the power of the lamp.

6 Calculate the power dissipated in a 10.0 kΩ resistor with 8.0 mA of current passing through it.

7 A hair dryer has a power rating of 800.0 W and is operational when connected to a mains supply of 240 V. Calculate how much energy is transferred when the hair dryer is used for 2.0 minutes.

MANDATORY PRACTICAL 3

Finding the resistance of an ohmic resistor

Conduct an experiment that obtains data for current through and potential difference across an ohmic resistor in order to find resistance.

- Write a research question.
- Suggest modifications to the method used in class to improve the outcome.
- Collect sufficient data (five variations of the independent variable and three repetitions of each variation).
- Consider safety.

Research and planning

Aim

- To find the resistance of an ohmic resistor by measuring the current that flows through it when the potential difference across it is varied.

Rationale (scientific background to the experiment)

The voltage, V, across an ohmic resistor and the current, I, through it are related to its resistance by the linear relationship Ohm's law, $V = IR$. The resistance is the inverse of the gradient of the line in a graph of the current drawn by a resistor when the potential difference is varied.

This experiment requires correct use of a voltmeter and ammeter.

Timing

30 minutes

Materials

- variable power supply
- connecting wires
- switch
- Ohmic resistor (200 Ω or 2 kΩ)
- DC voltmeter (0–10 V) or voltage sensor
- DC ammeter (0–1 A) or current sensor

Safety

The voltmeter and ammeter must be connected correctly; in particular, make sure that the ammeter is connected in series to avoid damaging it and the voltmeter is connected in parallel across the resistor.

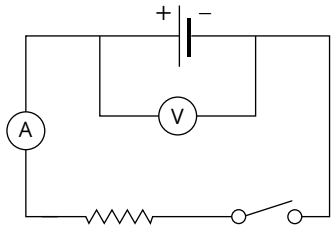
An appropriately sized resistor should be chosen to keep the current in the circuit small, otherwise the current will burn out the resistor and might cause a fire.

Method

Risk assessment

Before you commence this practical activity, you must conduct a risk assessment. Complete the template in your Skills and Assessment book or download it from your eBook.

1 Connect the circuit as shown in the diagram below.



2 For a range of voltmeter readings (e.g. 0, 2, 4, 6, 8 and 10 V), close the switch and take the ammeter reading. Include the uncertainty for each measurement.

3 Record the results in a table.

4 Repeat the same measurements two more times in order to obtain an average.

Variables

i Independent: voltage

ii Dependent: current

iii Controlled: resistance

Analysing

Raw data

TABLE 1.1 Measured current for different potential differences

Measured voltage (± _____ V)	Measured current (± _____ A)			
	Trial 1	Trial 2	Trial 3	Average
0				±
2				±
4				±
6				±
8				±
10				±

➤ Reflect and check that your data analysis demonstrates these characteristics

- ❑ Effective investigation of phenomena is demonstrated by the collection of sufficient and relevant raw data.
- ❑ Accurate application of algorithms, visual and graphical representations of data is demonstrated by appropriate processing and presentation of data to aid the analysis and interpretation of data.

Analysis

➤ Reflect and check that your analysis demonstrates these characteristics

- ❑ Systematic and effective analysis of evidence is demonstrated by a thorough and appropriate error analysis.
- ❑ Systematic and effective analysis of evidence is demonstrated by a thorough identification of relevant trends, patterns and relationships.
- ❑ Insightful and valid interpretation of evidence is demonstrated by drawing a valid and defensible conclusion based on the analysis.

1 Plot your results, including error bars, on a graph, with the independent variable, *V*, on the horizontal axis and the dependent variable, *I*, on the vertical axis. Take care with units and check that the units of current are in A, not mA.

2 Draw a line of best fit, including minimum and maximum lines.

Calculations

3 Calculate the gradient of the line of best fit. Use this to find the resistance of the resistor and its uncertainty. Remember that the gradient $= \frac{1}{R}$.

4 Compare this to Ohm's law in order to find the resistance of the resistor.

5 Calculate the uncertainty in the gradient to find the uncertainty of the resistance.

6 Are there any points on your graph that do not fit the trend? Explain why this may have been the case.

7 Compare your value for resistance with the values obtained by other groups who used the same resistor. Are they the same? Did the other groups use the same values of potential differences as their independent variable?

8 Compare your graph to the graphs drawn by other groups who used different resistors. What do you notice about the shape of the graphs?

9 Would you expect the graphs to be to same or different? Why?

Interpreting and communicating

Conclusion

1 The aim of the experiment was to determine the resistance of an ohmic resistor by varying the potential difference across it and measuring the current it drew. Were you able to find a single value for the resistance of the resistor?

2 Use the coloured bands on the resistor to identify its resistance. How does your experimental value compare with this?

Evaluation

3 Considering your analysis and conclusion, did the experiment provide an effective method of finding the resistance of the resistor?

4 Was there a reasonable level of uncertainty in your calculations for the resistors?

Improvements

5 If you were to repeat the experiment, what would you do differently?

Include in your answer:

- how you would change the methodology and how this might improve the results
- what skills you used to perform the tasks and how your technique could be improved
- how the collection of data could be made more reliable and the uncertainty reduced.

Extension

6 Do you think this methodology could be applied to determine the resistance of any component in a circuit, for example a light bulb?

7 Identify any limitations to using this method for other resistors.

➤ Reflect and check that your evaluation demonstrates these characteristics

- ❑ Critical evaluation of processes is demonstrated by a discussion of the reliability and validity of the experimental process supported by evidence such as the quality of the data (as quantified in the error analysis).
- ❑ Critical evaluation of the conclusion is demonstrated by a discussion of the veracity of the conclusions with respect to the error analysis and limitations or sufficiency of the data.
- ❑ Insightful evaluation of processes and conclusions is demonstrated by a suggestion of improvements or extensions to the experiment, which are logically derived from the analysis of the evidence.

Chapter review

04

KEY TERMS

ammeter
atom
charge
conductor
conventional current
coulomb
current
drift velocity
electrical circuit
electrical potential energy
electricity
electrostatic attraction
electrostatic repulsion
elementary charge
induction
insulators
ion
ionised
metal
net charge
non-metal
non-ohmic
ohmic
potential difference
power
resistance
resistor
transfer
transform
voltmeter
volts

KEY QUESTIONS

Retrieval

1 State approximately how many electrons make up a charge of –3.0 C.

2 Identify which of the following charged particles are moving when an electric current flows in a circuit:
- **A** negatively charged electrons
- **B** positively charged electrons
- **C** positively charged protons
- **D** both negative and positive charges

Comprehension

3 Determine the approximate charge on 4.2×10^{19} protons.

4 Select the option that best explains why water flowing in a pipe is a common analogy for electric current.
- **A** Water does not conduct electricity.
- **B** Water can leak out of a pipe.
- **C** Water is not compressed or lost as it flows through a pipe.
- **D** Water and electricity do not mix.

5 Identify which of the following best describes what the bicycle-chain analogy shows.
- **A** Electrons physically touch one another.
- **B** Only a small number of electrons move.
- **C** Electrons are the same shape as the links in a bicycle chain.
- **D** Electrons move simultaneously in every part of the circuit.

6 Identify the option that lists the quantities you would need to measure to calculate the amount of electrical energy used to heat water using an electric element.
- **A** potential difference, resistance and current
- **B** time, current and charge
- **C** current, time and potential difference
- **D** potential difference and current

7 Explain why even a good conductor such as copper wire provides some resistance to current.

Analysis

8 An alpha particle consists of two protons and two neutrons. Calculate the charge on an alpha particle.

9 Calculate the current that flows when 0.23 C of charge passes a point in a circuit each minute.

10 A current of 1.6 A flows for 100.0 seconds. Calculate:
- **a** the amount of charge, in coulombs, that moves past a point in this time
- **b** the number of electrons that move past a point in this time.

11 A current of 0.040 A flows for a certain amount of time. In this time 5.0×10^{18} electrons move past a point. Calculate:
- **a** the amount of charge, in coulombs, that moves past a point
- **b** the length of time that the current is flowing.

12 A phone battery has a voltage of 3.8 V. Determine the amount of energy provided if 2.0 C of charge is drawn from the battery.

13 A battery does 2.0 J of work on a charge of 0.50 C to move it from point A to point B. Calculate the potential difference between the two points A and B.

14 Calculate how much power an appliance uses if it does 2500 J of work in 30.0 minutes.

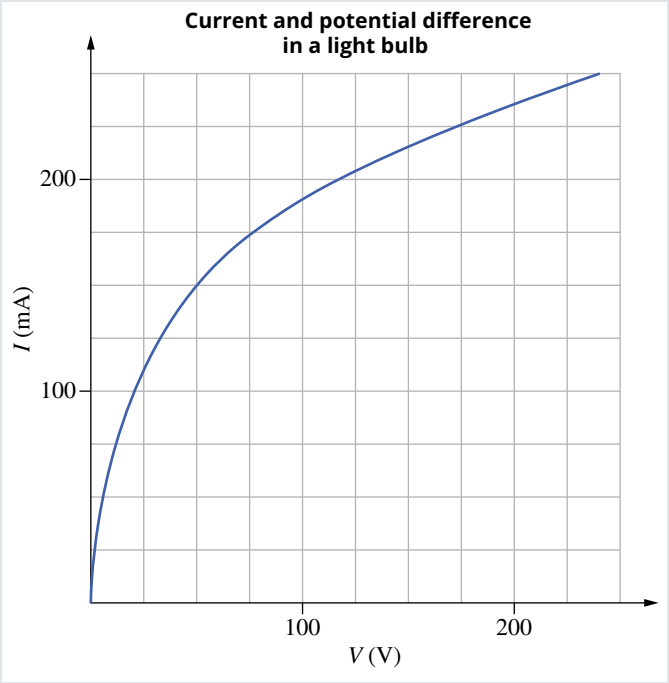
15 A battery gives a single electron 1.4×10^{-18} J of energy. Calculate the potential difference supplied by the battery.

16 A 230 V appliance consumes 2000.0 W of power. The appliance is left on for 2.0 hours. Calculate the amount of current that flows through the appliance in that time.

17 A student finds that the current through a wire is 5.0 A when a voltage of 2.5 V is applied to it. Calculate the resistance of the wire.

18 A 60.0 W incandescent globe draws 0.25 A when connected to a 240 V power supply. Calculate the resistance of the globe.

19 Calculate the resistance at 50.0 V of the non-ohmic conductor in the *I*–*V* graph shown.



20 A current of 0.25 A flows through an 80.0 Ω resistor. Calculate the voltage across it.

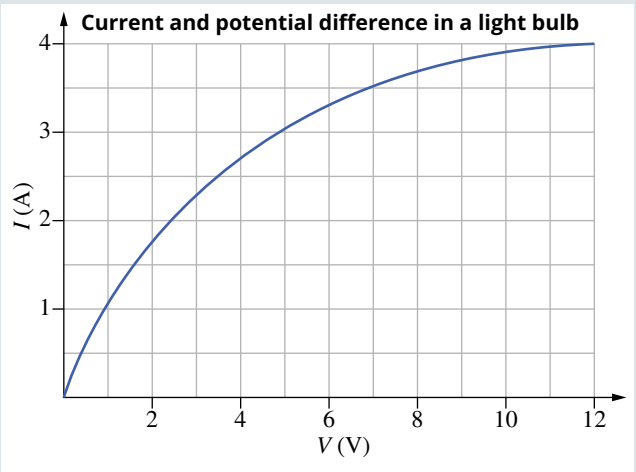
21 When 1.5 V is applied across a particular resistor, the current through the resistor is 50.0 mA. Calculate the resistance of the resistor.

22 The *I*–*V* graph of a non-ohmic conductor is shown below. Calculate the resistance of the conductor for each of the following voltages.

a 1.0 V

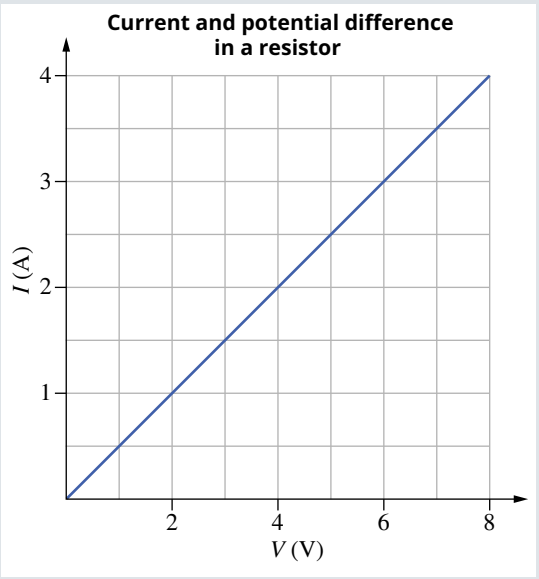
b 7.0 V

c 12.0 V



23 A potential difference of 240 V is used to generate a current of 5.00 A to heat water for exactly 3 minutes. Calculate the energy transferred to the water in that time.

24 Siobhan is measuring the current flowing through an ohmic conductor as she varies the potential difference of the power source. The results are shown in the graph shown. Calculate the resistance when the potential difference is 1.0 V.



25 A laptop computer draws 500.0 mA from a 240 V power point. Determine the power output of the computer.

26 A hair dryer is designed to produce 1600 W of power when connected to a 240 V power supply. Determine the resistance of the hair dryer.

27 A 120 V lamp draws 12.5 A when cold but only 0.80 A when hot. Calculate the resistance of the lamp at each temperature.

28 If 0.80 A of current flows through a light bulb, calculate the number of electrons that enter the light bulb each second.

29 A 3.0 V torch with a 0.30 A bulb is switched on for 1 minute.

a Calculate how much charge has travelled through the filament in this time.

b Calculate how much energy has been used.

c Deduce where this energy has come from.

Knowledge utilisation

30 A circuit contains a 50.0 Ω resistor and a power supply. The circuit is connected for 10.0 s, and during this time a charge of 5.00 C flows past a point in a circuit. Determine how much energy the resistor dissipates during this time.

31 A simple circuit contains a 100.0 Ω resistor and a 10.0 V power supply. Determine the number of electrons that flow through a point in the circuit if the circuit is connected for 1.0 minute.

CHAPTER

05 Electrical circuits

Electrical circuits are the basis of much of our modern society. This chapter introduces a range of circuits, from simple series circuits to the complex parallel wiring systems that are found in a modern home. Electrical circuits can be used to perform energy transfers and transformations through devices such as light bulbs, thermistors, light-dependent resistors and light-emitting diodes. It is essential that anyone working with electricity learns how to do so safely in the home and laboratory. Several safety mechanisms are examined that minimise the effect of current on humans.

Syllabus subject matter

Topic 3 • Electrical circuits

CURRENT, POTENTIAL DIFFERENCE AND ENERGY FLOW

- recall that electric charge is conserved at all points in an electrical circuit and recognise this as Kirchhoff's current law
- explain that the energy inputs in a circuit equal the sum of energy output from loads in the circuit and recognise this as Kirchhoff's voltage law.

CIRCUIT ANALYSIS AND DESIGN

- define *power dissipation* over resistors in a circuit
- solve problems involving electrical potential difference, electric current, resistance and power
- recall resistor, voltmeter, ammeter, cell, battery, switch and bulb circuit diagram symbols
- recognise series and parallel connections of components in electrical circuits
- solve problems involving finding equivalent resistance, electrical potential difference and electric currents in series and parallel circuits
- design simple series, parallel and series/parallel circuits.

SCIENCE AS A HUMAN ENDEAVOUR

- Powering the digital age

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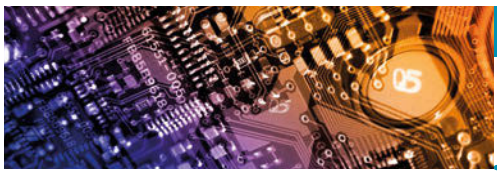
5.1 Electrical circuits



BY THE END OF THIS MODULE, YOU SHOULD BE ABLE TO:

- understand simple electrical circuits and read circuit diagrams
- measure current and voltage using an ammeter, voltmeter or multimeter.

SIMPLE ELECTRICAL CIRCUITS

As you will recall from Chapter 4, a flow of electric charge is called an electric current. Current can be carried by moving electrons in a wire or by ions in solution. This section explores current as it flows through wires in **electrical circuits**. Recall from Chapter 4 that an electrical circuit is a path made of conductive material, through which charges flow (an electric current) in a closed loop. Current will flow in a circuit only when the circuit forms a continuous (closed) loop from one terminal of a power supply to the other terminal.

Electrical circuits are involved in much of the technology used every day. To construct electrical circuits, you must know about the components of a circuit and be able to read circuit diagrams (Figure 5.1.1).

FIGURE 5.1.1 Circuit diagrams are used to help us to construct electrical circuits.

Common symbols for electronic components

A number of different components can be added to a circuit. It is not necessary to be able to draw detailed pictures of these components; simple symbols are much clearer. The common symbols used to represent the electrical components in electrical circuits are shown in Figure 5.1.2a.

Circuit diagrams

When constructing a building, it is important that the builder has a clear set of instructions from the designer. This is as much the case for an electrical circuit as it is for a tall building or a motor vehicle.

Circuit diagrams are used to clearly show how the components of an electrical circuit are connected. They simplify the physical layout of the circuit into a diagram that is recognisable by anyone who knows how to interpret it. You can use the list of common symbols for electrical components to interpret circuit diagrams (Figure 5.1.2a).

The circuit diagram in Figure 5.1.2b shows how a cell (or battery), resistor, switch and light globe are connected in a circuit. The circuit can be traced by following the straight lines representing the connecting wires.

a

Device	Symbol	Device	Symbol
wires crossed not joined		cell (DC supply)	
wires joined, junction of conductor		battery of cells (DC supply)	
fixed resistor	or	AC supply	or
light bulb	or	ammeter	A
		voltmeter	V
diode		fuse	
		switch open	
earth or ground		switch closed	

b

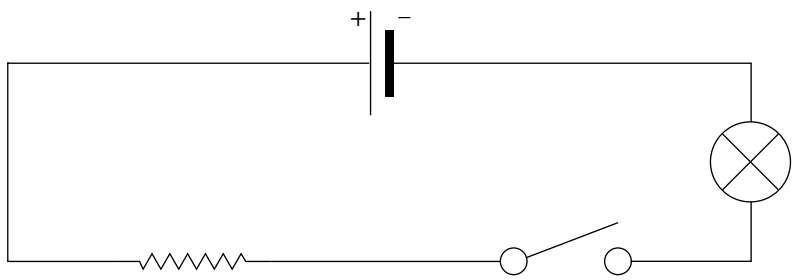


FIGURE 5.1.2 (a) Some commonly used electrical devices and their symbols, which can be used in circuit diagrams; (b) a simple circuit diagram

Conventional current vs electron flow

On a circuit diagram, current is indicated by a small arrow and the symbol *I*. This shows the conventional current or just current. Recall from Chapter 4 that the direction of conventional current is opposite to the direction of electron flow, as it was originally thought that the charges that flowed in circuits were positive, and flowed from the positive terminal to the negative terminal. This convention is still used today, even though scientists know now that it is actually the negative charges (electrons) that flow around a circuit.

MEASURING CIRCUITS

In this section, you will learn how to measure the current and voltage in a circuit using simple meters, and how to correctly connect them.

Measuring current: the ammeter

A device called an ammeter measures current. The ammeter is connected along the same path taken by the current flowing through the light bulb (Figure 5.1.3). This is referred to as connecting the ammeter 'in series'. The circuit is connected in series so there is only one path for the current to take. The positive terminal of the ammeter is connected so that it is closest to the positive terminal of the power supply. The negative terminal of the ammeter is closest to the negative terminal of the power supply.

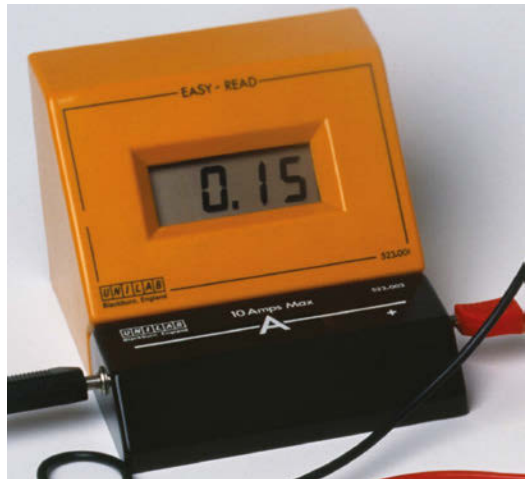


FIGURE 5.1.3 A digital ammeter (labelled with an A) measures current in a circuit (in this case 0.15 A). Note that the negative terminal is connected to the power supply, and the positive terminal is connected to the light globe.

Measuring the current is possible because charge is conserved at all points in a circuit. This means that the current is the same at all points in a series circuit. The current that flows into a light bulb is the same as the current that flows out of the light bulb. An ammeter can therefore be connected before or after the bulb in series to measure the current. The concept of conservation of charge will be explored further in Module 5.2.

Table 5.1.1 lists some typical values for electric current in various situations.

TABLE 5.1.1 Typical values for electric current

Situation	Current
1 electron moving past a point per second	10^{-19} A
nerve fibres in body	1 μA
pocket calculator	5 mA
mobile phone charger	200 mA (input), 1.5 A (output)
light globe	400 mA
USB port	500–900 mA
laptop charger	1.4 A (input), 2.3 A (output)
toaster	3 A
hair dryer	9 A
fan heater	10 A
starter motor in car	200 A
lightning	10 000 A
current flowing between Jupiter and its closest moon, Io, caused by charged particles escaping Io's volcanoes moving in Jupiter's huge magnetic field	3×10^6 A

Measuring voltage: the voltmeter

Recall from Chapter 4 that the voltage, or potential difference, is what gives electrons the energy to travel around a circuit. Voltage is a measure of the amount of energy per unit charge that a charge has. A device called a voltmeter measures voltage.

Voltmeters are wired into circuits differently from ammeters. Unlike an ammeter, which measures the current passing through a wire, a voltmeter measures the change in voltage (potential difference) as current passes through a particular component. This means that one wire of the voltmeter is connected to the circuit before the component and the other wire is connected to the circuit after the component; that is, as an extra side loop to the main circuit. This is called connecting the voltmeter 'in parallel'. Parallel circuits will be investigated in more depth in Module 5.3.

In Figure 5.1.4, the voltmeter is connected to the circuit on either side of the light globe; that is, in parallel. This is so that it can measure the voltage drop (potential difference) across the light globe. Like the ammeter, it is important to connect the voltmeter with the positive terminal closest to the positive terminal of the power supply. The voltmeter's negative terminal is connected closest to the negative terminal of the power supply.

FIGURE 5.1.4 A voltmeter measures the voltage change (in this case, 6.23 V) across a light globe. Note that the voltmeter is connected to either side of the light globe as an extra small loop attached to the main circuit (in parallel).

An ammeter measures current, *I*, in amps (A) and is connected in a circuit in series.

An voltmeter measures the potential difference or voltage, *V*, in volts (V) and is connected in a circuit in parallel.

Multimeters

The internal circuitry of a voltmeter is significantly different from that of an ammeter. Electricians and scientists who work with electrical circuits often find it inconvenient to keep collections of voltmeters and ammeters, so they have found a way to bundle the circuitry for both meters up into a single device known as a **multimeter** (Figure 5.1.5).

This is much more convenient because the multimeter can be quickly switched from being an ammeter to being a voltmeter as needed. However, when a multimeter is switched from one mode to another, it is important to make a corresponding change to the way it is connected to the circuit being measured. An ammeter is connected in series and a voltmeter in parallel. In fact, if a multimeter is working as an ammeter and it is connected in parallel like a voltmeter, it may draw so much current that its internal circuitry will be burnt out and the multimeter will be destroyed.

FIGURE 5.1.5 A digital multimeter can be used as either an ammeter or a voltmeter.

Internal resistance

Resistors and light globes aren't the only components in a circuit to have a resistance. Recall from Chapter 4 that everything a charge moves through in a circuit resists the flow of the charge. Cells and batteries also have their own **internal resistance** that affects the output voltage and the current through the circuit For the copper wire connecting other elements of a circuit, this internal resistance is negligible (extremely low) and you can ignore it for calculations.

Ideally, the meters you use to measure current or voltage in a component of a circuit do not disturb the circuit in which they are connected. An ideal ammeter has zero resistance so it can measure the current that flows through it without affecting the current that flows in the circuit. An ideal voltmeter has an infinitely large resistance so that, when it is connected in parallel, it does not offer an alternative pathway for the charges in the circuit. Batteries, cells and meters will not interfere with the circuit they measure, so you do not need to take into account their internal resistance in your calculations.

5.1 Review

SUMMARY

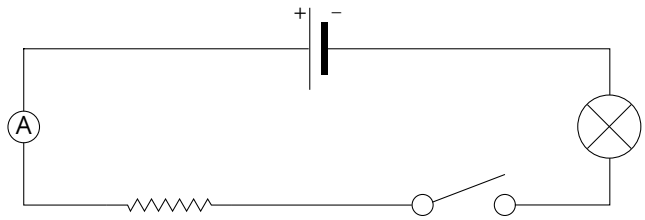
- Simplified diagrams can be used to represent electrical circuits.
- Current will flow in a circuit only when the circuit forms a continuous (closed) loop from one terminal of a power supply to the other terminal.
- Conventional current in a circuit flows from the positive terminal to the negative terminal.
- Current is measured with an ammeter connected along the same path as the current flowing within the circuit (i.e. in series).
- Voltage, or potential difference, is measured with a voltmeter connected in parallel with another component in the circuit.
- A multimeter can be used to measure either current or voltage, depending on how it is connected in a circuit.

KEY QUESTIONS

Retrieval

1 List the requirements for current to flow in a circuit.

2 List the electronic devices shown in the circuit diagram, starting from the top of the diagram and moving anticlockwise.



3 Name the component you would use to measure the following in a circuit.
- **a** the current
- **b** the voltage

Comprehension

4 Identify how you would connect a multimeter to measure the current in a circuit: in series or in parallel.

5 Explain why scientists refer to conventional current as flowing from positive to negative.

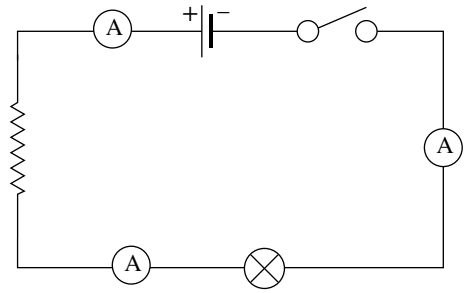
6 Draw a circuit diagram for a simple circuit containing a bulb, a cell and a resistor. Indicate the direction of the current.

7 Draw a circuit diagram for a circuit containing the following items set up correctly:
- **a** a cell, a bulb and an ammeter
- **b** a cell, a bulb and a voltmeter

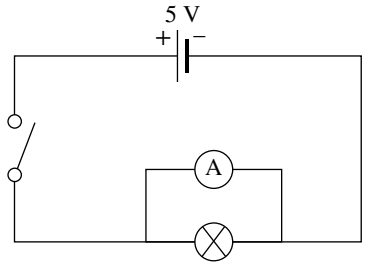
8 Explain why an ammeter is set up in series, whereas a voltmeter is set up in parallel.

Analysis

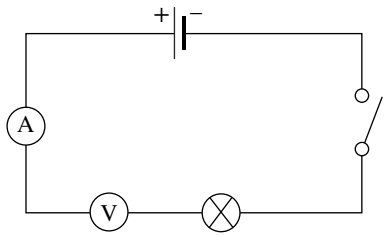
9 A student wants to measure the current flowing in a circuit, and sets up three ammeters at the positions shown in the diagram. Explain whether the readings on the ammeters will be the same or different.



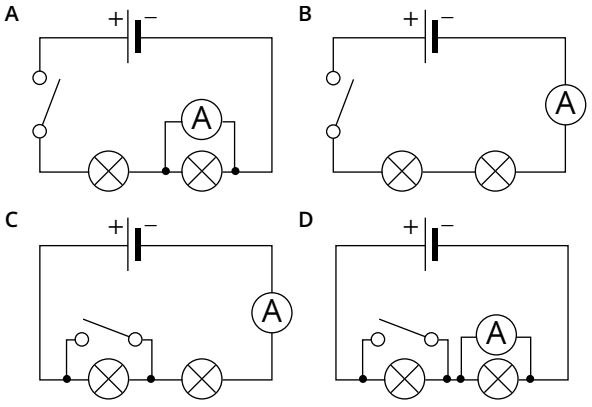
10 A student wants to measure the current flowing in a circuit, and sets up an ammeter as shown in the figure. When he turns on the power supply, the reading on the ammeter is extremely high, and the ammeter stops working. Deduce what this tells you about the internal resistance of the ammeter and the path the current took in this circuit.



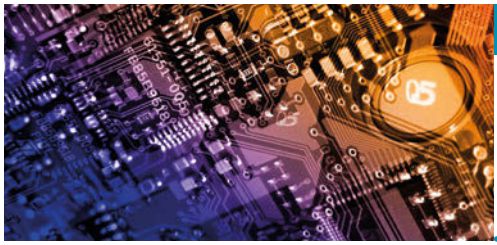
11 The student now sets up an ammeter in series, and adds a voltmeter as shown below. He notices that the current shown on the ammeter is almost zero and the bulb is not lit. Recall Ohm's law ($V = IR$) from Chapter 4. Consider what can be deduced about the internal resistance of the voltmeter from this.



12 The student decides to set up a circuit that contains a cell, two light bulbs and a switch, so that both bulbs will light when the switch is closed. He adds an ammeter to measure the current flowing through the bulbs. Assess which of the circuits shown below would achieve this.



5.2 Series circuits



BY THE END OF THIS MODULE, YOU SHOULD BE ABLE TO:

- understand what a series circuit is
- calculate the equivalent series resistance for a number of resistors in series
- apply Ohm's law to the equivalent series resistance to calculate the current drawn by a group of resistors connected in series.

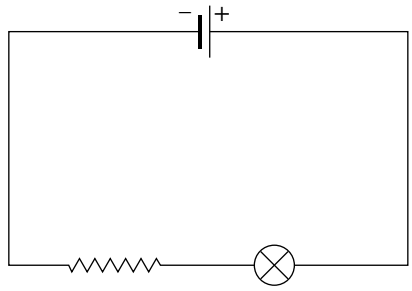


FIGURE 5.2.1 This circuit has a resistor and light bulb connected in series, so there is only one path for the current to flow.

Some circuits contain more than one electrical component. In a **series circuit**, components are connected one after another in a continuous loop, and there is only one way for the current to flow. Components connected in this way are said to have been connected 'in series'. The circuit shown in Figure 5.2.1 shows a resistor and a light bulb connected in series with an electric cell.

Series circuits are very easy to construct, but they have some disadvantages. As every component is connected one after the other, the components are dependent on each other. If one component is removed or breaks down, the circuit is no longer a closed loop and no current will flow. Figure 5.2.2 shows how removing a globe from a series circuit interrupts the entire circuit. Due to this characteristic, series circuits with more than one component are not commonly used in the home.

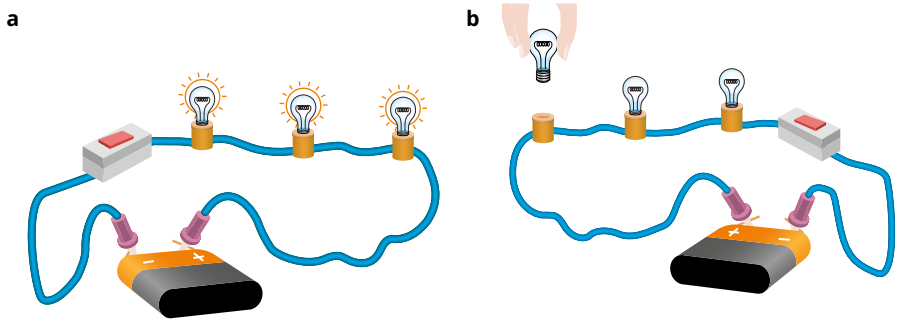


FIGURE 5.2.2 (a) All components in the circuit are intact and so the circuit is a closed loop. (b) When one light bulb is removed, the whole circuit is interrupted so no current flows and no bulbs light up.

Conservation of charge

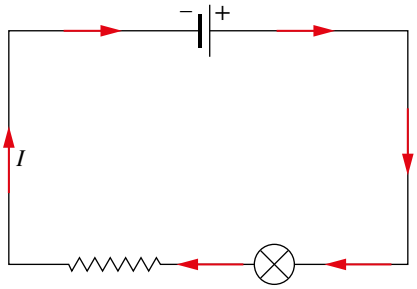


FIGURE 5.2.3 In a series circuit, the same current flows through each component.

When analysing a series circuit, it is important to understand that the same amount of current flows in every part of the circuit. Electric charges are not created or destroyed within an electrical circuit, so the current flowing out of the cell must be the same as the current flowing through the lamp, which is also the same as the current flowing through the resistor. This current also flows unchanged back into the cell (Figure 5.2.3). The unchanging nature of the amount of charge flowing in and out of a component in a circuit is known as the **law of conservation of electric charge**.

The current in a series circuit is the same in every part of the circuit.

The current (i.e. the number of electrons) entering a component in a circuit must be equal to the current (the number of electrons) leaving the component.

EQUIVALENT SERIES RESISTANCE

Consider the circuit in Figure 5.2.4. When analysing this circuit, it might be tempting to apply $V = IR$ to each resistor using the potential difference supplied by the cell for V. However, the potential difference is split between R_1 and R_2, so the potential difference across resistor R_1 is not the same as the potential difference supplied by the cell. Similarly, the potential difference across lamp R_2 is not the same as the potential difference supplied by the cell. If $V_{supply} = IR_1$ was used to calculate the current flowing in the circuit, the answer would be incorrect.

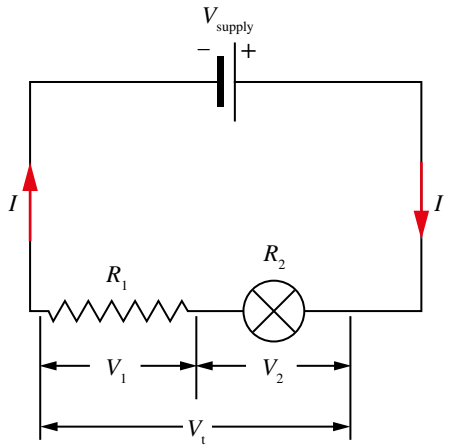


FIGURE 5.2.4 Using Ohm's law, it is possible to show the relationship between the potential difference supplied by the cell, V_t, the current flowing in the circuit, I, and the resistances of the two components R_1 and R_2.

To calculate voltage supplied by the cell, the voltage drop across each resistor should be considered. The law of conservation of energy tells you that the energy supplied by the cell must be the same as the energy transformed by the components in the circuit (e.g. the resistor and the bulb), so no energy can be lost or created. Therefore the potential difference across the cell (the voltage gain) must be equal to the total potential difference across the circuit (the voltage drop):

$$V_{supply} = V_t = V_1 + V_2$$

If the resistance of the fixed resistor is R_1, the resistance of the lamp is R_2 and the current flowing through both R_1 and R_2 is I, then using Ohm's law for the voltage drop over each resistor gives:

$$V_1 = I \times R_1 \text{ and } V_2 = I \times R_2$$

The total voltage drop, V_t, across the two components is the sum of the individual voltage drops:

$$V_t = V_1 + V_2 = IR_1 + IR_2 = I \times (R_1 + R_2)$$

This equation shows the relationship between the potential difference supplied by the cell and the potential differences of the lamp and resistor. The last part of the equation also shows that the total resistance of the lamp and resistor in series is the sum of their individual resistances. The lamp and resistor could be replaced with a single resistor, without changing the current in the circuit, if the single resistor has a resistance equal to $R_1 + R_2$.

In general, for any circuit:

$V_{supply} = V_1 + V_2 + \ldots + V_n$

where

V_{supply} is the voltage supplied by the cell

$V_1, V_2, \ldots, V_n$ are the individual voltage drops.

Figure 5.2.5 shows that two resistors can be replaced with a single resistor. In general, an **equivalent resistance** can replace a number of individual resistors connected in series. This is equal to the sum of the individual resistances and is also called the equivalent series resistance or total resistance, R_t.

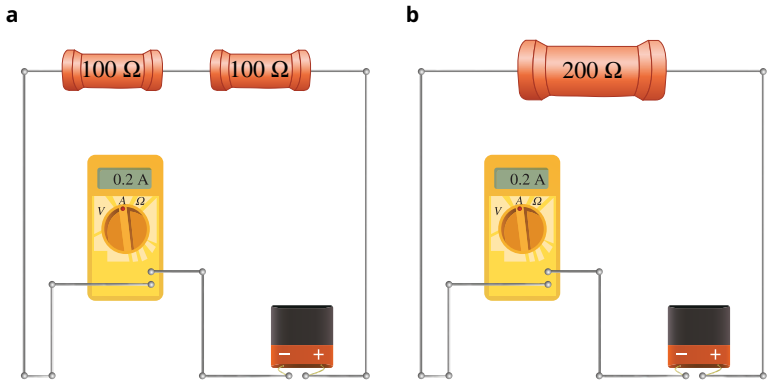


FIGURE 5.2.5 (a) Two 100 Ω resistors can be replaced with (b) a single 200 Ω resistor to draw the same current in a circuit.

$R_t = R_1 + R_2 + \ldots + R_n$
where
R_t is the equivalent series resistance
R_1, R_2, …, R_n are the individual resistances.

Equivalent resistances can be used in circuit analysis to simplify a complicated circuit diagram so that current and potential difference can be determined.

Identical resistors in series

Where identical resistors are placed in series, the total resistance of the combination can be found by simply multiplying the value of one of the resistors by the number of resistors.

For example, three 4 Ω resistors connected in series would have an equivalent resistance of 12 Ω.

$$R_t = 4\,\Omega \times 3 = 12\,\Omega$$

The three 4 Ω resistors in series could be replaced with a single 12 Ω resistor.

Worked example 5.2.1

CALCULATING AN EQUIVALENT SERIES RESISTANCE

A 100.0 Ω resistor is connected in series with a 690.0 Ω resistor and a 1.20 kΩ resistor. Calculate the equivalent series resistance.

Thinking	Working
Recall the formula for equivalent series resistance.	$R_t = R_1 + R_2 + \ldots + R_n$
Substitute in the given values for resistance. Make sure to convert kΩ to Ω. Solve to find the equivalent series resistance.	$R_t = 100.0 + 690.0 + 1200$ $= 1990\,\Omega$

➤ Try yourself 5.2.1

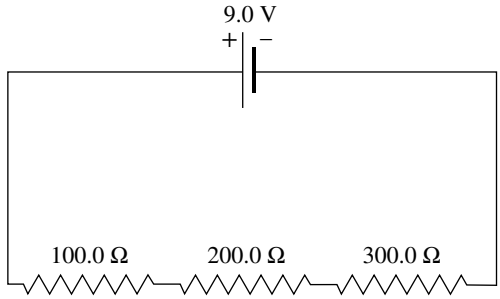
CALCULATING AN EQUIVALENT SERIES RESISTANCE

A string of Christmas lights consists of exactly 20 light bulbs connected in series. Each bulb has a resistance of 8.0 Ω. Calculate the equivalent series resistance of the Christmas lights.

Worked example 5.2.2

USING EQUIVALENT SERIES RESISTANCE FOR CIRCUIT ANALYSIS

Use an equivalent series resistance to calculate the current flowing in the series circuit below and the potential difference across each resistor. Comment on the sum of the potential differences.

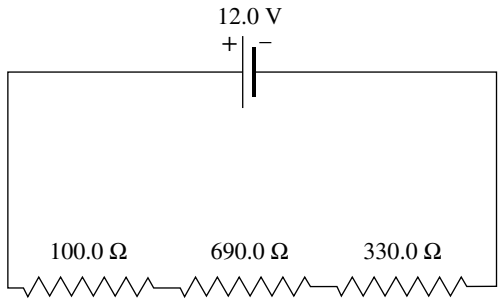


Thinking	Working
Recall the formula for equivalent series resistance.	$R_t = R_1 + R_2 + R_3 + \ldots + R_n$
Find the equivalent (total) resistance in the circuit.	$= 100.0 + 200.0 + 300.0$ $= 600.0\,\Omega$
Use Ohm's law to calculate the current in the circuit. Whenever calculating current in a series circuit, use R_t and the voltage of the power supply.	$I = \frac{V}{R}$ $= \frac{9.0}{600.0}$ $= 0.015\,A$
Use Ohm's law to calculate the potential difference across each separate resistor.	$V = IR$ $V_1 = 0.015\,A \times 100.0\,\Omega$ $= 1.5\,V$ $V_2 = 0.015\,A \times 200.0\,\Omega$ $= 3.0\,V$ $V_3 = 0.015\,A \times 300.0\,\Omega$ $= 4.5\,V$
Add up the individual potential differences.	$V_t = 1.5 + 3.0 + 4.5 = 9.0\,V$ This is the same as the supply voltage.

➤ Try yourself 5.2.2

USING EQUIVALENT SERIES RESISTANCE FOR CIRCUIT ANALYSIS

Calculate the current flowing in the series circuit below and the potential difference across each resistor, using an equivalent series resistance. Comment on the sum of the individual potential differences.



5.2 Review

SUMMARY

- When resistors are connected in series, the:
  - current through each resistor is the same
  - sum of the potential differences is equal to the potential difference provided to the circuit:

$$V_{supply} = V_1 + V_2 + \ldots + V_n$$

  - equivalent resistance R_t is equal to the sum of the individual resistances:

$$R_t = R_1 + R_2 + R_3 + \ldots + R_n$$

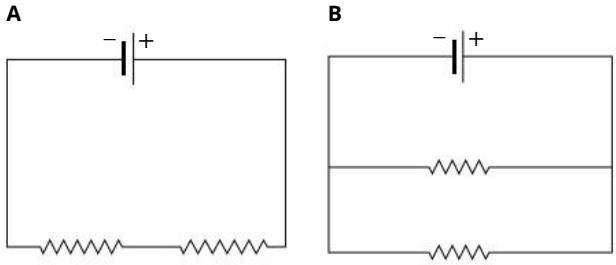
- Ohm's law can be applied to calculate the current drawn by a group of resistors connected in series:

$$I = \frac{V_{supply}}{R_t}$$

KEY QUESTIONS

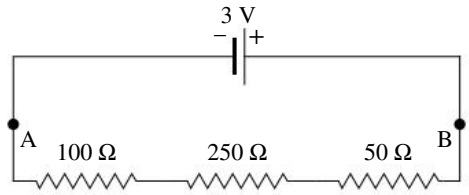
Retrieval

1 Identify which of the following diagrams shows a series circuit.



Comprehension

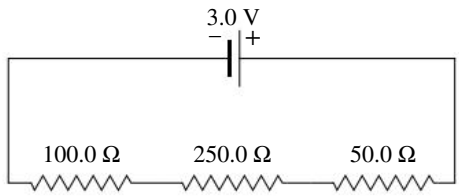
2 Consider the circuit shown. Explain whether the current at point A would be greater than, less than or the same as at point B.



3 Two 20.0 Ω resistors are connected in series with a 6.0 V battery. Determine the voltage drop across each resistor.

Analysis

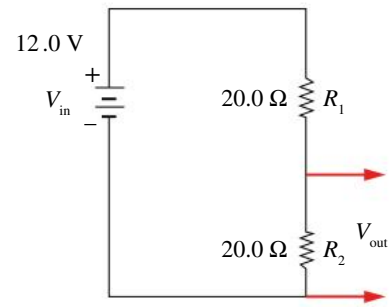
4 Consider the series circuit shown.



a Calculate the equivalent resistance of the group of three resistors.
b Calculate the current flowing in the circuit.
c Calculate the potential difference across the 100.0 Ω resistor in the circuit.

5 Two 100.0 Ω resistors and a 200.0 Ω resistor are connected in series with an 8.0 V battery.
a Calculate the current flowing in the circuit.
b Calculate the voltage drop across one of the 100.0 Ω resistors.

6 A voltage divider circuit, like the one shown in the diagram below, is simply a series circuit with two or more components. The circuit is called a voltage divider because the voltage supplied to the circuit is shared (or divided) between the components in the circuit. This voltage divider circuit has a 12.0 V battery and two 20.0 Ω resistors.



a Calculate the total resistance of the circuit.
b Calculate the current flowing through the circuit.
c Calculate V_{out}, the potential difference across R_2.

5.3 Parallel circuits

BY THE END OF THIS MODULE, YOU SHOULD BE ABLE TO:

- understand what a parallel circuit is
- calculate the equivalent parallel resistance for a number of resistors in parallel
- apply Ohm's law to the equivalent parallel resistance to calculate the current drawn by a group of resistors connected in parallel.

One of the disadvantages of series circuits is that if a switch is opened or a device is disconnected, then the circuit is broken and current stops flowing. In everyday life, you often want to switch devices on and off independently. **Parallel circuits** allow you to do this.

The circuit diagram in Figure 5.3.1 shows a simple parallel circuit. Even if switch A is open (as shown), lamp B will still light up as it is part of an unbroken complete circuit that includes the battery. Similarly, if switch A is closed and switch B is open, current will light up lamp A and not lamp B. Alternatively, both switches could be closed to light up both lamps or both switches could be opened to switch both lamps off.

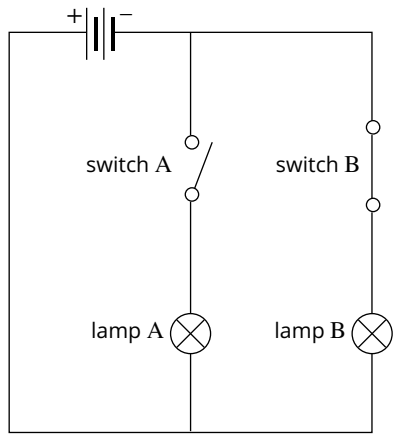


FIGURE 5.3.1 In this parallel circuit, lamp A will be off and lamp B will be on.

In a series circuit, all the components are in the same loop and therefore the same current flows through each component. In contrast, each loop of a parallel circuit acts like an independent circuit with its own current. Where the current divides, and also where it rejoins, is called a junction.

Consider again the water analogy used in Chapter 4. When water flows through pipes, it is not lost. If the pipe splits in two, some of the water flows in one pipe, and the remaining water will flow in the other pipe. If the two sections rejoin, the water comes back together again flowing at the same rate, just as it was before the pipe was split. The same occurs with charges flowing in a parallel circuit.

Figure 5.3.2 shows that each individual charge goes through one globe or the other. This means that although the current in the main part of the circuit remains constant, and the readings on ammeters A_1 and A_2 will be the same, the current through each bulb will be different, because in the parallel section the current is divided between the two branches.

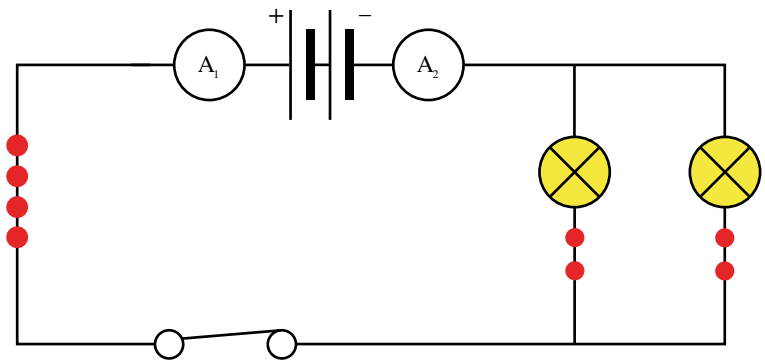


FIGURE 5.3.2 Unlike a series circuit, charges flowing in a parallel circuit have a choice of path. Here there are two paths for current to flow (indicated by two red dots) and two junctions where the circuit branches and then rejoins the main circuit (indicated by four red dots).

If the light bulbs are identical, as in the circuit in Figure 5.3.2, the current will be split evenly between the two bulbs:

$$I_1 = I_2 = \frac{I_t}{2}$$

The current in the main part of a parallel circuit is the sum of the currents in each branch of the circuit as the charges recombine to give the total current.

$$I_t = I_1 + I_2 + \ldots + I_n$$

In a parallel circuit the voltage is not shared between resistors, unlike a series circuit. The voltage is the same across each branch of a parallel circuit. This is because, although the charges take different pathways, they have the same amount of energy per charge no matter which path they take. In the water analogy, a pump (the battery) can be used to raise the water to a certain level above the ground. The water will have gravitational potential energy, which will cause it flow back down through the pipe to the ground, where it will flow back to the pump. If another pipe is added next to the original one, some water will flow down each pipe, but the potential energy due to gravity of the water at the top of each pipe will be the same, and the difference in potential energy of the water between the top of the pipe and the bottom of the pipe (where it is zero) will be the same for the two pipes.

An advantage of parallel circuits is that globes connected in this way are brighter than if they were connected in series, because the potential energy of the charges is not shared between the globes.

The voltage drop is the same over each branch of a parallel circuit.

EQUIVALENT PARALLEL RESISTANCE

When additional resistors are added in a series circuit, the total resistance of the circuit increases. Additional resistance means that less current flows through the circuit.

In contrast, adding an additional resistor in parallel means that more current flows through the circuit because another path for charges has been added. This means that the total resistance for the circuit decreases.

Parallel circuits are more complicated than series circuits, so the formula used to calculate the equivalent (total) resistance is more complicated. The total current in a parallel circuit is given by $I_t = I_1 + I_2$, where I_1 and I_2 are the individual currents that flow in two parallel branches of the circuit. Substituting this into Ohm's law gives you an equation for calculating the resistance in parallel circuits:

$$I = \frac{V}{R}$$
$$I_t = I_1 + I_2$$
$$\frac{V}{R_t} = \frac{V}{R_1} + \frac{V}{R_2}$$

The voltage drop across each branch of a parallel circuit is the same, so cancel V.

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

For a general parallel circuit with n resistors:

$$\frac{1}{R_t} = \frac{1}{R_1} + \frac{1}{R_2} + \ldots + \frac{1}{R_n}$$

where

R_t is the equivalent resistance

R_1, R_2, … R_n are the individual resistances.

Worked example 5.3.1

CALCULATING AN EQUIVALENT PARALLEL RESISTANCE

A 100.0 Ω resistor is connected in parallel with a 300.0 Ω resistor. Calculate the equivalent parallel resistance.

Thinking	Working
Recall the formula for equivalent resistance.	$\frac{1}{R_t} = \frac{1}{R_1} + \frac{1}{R_2} + \ldots + \frac{1}{R_n}$
Substitute in the given values for resistance. Solve for R_t.	$\frac{1}{R_t} = \frac{1}{100.0} + \frac{1}{300.0}$ $= \frac{3}{300.0} + \frac{1}{300.0}$ $= \frac{4}{300.0}$ $R_t = \frac{300.0}{4}$ $= 75.00\,\Omega$

➤ Try yourself 5.3.1

CALCULATING AN EQUIVALENT PARALLEL RESISTANCE

A 20.0 Ω resistor is connected in parallel with a 50.0 Ω resistor. Calculate the equivalent parallel resistance.

The equivalent resistance of a set of resistors connected in parallel will always be smaller than the smallest resistor in the set.

In a parallel circuit:

$$R_t < R_{\text{smallest resistor}}$$

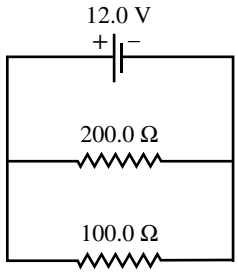
Notice that in the previous worked example, the equivalent resistance was smaller than the smallest individual resistance. This is because adding a resistor provides an additional pathway for current. More current flows, so the resistance of the circuit has been effectively reduced.

Consider the resistors in Try yourself 5.3.1. The smaller individual resistor is 20.0 Ω. The addition of the 50.0 Ω resistor in parallel allows the current an extra pathway and therefore it is easier for the current to flow through the combination. The equivalent resistance of the pair must be less than the 20.0 Ω alone.

Worked example 5.3.2

USING EQUIVALENT PARALLEL RESISTANCE FOR CIRCUIT ANALYSIS

A current flows out of the 12.0 V cell in the parallel circuit shown below.



a Determine the equivalent parallel resistance, R_t.

Thinking	Working
Recall the formula for equivalent parallel resistance.	$\frac{1}{R_t} = \frac{1}{R_1} + \frac{1}{R_2} + \ldots + \frac{1}{R_n}$
Substitute in the given values for resistance.	$\frac{1}{R_t} = \frac{1}{100.0} + \frac{1}{200.0}$
Solve for R_t.	$\frac{1}{R_t} = \frac{2}{200.0} + \frac{1}{200.0}$ $= \frac{3}{200.0}$ $R_t = \frac{200.0}{3}$ $= 66.7\,\Omega$

b Determine the current flowing through each resistor.

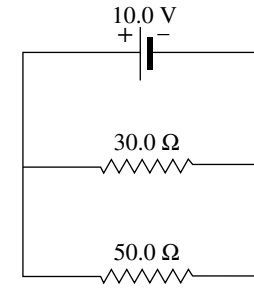
Thinking	Working
Use Ohm's law to calculate the current through each separate resistor. Remember that the voltage through each resistor is the same as the voltage of the power supply, which is 12.0 V.	100.0 Ω resistor: $I_{100} = \frac{V}{R} = \frac{12.0}{100.0} = 0.120\,\text{A}$ 200.0 Ω resistor: $I_{200} = \frac{V}{R} = \frac{12.0}{200.0} = 0.0600\,\text{A}$

c Determine the total current flowing through the circuit.	
Thinking	**Working**
The total current is the sum of the currents through each branch.	$I_t = I_{100} + I_{200}$ $= 0.120 + 0.060$ $= 0.180\,A$
d Compare the sum of the individual currents to the total current.	
Use Ohm's law to calculate the current in the circuit. To calculate I, use the voltage of the power supply and the total resistance.	$I_{circuit} = \frac{V}{R} = \frac{12.0}{66.67} = 0.180\,A$
Compare the sums of total current and individual currents.	$I_{circuit} = 0.180\,A$ $I_t = 0.180\,A$ The sum of the individual currents is equal to the total current.

➤ Try yourself 5.3.2

USING EQUIVALENT PARALLEL RESISTANCE FOR CIRCUIT ANALYSIS

A current flows through each resistor of the parallel circuit shown below.



a Determine the equivalent parallel resistance, R_t.

b Determine the current flowing through each resistor.

c Determine the total current flowing through the circuit.

Identical resistors in parallel

When identical resistors are placed in parallel, the equivalent resistance of the combination can be found by simply dividing the value of one of the resistors by the number of resistors.

For example, three 12 Ω resistors connected in parallel would have an equivalent resistance of 4 Ω.

$$R_t = 12 \div 3 = 4\,\Omega$$

The three 12 Ω resistors in parallel could be replaced with a single 4 Ω resistor.

Similarly, the equivalent resistance of two 10 Ω resistors placed in parallel would be 5 Ω.

RESISTORS AND POWER

A particular combination of resistors will draw different amounts of power depending on whether the resistors are wired in series or parallel. In general, resistors in parallel circuits will draw more current than resistors in series circuits, so parallel circuits use more power than series circuits containing the same resistors.

Recall from Chapter 4 that the power equation where P is the power (W), V is the voltage (V), I is the current (A):

$$P = V \times I$$

Worked example 5.3.3

COMPARING POWER IN SERIES AND PARALLEL CIRCUITS

Consider a 100.0 Ω and a 300.0 Ω resistor wired in a circuit with a 12.0 V cell.

a Calculate the power drawn by these resistors if they are wired in parallel.

Thinking	Working
Calculate the equivalent resistance for the parallel circuit.	$\frac{1}{R_t} = \frac{1}{R_1} + \frac{1}{R_2} + \ldots + \frac{1}{R_n}$ $= \frac{1}{100.0} + \frac{1}{300.0}$ $= \frac{3}{300.0} + \frac{1}{300.0}$ $= \frac{4}{300.0}$ $R_t = \frac{300.0}{4}$ $= 75.0\,\Omega$
Calculate the total current drawn by the parallel circuit. Rearrange $V = IR$.	$I = \frac{V}{R}$ $= \frac{12.0}{75.0}$ $= 0.160\,A$
Use the power equation to calculate the power drawn by the parallel circuit.	$P = VI$ $= 12.0 \times 0.160 = 1.92\,W$

b Calculate the power drawn by the same two resistors if they are wired in series.

Thinking	Working
Calculate the equivalent resistance for the series circuit.	$R_t = R_1 + R_2 + \ldots + R_n$ $= 100.0 + 300.0$ $= 400.0\,\Omega$
Calculate the total current drawn by the series circuit. Rearrange $V = IR$.	$I = \frac{V}{R}$ $= \frac{12.0}{400.0}$ $= 0.0300\,A$
Use the power equation to calculate the power drawn by the series circuit.	$P = VI$ $= 12.0 \times 0.030$ $= 0.360\,W$

c Compare the power drawn by the same two resistors when wired in parallel and in series.

Thinking	Working
Compare the power drawn by the two circuits.	$\frac{P_{parallel}}{P_{series}} = \frac{1.92}{0.36} = 5.33$ The parallel circuit draws more than 5 times as much power as the series circuit.

➤ Try yourself 5.3.3

COMPARING POWER IN SERIES AND PARALLEL CIRCUITS

Consider a 200.0 Ω and an 800.0 Ω resistor wired in parallel with a 12.0 V cell.

a Calculate the power drawn by these resistors if they are wired in parallel.

b Calculate the power drawn by the same two resistors if they are wired in series.

c Compare the power drawn by the two resistors when wired in parallel and in series.

Parallel circuits in the home

All household appliances and lights are connected in parallel. This is done for two reasons. Figure 5.3.3 shows a TV, an air-conditioner, a heater and a washing machine connected in series. Each device is designed to operate at 240V.

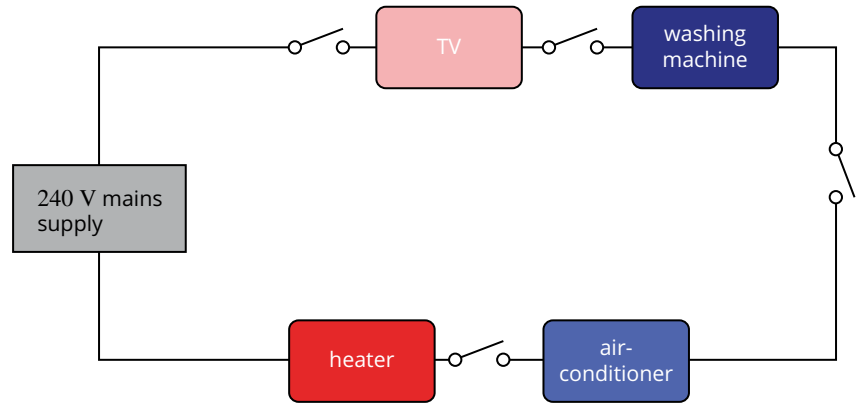


FIGURE 5.3.3 Household appliances connected in series

A circuit designed like the one in Figure 5.3.3 poses many problems. First, all of the devices need to be switched on for the circuit to operate. Second, the 240V supplied to the circuit needs to be shared among all the components. Each component in the circuit would receive far less than the 240V they require to operate. Also, as more and more devices are added to the circuit, the share of the 240V would become smaller. This system could never be practical.

The circuit diagram in Figure 5.3.4 shows the same devices connected in parallel.

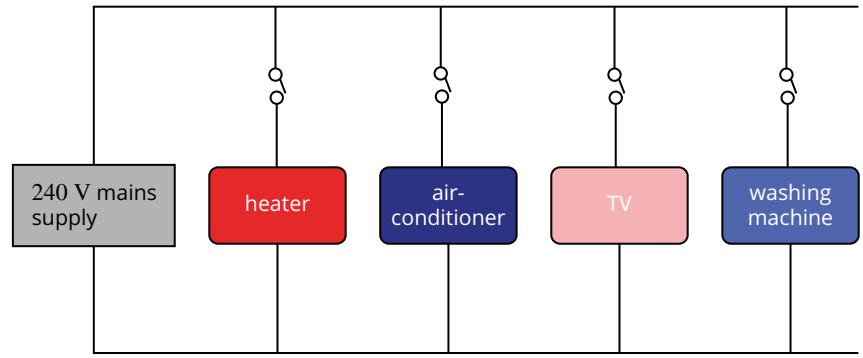


FIGURE 5.3.4 Household appliances connected in parallel

Each device in the parallel circuit receives the same voltage, 240V. Each device can be independently switched on or off without affecting the others, and more devices can be added to this system without affecting the operation of the devices already connected.

Sometimes the different features of series and parallel circuits can be used to control appliances used in the home. For example, simple heaters of various sorts often have a 'three heat' switch. An electric blanket will usually have 'low', 'medium' and 'high' settings (Figure 5.3.5). Rather than making three different heating elements, the manufacturer can use two elements in different series and parallel combinations to obtain the three heat settings. If the two elements are placed in series (the low setting), the total resistance will be relatively high and therefore the power will be a minimum, as $P = \frac{V^2}{R}$. For the medium setting, one of the elements will be used by itself. The high setting is then achieved by placing both elements in parallel.

It is a simple matter to work out the relative power being used for the three settings. If it is assumed that the resistance of both elements is the same (R) and does not change appreciably with temperature, the equivalent resistance in the three cases will be given by:

Low heat (two elements in series): $R_t = R + R = 2R$

Medium heat (one element only): $R_t = R$

High heat (both in parallel): $R_t = \frac{1}{2}R$

The power is inversely proportional to the resistance $P = \frac{V^2}{R}$, so if the high setting is 100%, then the medium setting is 50% and the low setting is 25%. For example, in the set-up shown in Figure 5.3.5, the following circuits are used to obtain the various settings:

OFF Not connected to power

• Resistors connected in series, $R = 960\,\Omega$, $I = 0.25\,\text{A}$, $P = 60\,\text{W}$

•• Only one element is connected, $R = 480\,\Omega$, $I = 0.5\,\text{A}$, $P = 120\,\text{W}$

••• Resistors connected in parallel, $R = 240\,\Omega$, $I = 1.0\,\text{A}$, $P = 240\,\text{W}$

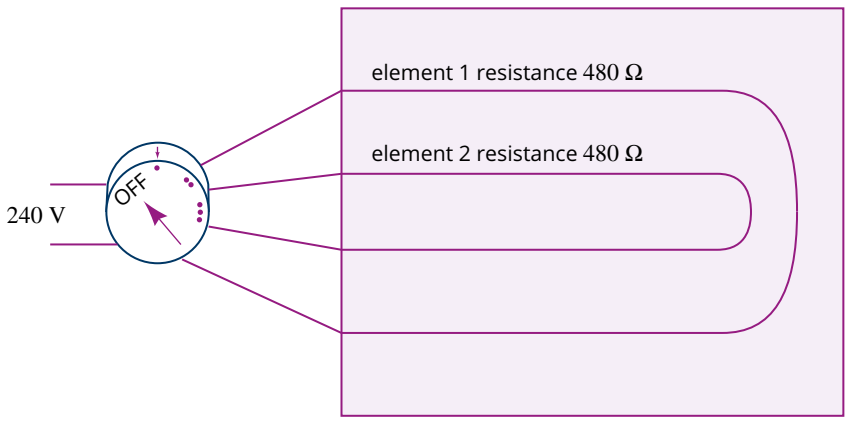


FIGURE 5.3.5 An example of the use of series and parallel combinations of resistors to achieve three heat settings for an electric blanket

5.3 Review

SUMMARY

- Parallel circuits allow individual components to be switched on and off independently.
- When resistors are connected in parallel, the:
  - voltage across each resistor is the same
  - current is shared between the resistors, where $I_t = I_1 + I_2 + I_3 + \ldots + I_n$
  - equivalent resistance is given by the equation:

$$\frac{1}{R_t} = \frac{1}{R_1} + \frac{1}{R_2} + \ldots + \frac{1}{R_n}$$

- Ohm's law can be applied to calculate the current drawn by a group of resistors connected in parallel:

$$I = \frac{V_{supply}}{R_t}$$

- A parallel circuit generally draws more power than a series circuit using the same resistors.

KEY QUESTIONS

Retrieval

1 State two reasons why household circuits are wired in parallel.

Comprehension

2 Max connects two identical resistors in parallel. Determine whether the equivalent resistance of this set of resistors is the same as, greater than or smaller than the individual resistance of a single resistor.

Analysis

3 Two identical resistors are connected in parallel and are found to have an equivalent resistance of 68.0Ω. Calculate the resistance of each resistor.

4 A 20.0Ω resistor and a 10.0Ω resistor are connected in parallel to a 5.0V battery.
- **a** Calculate the current drawn from the battery.
- **b** Calculate the current flowing through the 20.0Ω resistor.
- **c** Calculate the current flowing through the 10.0Ω resistor.

5 A 40.0Ω resistor and a 60.0Ω resistor are connected in parallel to a battery, with 300.0mA flowing through the 40.0Ω resistor.
- **a** Calculate the voltage of the battery.
- **b** Calculate the current flowing through the 60.0Ω resistor.

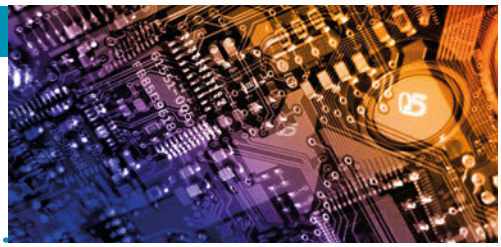
6 A circuit has a 20.0Ω, 30.0Ω and 60.0Ω resistor connected in parallel, with a 10.0V battery.
- **a** Calculate the equivalent parallel resistance of the resistors.
- **b** Calculate the current through each branch of the circuit.

7 A 10.0V battery is connected to four 20.0Ω light bulbs. Determine the total power output of the circuit if the light bulbs are connected in the following ways.
- **a** in series
- **b** in parallel

5.4 Kirchhoff's laws and complex circuit analysis

BY THE END OF THIS MODULE, YOU SHOULD BE ABLE TO:

- analyse complex circuits containing series and parallel components
- understand Kirchhoff's laws about potential difference and current in a circuit
- apply Kirchhoff's laws to check your calculations for complex circuits.



Complex circuit analysis

In Chapter 4, you learnt that Ohm's law, $V = IR$, can be used to relate the voltage and current in a simple circuit with a single resistor of resistance R. As you have already seen in this chapter, when a circuit contains more than one resistor, Ohm's law alone is not sufficient to predict the current flowing through, and the potential difference across, each resistor.

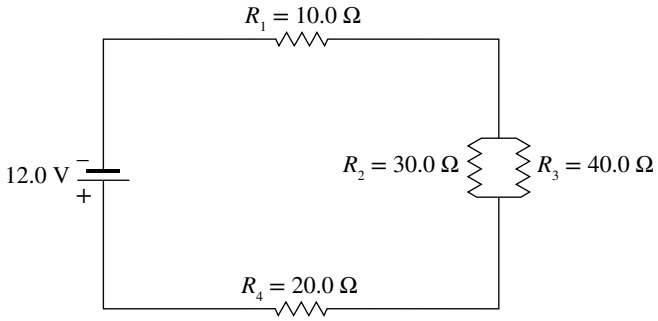
However, no matter how complex the circuit, it can always be divided up into sections of series and parallel circuits, which can be analysed using the equations from Modules 5.2 and 5.3.

Some circuits combine elements of both series wiring and parallel wiring. A general strategy for analysing these circuits is to reduce the complex circuit to a single equivalent resistance to determine the current drawn by the circuit. It is then possible to step back through the process of simplification to analyse each section of the circuit as needed.

Worked example 5.4.1

COMPLEX CIRCUIT ANALYSIS

Calculate the potential difference across and current through each resistor in the circuit below.



Thinking	Working
Find an equivalent resistance for the parallel resistors. The equivalent resistance of these should be less than the resistance of the smaller resistor, that is, smaller than 30.0 Ω.	$\frac{1}{R_{2-3}} = \frac{1}{R_2} + \frac{1}{R_3}$ $= \frac{1}{30.0} + \frac{1}{40.0}$ $= \frac{4}{120.0} + \frac{3}{120.0}$ $R_{2-3} = \frac{120.0}{7}$ $= 17.1\ \Omega$
Find an equivalent series resistance for the circuit, as the circuit can now be thought of as three resistors in series: 10.0 Ω, 17.1 Ω and 20.0 Ω.	$R_t = 10.0\ \Omega + 17.1\ \Omega + 20.0\ \Omega$ $= 47.1\ \Omega$

Use Ohm's law to calculate the current in the circuit. Use the supply voltage and total resistance to do this calculation. Rearrange $V = IR$.	$I = \frac{V}{R}$ $= \frac{12.0}{47.1}$ $= 0.255\,\text{A}$
Use Ohm's law to calculate the potential difference across each resistor (or parallel group of resistors) in series. (Note that the potential difference across R_2 is the same as that across R_3, as they are in parallel.)	$V = IR$ $V_1 = 0.255 \times 10.0 = 2.55\,\text{V}$ $V_{2\text{–}3} = 0.255 \times 17.1 = 4.36\,\text{V}$ $V_4 = 0.255 \times 20.0 = 5.10\,\text{V}$
Use Ohm's law where necessary to calculate the current through each resistor.	$I_1 = I_4 = 0.255\,\text{A}$ $I = \frac{V}{R}$ $I_2 = \frac{4.36}{30.0} = 0.145\,\text{A}$ $I_3 = \frac{4.36}{40.0} = 0.109\,\text{A}$

➤ Try yourself 5.4.1

COMPLEX CIRCUIT ANALYSIS

Calculate the potential difference across, and current through, each resistor in the circuit below.

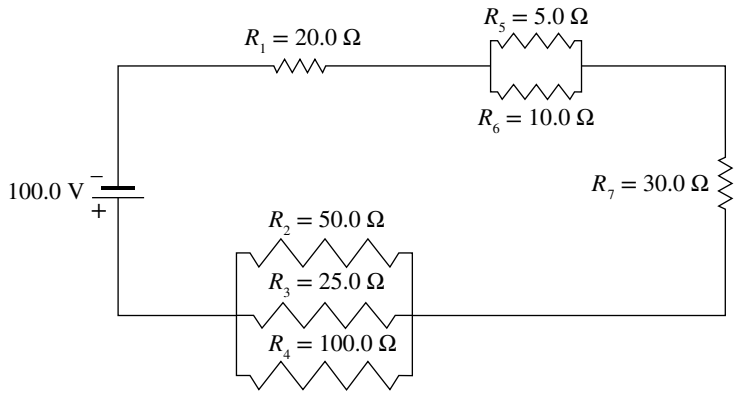


FIGURE 5.4.1 Gustav Kirchhoff discovered the rules that underpin our understanding of how electrical circuits work.

KIRCHHOFF'S LAWS

German physicist Gustav Kirchhoff (1824–87), shown in Figure 5.4.1, formulated two laws to describe the behaviour of current and potential difference in a circuit. These are useful for analysing current and potential difference in complex circuits.

Kirchhoff also made important contributions in the fields of spectroscopy, thermochemistry and the study of black-body radiation. He worked with Robert Bunsen, the German chemist who developed the Bunsen burner.

Kirchhoff's voltage law

Kirchhoff's voltage law (sometimes called Kirchhoff's loop rule) tells you that the sum of the potential differences across all the elements around any closed circuit loop must be zero. This means that the total potential drop around a closed circuit must be equal to the total potential gain in the circuit. For example, if a battery provides 9 V to a circuit, then the sum of all of the potential drops across the components must add to 9 V.

This rule is essentially another version of the law of conservation of energy.

The potential gain (e.g. the voltage supplied by the battery) is equal to the potential drop across the circuit. So for n components in a circuit:

$$V_{supply} = V_t = V_1 + V_2 + \ldots + V_n$$

If you apply a sign convention to the change in potential so that a potential gain is positive and a potential drop is negative, then the positive and negative values will cancel. You can write Kirchhoff's voltage law using the 'sum of' symbol (Σ). This means that the sum of the changes in potential will be zero.

$$\Sigma \Delta V = 0$$

Figure 5.4.2 shows how the voltage provided by the battery is shared across a resistor and a lamp connected in series.

The energy changes in this circuit can be visualised in a number of ways. In Chapter 4 and Module 5.3, the analogy was used of the charges as water being pumped around an elevated watercourse. The water gains potential energy as it is pumped higher, and as it flows back down the potential energy is converted into other forms. The diagram in Figure 5.4.3 shows how the analogy works with the energy changes that occur in a circuit. The battery acts as a 'pump' that pushes electrons up to a higher energy level and the electrons gain potential energy. As the electrons pass down through components in the circuit, their energy is transformed into other forms.

The energy given to each charge (potential gain) must be equal to the energy lost by each charge (potential drop).

In a series circuit, the energy loss will be spread across a number of different components.

In a parallel circuit, the energy loss (potential drop) will be the same across each of the parallel components.

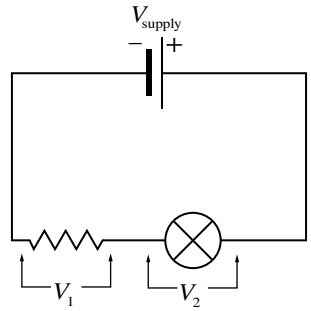


FIGURE 5.4.2 Kirchhoff's voltage law. In this series circuit, the sum of the potential drops across the resistor and the lamp ($V_1 + V_2$) will be equal to the potential difference provided by the battery.

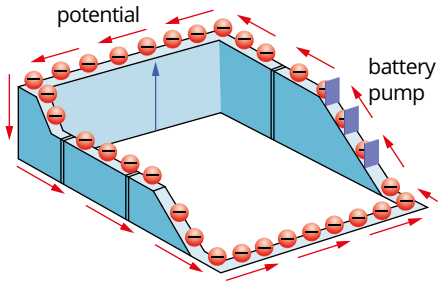


FIGURE 5.4.3 An analogy for analysing a circuit: the battery acts as a 'pump' that transfers potential energy to electrons. The electrons lose potential energy as they flow 'down' through components in the circuit.

The change in electrical energy available to electrons can also be represented graphically, as shown in Figure 5.4.4. The potential energy provided by the cell, V_{supply}, is the same as the sum of the potential drop across the resistor, V_1, and the potential drop across the light bulb, V_2.

Recall from Module 5.3 that in a parallel circuit the voltage (potential drop) across the parallel components is the same: the voltage across resistor R_1 is the same as the voltage (potential drop) across resistor R_2. Figure 5.4.5 shows that electrons at points B and D will have the same energy as they have when they leave the negative battery terminal; i.e. the potential at points B and D is the same as it is as the battery terminal. The potential at points A and C is also the same as the potential at the positive battery terminal. Therefore, the potential drop across each resistor is the same.

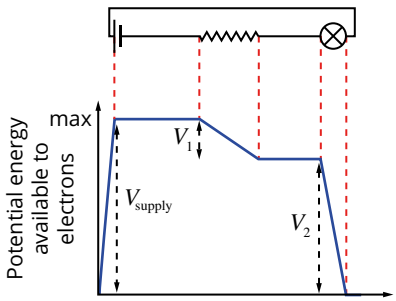


FIGURE 5.4.4 The electrical potential energy of an electron changes as it moves around the circuit. Some of this energy is lost as the electrons pass through the resistor. The remaining energy is lost as the electrons pass through the bulb. In this circuit, the bulb has more resistance than the resistor.

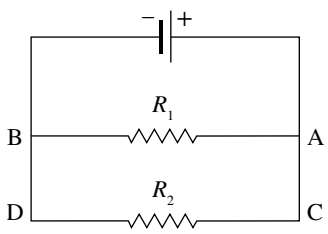


FIGURE 5.4.5 In a parallel circuit, the potential at points B and D is the same as the potential at the negative battery terminal. The potential at points A and C is the same as the potential at the positive battery terminal.

If $R_1 \neq R_2$, then a different current will flow along each branch of the parallel part of the circuit, but the potential across each resistor will be the same. Using the water analogy from Figure 5.4.3, the water reaches the same height and falls the same distance, but the amount of water flowing in each path will vary depending on the size of the course it flows along.

You might assume that wires ideally have zero resistance so that the potential at B and D will be the same, but in fact the wires will have a very small resistance so that the potential at B and D will be slightly different. However, this is such a small difference that you do not need to take it into account in your calculations. It only becomes significant when long lengths of wire are used, such as in power lines.

Worked example 5.4.2

APPLYING KIRCHHOFF'S VOLTAGE LAW

A 12.0 V battery is connected in series to a 100.0 Ω resistor and a 300.0 Ω resistor.

a Determine the equivalent resistance of the two resistors.

Thinking	Working
The equivalent resistance of two resistors in series: $R_t = R_1 + R_2$	$R_t = 100.0 + 300.0$ $= 400\,\Omega$

b Calculate the potential difference across each resistor, using Ohm's law.

Thinking	Working
Use Ohm's law to find the current in the circuit. Rearrange $V = IR$.	$I = \frac{V}{R}$ $= \frac{12.0}{400.0}$ $= 0.030\,\text{A}$
Calculate the potential difference across the 100.0 Ω resistor.	$V = IR$ $= 0.03 \times 100.0$ $= 3.00\,\text{V}$
Calculate the potential difference across the 300.0 Ω resistor.	$V = IR$ $= 0.03 \times 300.0$ $= 9.00\,\text{V}$

c Apply Kirchhoff's voltage law to verify your answers.

Thinking	Working
Use Kirchhoff's voltage law: $V_{supply} = V_t = V_1 + V_2 + \ldots + V_n$	In a series circuit: $V_{supply} = V_{100} + V_{300}$ $12.0 = 3.0 + 9.0$ Kirchhoff's law holds, so the answers for the potential difference across each resistor are correct.

➤ Try yourself 5.4.2

APPLYING KIRCHHOFF'S VOLTAGE LAW

A 10.0 V battery is connected in series with two 50.0 Ω resistors.

a Determine the equivalent resistance of the two resistors.

b Calculate the potential difference across each resistor, using Ohm's law.

c Apply Kirchhoff's voltage law to verify your answers.

Kirchhoff's current law

Parallel circuits involve **junctions** at which current can flow in a variety of directions. **Kirchhoff's current law** (sometimes called Kirchhoff's junction rule) predicts the behaviour of current at these points. Kirchhoff's current law tells you that the total amount of current flowing into a junction must be the same as the total current flowing out of the junction.

Kirchhoff's current law is just an extension of the idea of conservation of charge; that charges cannot be created or destroyed. Although the number of electrons flowing into a junction might be very large, electrons are not created or destroyed in the junction, so the same number of electrons must flow out again. This is illustrated in Figure 5.4.6. Kirchhoff's junction rule explains how current splits in a parallel circuit. It explains why the current in the main part of the circuit is the sum of the currents in each parallel branch.

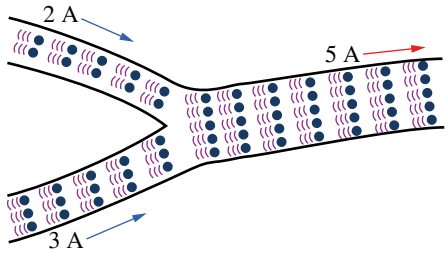


FIGURE 5.4.6 The current flowing into any junction must be equal to the current flowing out of it.

This is shown in the circuit diagram in Figure 5.4.7, where $I_t = I_1 + I_2 + I_3$.

If you apply a sign convention such that the current into a junction is positive and the current flowing out of a junction is negative, then the positive and negative values will cancel. You can write this using the 'sum of' symbol Σ. This means that the sum of the current into a junction will be zero.

$$\Sigma I = 0$$

> **The total amount of current flowing into a junction must be the same as the total current flowing out of the junction.**

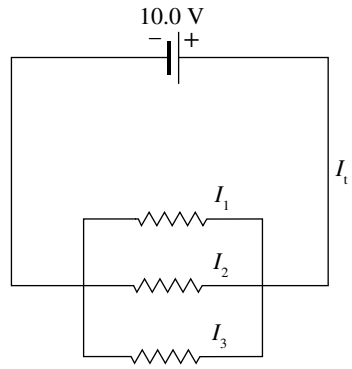


FIGURE 5.4.7 The current flowing into any junction must be equal to the current flowing out of it.

Worked example 5.4.3

APPLYING KIRCHHOFF'S CURRENT LAW

In the circuit shown in Figure 5.4.7, a 10.0 V battery is connected to three resistors in parallel. The equivalent parallel resistance of the three resistors is 20.0 Ω. The branch currents are $I_1 = 0.1$ A and $I_2 = 0.2$ A. Calculate the branch current I_3, using Kirchhoff's current law.

Thinking	Working
First find I_t, the current in the main part of the circuit.	$I_t = \frac{V}{R} = \frac{10.0}{20.0} = 0.5\,\text{A}$
Use Kirchhoff's current law to find the branch current I_3.	$I_t = I_1 + I_2 + I_3$ $I_3 = I_t - I_1 - I_2$ $= 0.5 - 0.1 - 0.2$ $= 0.2\,\text{A}$

➤ Try yourself 5.4.3

APPLYING KIRCHHOFF'S CURRENT LAW

In the circuit shown in Figure 5.4.7, a 9.0 V battery is connected to three resistors in parallel. The equivalent parallel resistance of the three resistors is 30.0 Ω. The branch currents are $I_1 = 0.1$ A and $I_2 = 0.1$ A. Calculate the branch current I_3, using Kirchhoff's current law. Explain what you can deduce about the three resistors from this.

PA 1.3.3 WS 1.3.4

Powering the digital age

Computers, smartphones and the internet have changed the world, but none would be possible without a reliable supply of electricity.

Look around an unrenovated home from the 1960s and you'll find few electrical sockets; perhaps one or two single outlets in each room. Planning electricity supplies in the 1960 and 1970s was much simpler than today. Electricity needs would peak during the ad breaks for popular TV programmes as everyone switched on the kettle, and air conditioning at home was unusual. Home computers were unthought of.

Today our need for power in the home is much higher, and is increasing as technology becomes more affordable and more essential to everyday life. Changing climate means increased need for power-hungry heating and cooling.

However, planning Australia's power distribution has always been complex. Outside the major cities, the population density is low and distances between communities are large. Power transmission over long distances leads to energy losses, problems managing and maintaining the infrastructure, and the risk of bushfire.

Australia also faces the challenge of changing energy production from centralised coal- and gas-fired power stations to a model that includes large-scale renewables together with energy generated in the home by solar panels, to reduce carbon emissions and cut energy costs. Queensland has signed up to the Renewable Energy Target Scheme, which aims to produce 20% of Australia's energy from renewables by 2020. In a 2-year roadmap into future energy provision, the CSIRO has drawn up a plan to make the electricity sector achieve zero net emissions by 2050.

In the past 20 years, rooftop solar panels (Figure 5.4.8) have moved from new technology to a common sight on Australian homes. Rooftop solar is now on 27% of detached homes in south-east Queensland, generating a total of more than 937 MW. However, the large-scale adoption of solar panels is hampered by problems connecting to the electricity grid, which was designed to deliver power to homes, and not the other way around.

FIGURE 5.4.8 Rooftop solar panels on an Australian home

One way around this is to use batteries to store extra power for later use, particularly in the evenings when electricity use is at its highest and when solar panels don't generate electricity. As battery technology improves, these will become available and affordable to have at home. The CSIRO estimates that 'By 2050, over 10 million customers will own distributed resources like solar, storage, home energy management systems and electric vehicles, which they can use to sell grid support services worth $2.5 billion per year'.

Large-scale renewable-energy projects are also being developed. But what happens when the sun doesn't shine or the wind doesn't blow, and energy is still needed? The large-scale adoption of renewable energy has been held back by these concerns and by limitations in battery technology. But battery storage has improved dramatically. The Queensland company Solar Q is planning to build a solar farm and battery storage facility near Gympie, with a proposed eventual power output 800 MW, enough electricity to power about 315 000 homes. Tesla has already built a 100 MW battery, the largest lithium ion battery in the world, to store energy from a new wind farm in South Australia (Figure 5.4.9). This will stabilise the network by providing energy if there is a shortfall. Power plants in the US and Spain use molten salt to store heat from the Sun and then use this heat to generate steam to drive turbines at night.

Review

1. Describe three difficulties that Australia faces with energy provision.
2. Outline the main problems with the adoption of renewable energy in Australia.
3. Explain how technology helps solve these problems.

FIGURE 5.4.9 South Australia's gigantic Tesla lithium ion battery is the world's largest and most powerful. It can dispatch power to 30 000 homes for just over an hour. The battery began dispatching stored wind power to the electricity grid in November 2017.

5.4 Review

SUMMARY

- Kirchhoff's current law states that the total amount of current flowing into a junction must be the same as the total current flowing out of the junction. At each junction, $\Sigma I = 0$.
- Kirchhoff's voltage law states that the energy given to the charges (potential gain) must be equal to the energy lost by the charges (potential drop). At each junction, $\Sigma \Delta V = 0$.
- In a series circuit, the energy loss (potential difference) will be spread across a number of different components.
- In a parallel circuit, the energy loss (potential difference) will be the same across each of the parallel components.

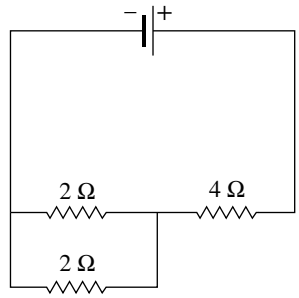
KEY QUESTIONS

Retrieval

1 Complete the following sentence by selecting the correct term from the terms in brackets.
Kirchhoff's voltage law states that the sum of the potential drops **[at a junction/across a circuit]** must equal the total potential gain in the circuit.

Comprehension

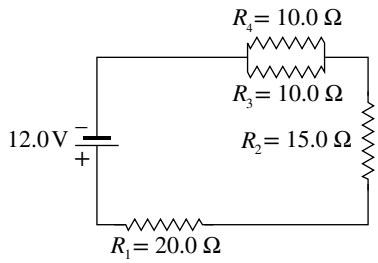
2 Gary connects two 2Ω resistors in parallel, and then connects another 4Ω resistor in series, as shown. To work out the equivalent resistance of the circuit, he adds up the resistance of each resistor to make an equivalent resistance of 8Ω. Determine if he is correct. If he is not correct, describe how he should calculate the equivalent resistance of the circuit.



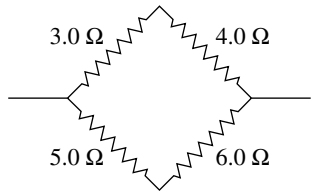
3 Susan says that Kirchhoff's current law states that the current flowing in Gary's circuit is the same at every point. Determine if she is correct. If not, explain how she is incorrect.

Analysis

4 Calculate the potential difference across, and the current through, each resistor in the circuit.



5 A circuit contains four resistors as shown in the diagram.



a Calculate the equivalent resistance of this combination of resistors.

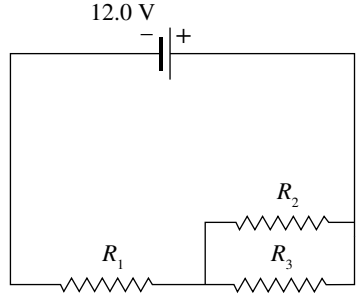
b If a 10.0V battery is connected to this set of resistors, calculate the total current flowing through the circuit, and the current flowing through each branch of resistors.

c Use Kirchhoff's current law to verify your answer to part **b**.

6 For the circuit shown in the diagram, $R_1 = 10.0\Omega$, $R_2 = 10.0\Omega$ and $R_3 = 15.0\Omega$.

a Calculate the potential difference across resistor R_2.

b Calculate the current through resistor R_3.



7 The resistors R_1 and R_2 in the circuit in Question 4 are replaced with 10.0Ω resistors. Calculate the potential difference across, and the current through, each resistor in the circuit.

Chapter review

WS 1.3.6 | WS 1.3.7 | TR 1.3 | S.A.T. IA1 Data Test | S.A.T. IA3 Research Investigation

05

KEY TERMS

equivalent resistance
electrical circuit
internal resistance
junction
Kirchhoff's current law
Kirchhoff's voltage law
law of conservation of electric charge
multimeter
parallel circuit
series circuit

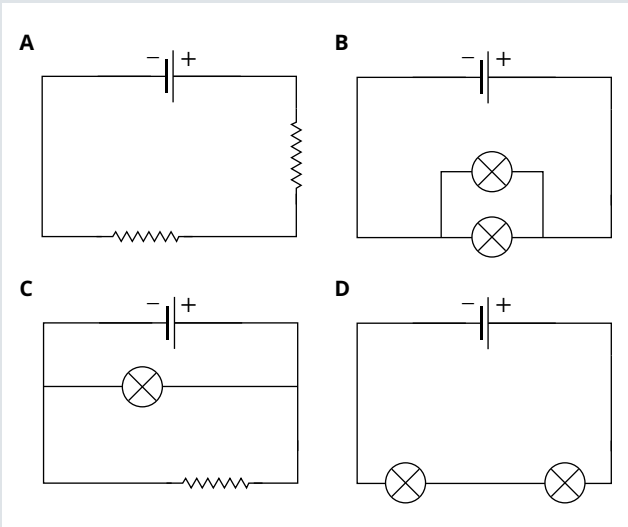
KEY QUESTIONS

Retrieval

1 Identify which of the following conditions is necessary for current to flow in a circuit. More than one correct answer is possible.

A There must be a voltage applied across the circuit.
B The circuit must contain a resistor.
C The circuit must be a closed loop.
D The circuit must be an open loop.

2 Identify which of these circuits are wired in series, and which are wired in parallel.



3 Two resistors, R_1 and R_2, are wired in series. Identify which of the following gives the equivalent series resistance for these two resistors.

A $R_t = R_1 + R_2$
B $\frac{1}{R_t} = \frac{1}{R_1} + \frac{1}{R_2}$
C $R_t = R_1 - R_2$
D $R_t = R_1 \times R_2$

4 Two resistors, R_1 and R_2, are wired in parallel. Identify which of the following gives the equivalent parallel resistance for these two resistors.

A $R_t = R_1 + R_2$
B $\frac{1}{R_t} = \frac{1}{R_1} + \frac{1}{R_2}$
C $R_t = R_1 - R_2$
D $R_t = R_1 \times R_2$

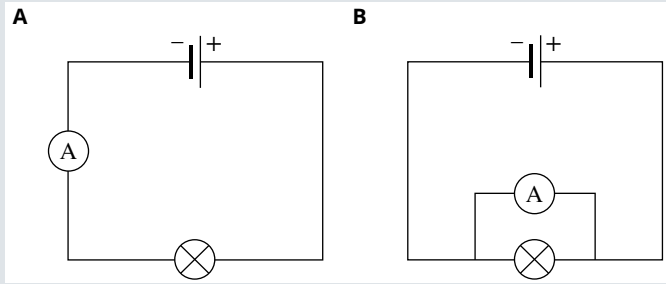
5 **a** State Kirchhoff's voltage law.
b State Kirchhoff's current law.

Comprehension

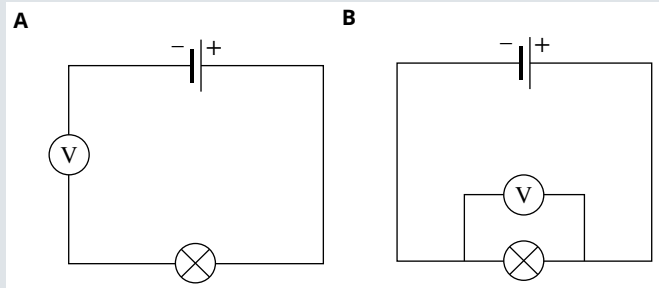
6 Draw a circuit containing a battery, a light globe, a resistor and a switch in series. Indicate the direction of conventional current and electron flow.

7 Finn wants to measure the total current flowing to and from a battery in a circuit.

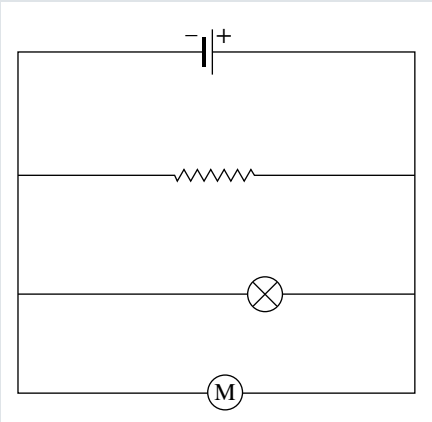
a Identify which of the circuits in the figure has the ammeter connected correctly.



b Finn now wants to measure the potential difference over the light globe in the circuit. Which of the diagrams has the voltmeter connected correctly?



c When Finn gets to class, a circuit is already set up as shown in the diagram. A multimeter, marked M, is included. Identify whether he should set this to measure current or potential difference, and determine what would happen if he chose the other option.



8 Two identical resistors are wired in series. Determine whether you would expect their equivalent series resistance to be the same as, greater than or less than the individual resistance of each of the resistors. Explain your answer.

9 Two identical resistors are wired in parallel. Determine whether you would expect their equivalent parallel resistance to be the same as, greater than or less than the individual resistance of each of the resistors. Explain your answer.

10 Kim and Taylor are shopping for a string of exactly 100 light globes for a party. There are two types on offer: Kim wants to buy the set of lights connected in parallel, and Taylor wants to buy the lights connected in series. Identify which is the better choice, and explain why.

11 Identify the best definition of power from the following choices.

A the total amount of energy consumed by a circuit component

B the current drawn by a circuit component each second

C the rate at which voltage is supplied to a circuit component

D the rate at which energy is transformed by a circuit component

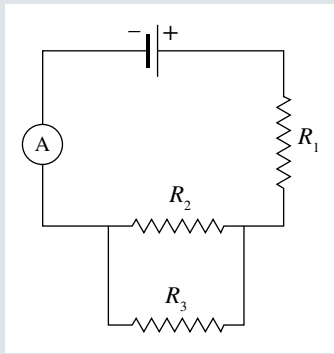
Analysis

12 a A student accidentally sets up an ammeter in parallel to a light bulb instead of in series. When the power supply is switched on, the ammeter draws a large current and is damaged. Determine the effect on the internal resistance of the ammeter from this information.

b The student, who is not having a very good day, removes the ammeter and sets up a voltmeter in series with the light bulb. When the power supply is switched on, the light globe does not light. Explain why.

13 Three resistors of 2.0Ω, 3.0Ω and 5.0Ω are wired in series. Calculate their equivalent series resistance.

14 In the circuit shown, a student connects a 10.0V battery and measures the reading on the ammeter as 500.0mA.

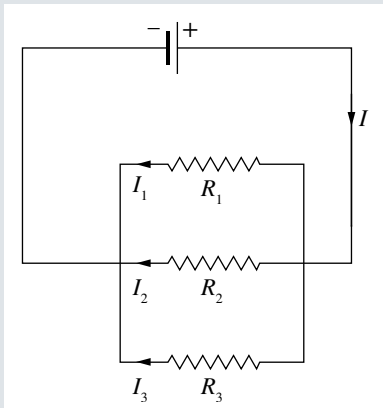


a Calculate the equivalent resistance of resistors R_1, R_2 and R_3.

b Calculate the individual resistances of R_1, R_2 and R_3 if R_2 and R_3 are identical and if the potential difference across R_1 is 5.0V.

c Determine the current, in milliamps, flowing through R_3.

15 In the circuit shown, a 10.0V battery is connected to three resistors in parallel: $R_1 = 3.0\Omega$, $R_2 = 4.0\Omega$ and $R_3 = 5.0\Omega$.

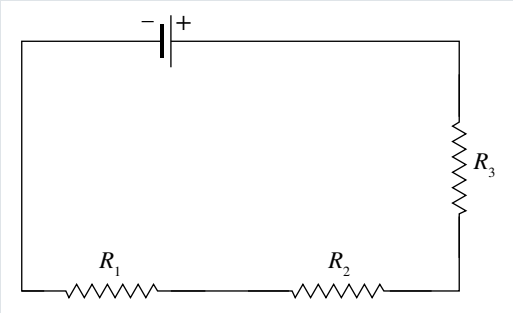


a Calculate the equivalent parallel resistance of R_1, R_2 and R_3.

b Calculate the current flowing in each branch of the circuit, I_1, I_2 and I_3.

c Calculate the current flowing in the main part of the circuit, I, and use Kirchhoff's current law to check your answer to part **b**.

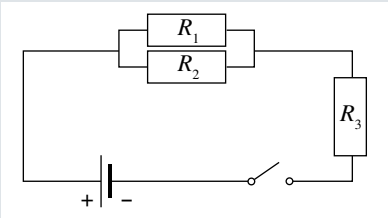
16 In the circuit shown, a 10.0V battery is connected to three resistors in series: $R_1 = 4.0\,\Omega$, $R_2 = 8.0\,\Omega$ and $R_3 = 12.0\,\Omega$.



a Calculate the equivalent series resistance of the three resistors.
b Calculate the current flowing in the circuit.
c Calculate the potential difference across each resistor. Use Kirchoff's voltage law to check your answer.

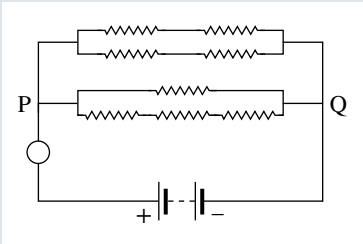
17 An electrical circuit is constructed as shown. Use the information given about the circuit diagram to answer parts **a**–**f**.

- The electric cell provides 3.0V.
- The total resistance, R_t, of the circuit is $8.5\,\Omega$.
- R_2 has a resistance of $15.0\,\Omega$.
- The total resistance of resistors R_1 and R_2 is $5.0\,\Omega$.



a Find the value of R_3.
b Find the current through R_3.
c Find the potential difference across the parallel pair R_1 and R_2.
d Find the current through R_2.
e Find the current through R_1.
f Find the value of R_1.

18 In the circuit shown, eight $20.0\,\Omega$ resistors are connected between points P and Q.

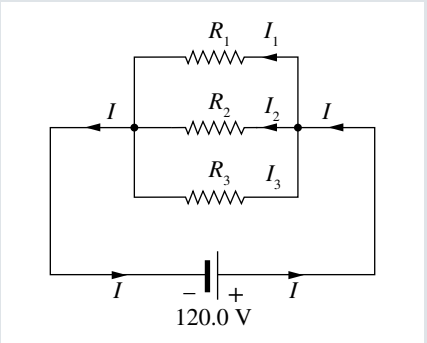


a The circle in the circuit diagram represents either an ammeter or a voltmeter. Identify which type of meter this should be.
b Calculate the total equivalent resistance of the circuit. Assume that the resistance of the meter and power source can be ignored.

19 Sketch a circuit diagram showing how four $10\,\Omega$ resistors can be connected using a combination of series and parallel wiring to have a total equivalent resistance of $10\,\Omega$.

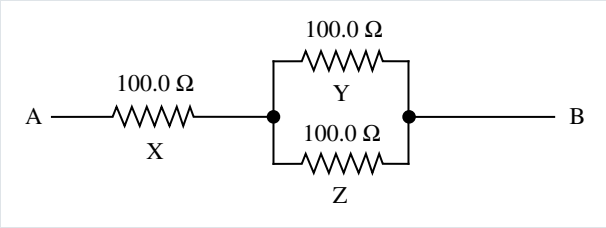
20 A circuit consists of a 12.0V battery and three $20.0\,\Omega$ light bulbs. The bulbs are initially connected in series.
a Calculate the power output of the circuit.
b The circuit is changed so that the bulbs are connected in parallel. Calculate the power output of the circuit.
c Compare the power drawn in the parallel circuit with that of the series circuit.

21 Consider the following circuit in which three resistors R_1, R_2 and R_3 are connected in parallel. Assume that $R_1 = 100.0\,\Omega$, $R_2 = 200.0\,\Omega$ and $R_3 = 600.0\,\Omega$. The battery provides a potential difference of 120.0V.



a Calculate the total resistance, R_t, in the circuit.
b Calculate the total current, I, in the circuit.
c Determine the branch currents I_1, I_2 and I_3.
d Use Kirchhoff's current law to verify your answer to parts **b** and **c**.
e Determine the power output, P, of the battery.
f Calculate the total power consumed by each of the resistors in the circuit.

22 Three 100.0 Ω resistors are connected as shown. The maximum power that can safely be dissipated in any one resistor is 25.0 W.



a Determine the maximum potential difference that can be applied between points A and B.

b Determine the maximum power that can be dissipated in this circuit.

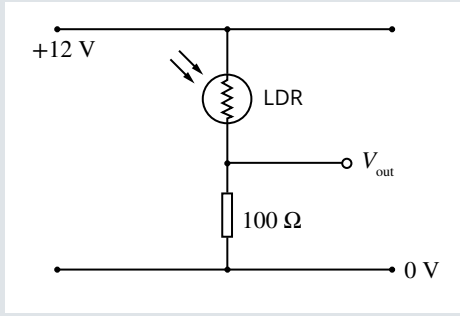
23 Four 20.0 Ω light bulbs are connected to a 10.0 V battery. Determine the total power output of the circuit if the light bulbs are connected in the following ways.

a in series

b in parallel

Knowledge utilisation

24 A light-dependent resistor, or LDR, is a device whose resistance varies according to the amount of light that hits it. Usually its resistance is very high in the dark, and decreases as more light hits it. A simple light-detector circuit using an LDR is shown. V_{out} is to be used to activate an alarm when the ambient light rises above a certain level. At this particular light level, the resistance of the LDR is 200.0 Ω. The alarm activates whenever V_{out} is above the trigger level.



a Calculate the value of V_{out} at which the alarm should activate.

b Determine what would you expect V_{out} to become when it is very dark.

REVIEW QUESTIONS

Topic 1: Heating processes

Multiple choice

1 Select which of the following is the best example of heat transfer by conduction.

A heat transfer from the bottom of the ocean to the top
B heat transfer from the Sun to Earth
C heat transfer from Earth's mantle through Earth's crust
D heat transfer from Earth's surface to the upper atmosphere

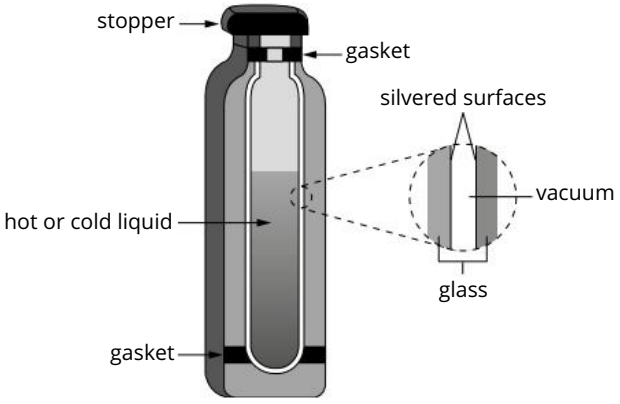
2 4000 joules of energy is required to raise the temperature of 1 kg of paraffin by 2°C. Calculate how much energy is required to raise the temperature of 5 kg of paraffin by 1°C.

A 20 kJ
B 2 kJ
C 1 kJ
D 10 kJ
E 10 MJ

3 A bucket is filled with equal amounts of hot and cold water. The hot water was originally at 80°C and the cold water at 10°C. The temperature of the final mixture will be approximately:

A 10°C
B 25°C
C 45°C
D 70°C
E 90°C

4 A vacuum flask, or 'thermos', has a reflective coating of aluminium on the internal surface. This 'silvered' surface reduces heat transfer by:



A conduction
B convection
C radiation
D all of the above

5 The name for the property of a substance that determines how much energy it takes to change the temperature of a unit mass of the substance by 1 degree Celsius is:

A refractive index
B emissivity
C albedo
D specific heat capacity

6 Two students were comparing the temperature and internal energy of two beakers of water. The temperature of beaker A was measured at 25°C, and beaker B was 290 K. Select the statement that best describes the two beakers.

A Beaker B has a higher temperature than beaker A but there is not enough information to compare internal energies.
B Beaker B has a higher temperature and internal energy than beaker A.
C Beaker A has a higher temperature and internal energy than beaker B.
D Beaker A has a higher temperature than beaker B but there is not enough information to compare internal energy.

7 The amount of energy required to melt 3 kg of ice at 0°C to water at 0°C is:

A 1.00×10^6 J
B 3.34×10^5 J
C 1.00×10^5 J
D 3.34×10^6 J

8 A kettle uses 500 kJ of energy when heating the 1.25 L of water inside from 25°C to 90°C. The efficiency of the kettle is:

A 147%
B 53%
C 78%
D 68%

9 Select the statement that best describes the difference between specific heat capacity and specific latent heat.

A Specific heat capacity is the amount of energy it takes to raise one unit of mass 1°C, whereas latent heat is the amount of energy it takes to change the state of one unit of mass.
B Specific heat capacity is the amount of energy it takes to raise one unit of mass 1°C, whereas latent heat is the amount of energy it takes to change the state of one unit of mass while raising it 1°C.
C Specific heat capacity is the same as latent heat capacity.
D Specific heat capacity is the amount of energy it takes to change the state of one unit of mass, and latent heat is the amount of energy it takes to increase the temperature of one unit of mass 1°C.

10 A pot of soup is taken off the stove to cool down. It is placed on a cold bench that removes 300 J s^{-1} of heat energy. The soup is stirred, providing 10 J s^{-1} of work to the soup. Assuming there is no heat transfer from the top of the soup, calculate the change in internal energy.

A 310 J s^{-1}
B –290 J s^{-1}
C –310 J s^{-1}
D 290 J s^{-1}

Short answer

1 Determine whether two objects have the same temperature when the average kinetic energy of the particles in the two objects is identical. Give reasons for you answer.

2 A student attempts to identify a metal by measuring its specific heat capacity. A 90.0 g sample of the metal is heated to 70°C and then transferred to a foam cup containing 200 g of water at 20°C. The temperature of the final mixture is 25°C. Using Table 1 below, determine the metal the student is probably testing.

Table 1 Approximate specific heat capacities of some common materials

Material	Specific heat capacity (J kg^{-1} K^{-1})
lead	130
mercury	140
methylated spirits	250
brass	370
copper	390
iron	440
glass	840
aluminium	900
air	1000
human body	3500
water ice liquid steam	 2100 4200 2000

3 Energy must be supplied to ice to melt it. However, the temperature of the resulting water is no higher than that of the original ice. Explain.

4 Burns caused by steam are much worse than those caused by boiling water. Compare the amount of energy the body, at a temperature of 37°C, receives from the cooling of 0.10 kg of water from 100°C, with that received from the cooling of 0.10 kg of steam originally at 100°C.

5 A 0.50 kg piece of ice at 0°C is mixed with 0.10 kg of steam at 100°C. Determine the final temperature of the mixture.

6 Explain why closing the curtains in the evening helps to keep the inside of a house warm.

7 A 300 g block of copper at a temperature of 120°C is dropped into an insulated thermos filled with 1 L of water at 10°C. Describe the initial energy of the particles in the copper block, compared with those in the water, and how the internal energy changes until thermal equilibrium is reached.

8 A tennis player is practising her serve and notices that balls that have been served multiple times are warmer than balls that have been sitting on the court without being hit. Explain why this is the case, detailing the transfer of energy in this system.

9 Explain why, if all objects are at 'room temperature', metal objects feel cooler to touch than wooden objects.

10 Humans have evolved to sweat in order to avoid overheating. Elephants cannot sweat, but are able to increase the blood flow to areas where the skin is thin. Compare and contrast these two different methods for temperature control, explaining how they work.

11 Students have 0.67 kg of an unknown liquid in a calorimeter. They collected the following data:

Energy in (J)	Temperature (°C)
0	–10
20 000	2.1
40 000	14.3
60 000	26.4
80 000	38.5
100 000	50.7
120 000	62.8
140 000	74.9

a Create a graph of the results, including an appropriate trend line with equation.
b Interpret the equation of the trend line, include the significance of the intercept and the gradient.
c Using the table below, determine the unknown liquid.

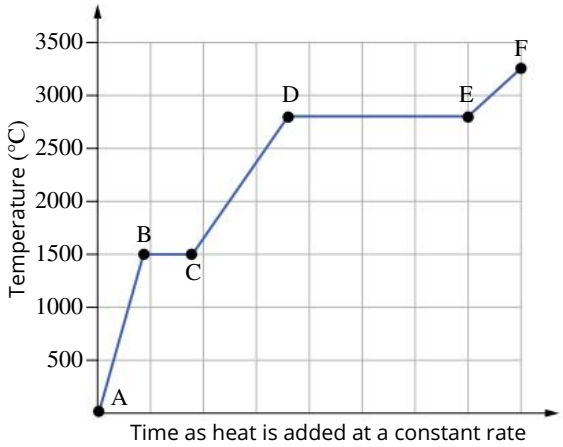
Material	c (J kg^{-1} K^{-1})	Boiling point (°C)
liquid water	4200	100
glucose solution	1213	–
ethanol	2460	78
methanol	2500	65

12 **a** A student would like to design a model hot air balloon using a candle, a waxed paper bag and string. Describe the energy transformations involved as the balloon rises in the air.

b Define 'efficiency', and design an experiment that can be used to measure the efficiency of the energy transformation from heat energy to mechanical energy.

13 A block of solid iron is placed in a furnace that maintains a constant heat output. The temperature of the iron is recorded and graphed below.

Heating curve for iron



a Using a diagram, describe the difference between the molecular structure and behaviour at point A and that at point F.

b Describe the change caused by the addition of heat between points C and D.

c Describe the change caused by the addition of heat between points D and E. Explain how this is different from the change between C and D.

Topic 2: Ionising radiation and nuclear reactions

Multiple choice

1 Name the force that must be overcome in order to get two hydrogen nuclei close enough to each other for the strong nuclear force to act and subsequently join them to form one nucleus.

A the gravitational force
B the weak nuclear force
C the electromagnetic force
D the force of nature

2 Beta negative radiation is:

A energy emitted from an electron of an atom
B an electron ejected from an atom
C a helium nucleus emitted from an atom
D an electron emitted from the nucleus of an atom

3 Name the type of radiation that is most ionising.

A gamma
B beta
C alpha
D none of the above

4 The value of x in the decay equation ${}^{238}_{92}\mathrm{U} \rightarrow {}^{x}_{90}\mathrm{Th} + {}^{4}_{2}\alpha + \gamma$ is:

A 238
B 236
C 234
D 232

5 A radioactive sample of oxygen-15 has a half-life of 110 minutes. If the amount remaining after 5.5 h is 0.80 g, the original sample had a mass of:

A 2.4 g
B 2.8 g
C 6.4 g
D 9.6 g

6 When exploring the nature of the nucleus, electrons were not fired at nuclei because:

A they were too small
B they travelled too fast
C they bonded to the atom
D they couldn't get past the outer shell electrons

7 Nuclear fission is:

A the joining together of two or more small nuclei
B splitting a nucleus into two or more pieces
C absorbing a neutron
D undergoing radioactive decay

8 The electron volt (eV) is a unit of measure of:

A mass
B charge
C potential difference
D energy

9 Select the statement that best describes the main hazard of radiation.

A There is damage to living cells due to ionisation.
B The heat produced damages cells.
C Chemical reactions within the body create impurities.
D Radioactive atoms replace other atoms in living organisms.

10 Critical mass is:

A the mass of the 'critical' elements in a reactor such as the uranium
B the minimum amount of fissionable material required to sustain a chain reaction
C the amount of mass needed to make a power reactor economically feasible
D the material that is just on the verge of becoming radioactive

Short answer

1 Complete the following decay equations by replacing ψ:

a $^{14}_{6}C \rightarrow {}^{14}_{7}N + \Psi$

b $^{214}_{82}Pb \rightarrow {}^{214}_{83}Bi + \Psi$

c $^{60}_{27}Co^{*} \rightarrow {}^{60}_{27}Co + \Psi$

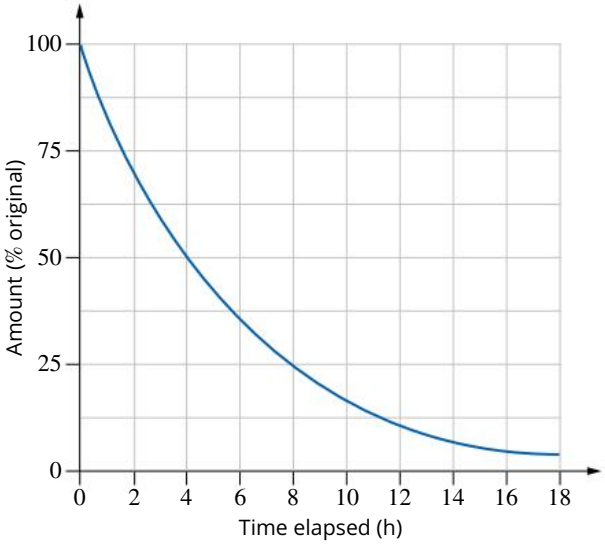
2 Cobalt-60 has a half-life of 5.3 years. A sample of pure cobalt-60 has a mass of 50 μg. Determine the amount of Co-60 that remains after:

a 10.6 years

b 15.9 years

c 21.2 years.

3 The radioactive decay of a particular isotope is shown on the graph below. The initial mass of the radioisotope is 20 g.



a Determine the time it takes for a 20 g sample to decay to 5.0 g.

b Determine the half-life of the sample.

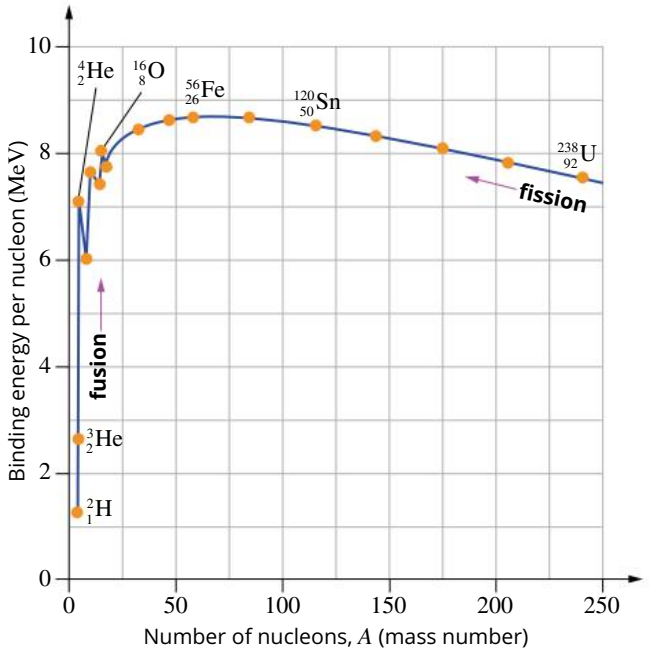
c Calculate how much of the original radioisotope (in grams) remains after 6.0 hours.

d Calculate the amount of the radioisotope remaining (in grams) after 20 hours have elapsed.

4 Define 'binding energy' and 'mass defect'.

5 Uranium-235 undergoes fission and splits into daughter products of roughly equal mass. Use the graph of binding energy per nucleon to determine how much energy is released per nucleon.

Binding energy per nucleon vs mass number



6 The Sun is currently releasing approximately 3.9×10^{26} W from nuclear fusion reactions. Calculate the mass loss this equates to each day.

7 Lead-210 undergoes beta negative decay twice to become polonium, which then undergoes alpha decay.

a Write a series of equation that describes this decay chain, identifying the daughter nuclides.

b Explain why the polonium isotope in this decay chain would be dangerous to ingest, but is relatively safe to observe from close proximity.

8 Carbon-14 has a half life of 5730 years. Define 'half-life', and explain how this can be used to estimate the age of organic materials.

9 As a doctor you prescribe a course of radiotherapy for a patient with breast cancer. The procedure involves inserting a radioactive source into the affected region. Explain which type of radiation source—alpha, beta negative or gamma—you would prefer to use and why.

10 Consider the fission reaction below:

$^{235}_{92}U + {}^{1}_{0}n \rightarrow {}^{141}_{56}Ba + {}^{92}_{36}Kr + \ldots + 170\ \text{MeV}$

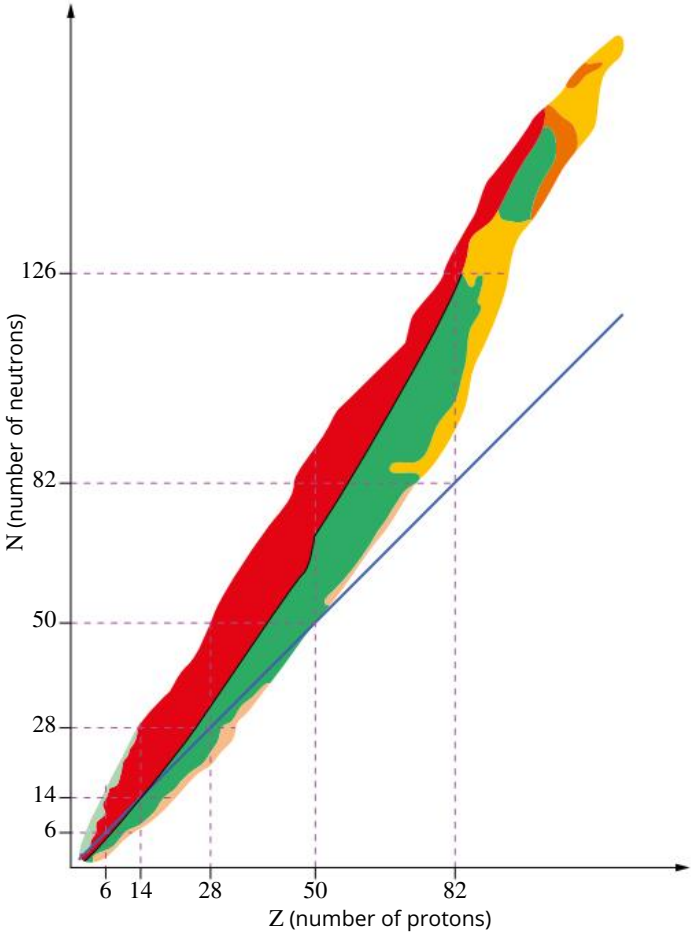
a Determine the identity of the missing item.

b Convert the energy released into joules.

c Determine how many of these reactions are needed each second to generate 3.0 GW of power.

d The rest mass of a proton and neutron are almost equal at 1.67×10^{-27} kg. Calculate the mass of U-235 that is needed each second to generate 3.0 GW.

11 The figure below shows the number of protons for different isotopes. Each isotope is colour-coded with the type of radioactive decay that is most often observed. Stable nucleotides are represented in black.



a Describe the forces that act within the nucleus of a stable atom, and identify the type of nucleon each force acts between. Sketch a graph showing the strength of the force vs distance apart.

b In the figure above, the red nuclei have more neutrons within them than the stable isotope of the same element. Describe the forces acting within these nuclei and compare these with the forces acting in the stable nuclei.

c Predict the type of decay the red nuclei would most commonly experience, detailing how this decay leads to a more stable nucleus.

d Both the yellow- and green-coloured nuclei have fewer neutrons than the stable isotopes. Describe the type of decay each would undergo, and explain how this decay creates a more stable nucleus for these nucleotides.

12 Uranium-235 has a half-life of approximately 703.8 million years and decays to thorium-231, releasing energy in the process. Alternatively, uranium-235 can be bombarded with a neutron and fission into smaller nuclei, releasing energy.

a Define 'artificial transmutation', and compare it with natural radioactive decay.

b Uranium-235 can fission into different products. One option is given below.

$${}^{235}_{92}\mathrm{U} + {}^{1}_{0}\mathrm{n} \rightarrow {}^{131}_{53}\mathrm{I} + {}^{102}_{39}\mathrm{Y} + x\,{}^{1}_{0}\mathrm{n}$$

Calculate the number of neutrons produced in this reaction.

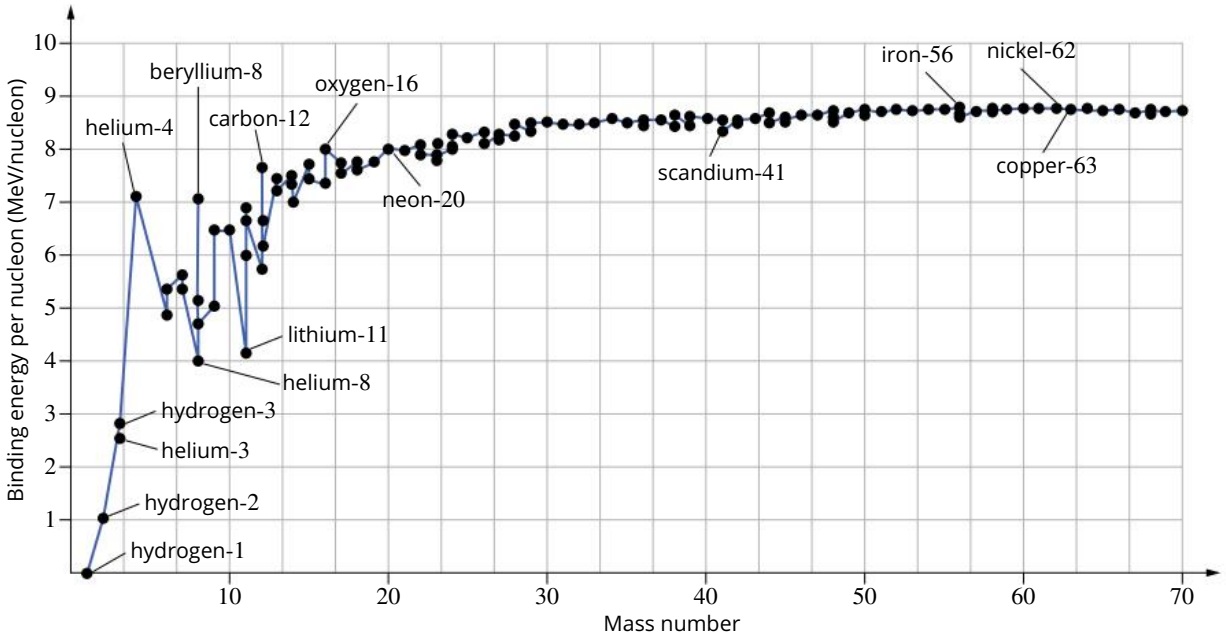
c Describe fission chain reactions, using the U-235 fission reaction as an example, and the role of control rods and moderators in nuclear reactors.

d Iodine-131, a daughter nuclide of this fission reaction, is radioactive, with a half-life of approximately 8 days. It is often used in medical procedures, including the treatment of cancer. Using your understanding of nuclear waste, determine if the iodine produced could be used for medical treatment. Explain your reasoning.

e Find the energy released during one fission reaction. The required data are:
Mass of neutron = 1.008 665 u
Mass of uranium-235 = 235.043 929 9 u
Mass of iodine-131 = 130.906 124 6 u
Mass of yttrium-102 = 101.933 56 u

13 The graph below shows the binding energy per nucleon up to mass number 70.

Binding energy per nucleon for selected isotopes from mass number 1 to mass number 70



a Using the information from the graph, determine the energy release for the fusion equation of hydrogen-2 (deuterium) with hydrogen-3 (tritium).

b Using the information from the graph of binding energy per nucleon above, describe the process that nuclei below nickel undergo in order to become more stable.

c Describe the conditions that are required for this process, and why they are necessary.

d Compare this process with the process that heavy elements undergo to release energy and become more stable.

Topic 3: Electrical circuits

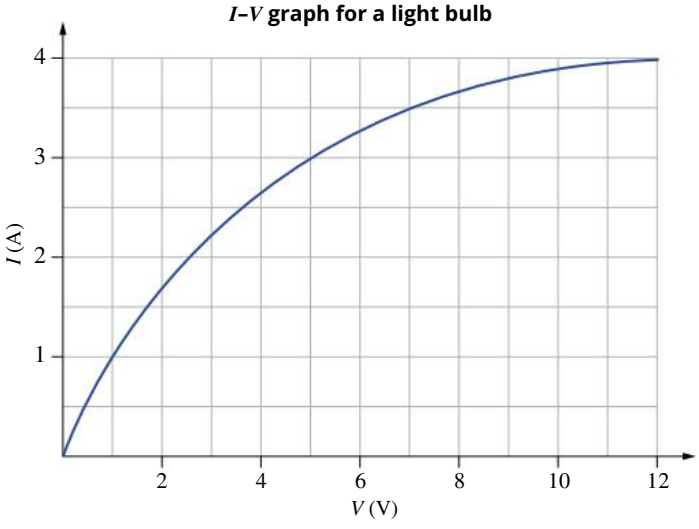
Multiple choice

1 Electricity passing through a copper wire primarily relates to the movement of:

A protons
B neutrons
C electrons
D atoms

2 The *I*–*V* graph for a light bulb is shown. Determine the resistance of the bulb when a 4.0 A current is passing through it.

***I*–*V* graph for a light bulb**



A 3.0 W
B 3.0 Ω
C 0.33 Ω
D 0.33 W

3 A circuit is made from a battery and four light bulbs. The battery will go flat quickest when:

A all of the lights are wired in series
B some of the lights are wired in series and some in parallel
C all the lights are wired in parallel
D It can't be determined unless the resistance of the light bulbs is known

4 Determine which of these statements is correct for a series circuit.

A The supply voltage divides among the components and the current is constant everywhere around the circuit.
B The current divides among the components and the supply voltage is constant everywhere around the circuit.
C The power dissipated by all components is equal regardless of their resistance.
D The power dissipated by all components depends on the differing current through each.

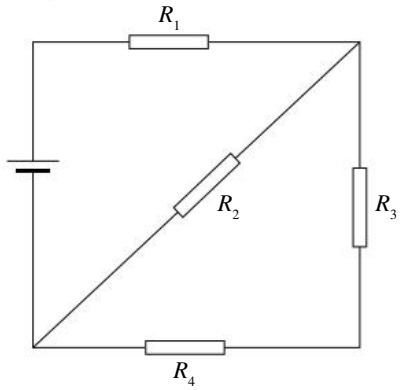
5 The potential difference between the two terminals on a battery is 12.0V. Calculate the amount of work required to transfer 8.0C of charge across the terminals.

A 1.5J
B 96J
C 0.66J
D 12.0J

6 Kirchhoff's current law is a consequence of the conservation of:

A mass
B energy
C power
D charge

7 In the following circuit, resistor 2 and resistor 3 are:



A in series
B in parallel
C opposite
D in order

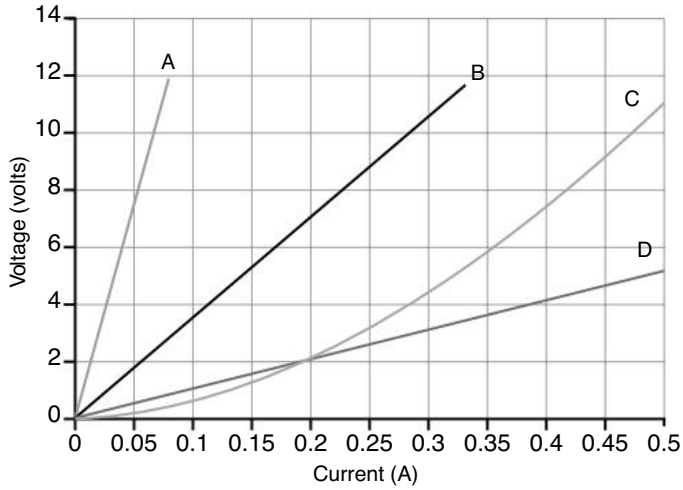
8 A heating radiator is connected to a 240V power supply. The heater dissipates 2.4MJ of energy in 20min. Calculate the power dissipated by the heating element.

A 500W
B 0.5W
C 2000W
D 2W

9 Kirchhoff's voltage law is a consequence of the conservation of:

A mass
B energy
C power
D charge

10 The voltage–current characteristics were measured for four different resistors. Identify the resistor with the highest resistance.



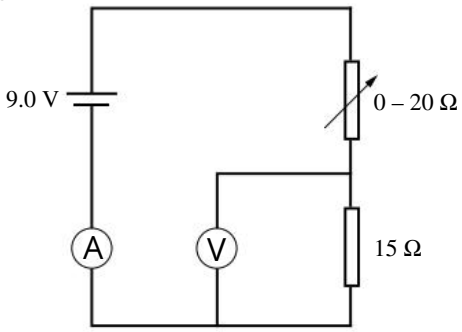
A A
B B
C C
D D

Short answer

1 A negatively charged balloon and some positively charged confetti in a container are brought together so they are close but do not touch. Explain and justify what will happen.

2 Sketch the shape of the *I–V* graph for an ohmic resistor and a non-ohmic resistor on the same axis (no numbers are needed).

3 A variable resistor and a fixed resistor are wired to a supply as shown.



a Determine the possible range of readings on the ammeter.

b Determine the possible range of readings on the voltmeter.

4 A kettle rated at 2.0 kW is plugged into the mains supply (230 V).

a Determine how much current flows when the kettle is in operation.

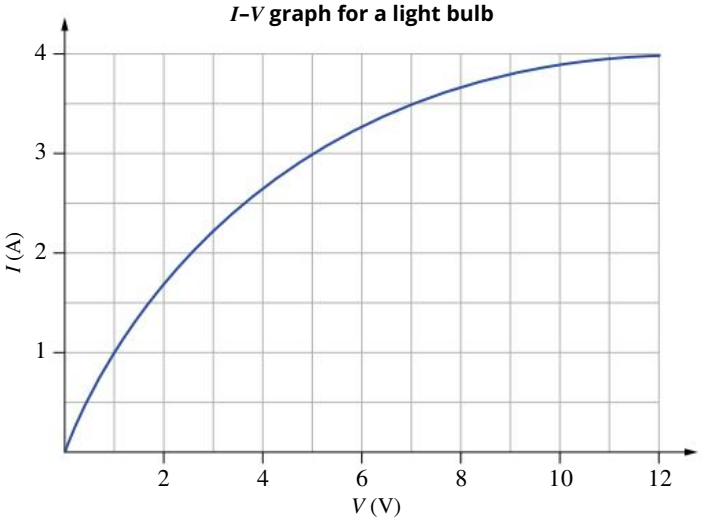
b Calculate how many joules of energy the kettle uses if it takes 3.0 minutes for it to boil some water.

c Determine how many coulombs of charge flow in the 3.0 minutes.

d Determine how many electrons flow in the 3.0 minutes.

5 A light bulb with the *I*–*V* characteristics shown below is connected to a 9 V battery. Calculate the power dissipated in the bulb.

***I*–*V* graph for a light bulb**



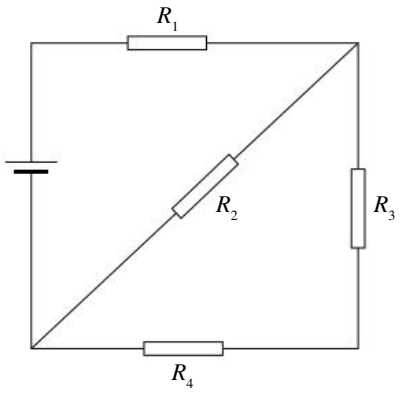
6 Define the following terms, include the unit of measurement.

a electric current

b electrical potential difference

c power dissipation over resistors

7 Four identical 200 Ω resistors and a 12 V power supply are arranged as shown in the circuit. Calculate the current through R_3, and the power dissipated by R_2.



8 An unknown ohmic component was placed into a simple circuit and the voltage drop and current through the resistor were measured. Determine the resistance of the unknown component.

Voltage (V)	Current (mA)
2	19
4	43
6	62
8	78
10	101

9 Draw a circuit diagram, using standard symbols that would allow the resistance of an unknown fixed resistor to be determined.

10 For an unknown reason, Owen rubs a balloon on his hair. As he slowly raises the balloon, his friend Nick notices that Owen's hair appears to be lifted up towards the balloon. Explain why.

11 Christmas-tree lights consist of a string of bulbs that can be wired in either series or parallel.

a State whether it is better to arrange the bulbs in series or parallel. Justify your answer.

b Describe what would happen to the total resistance if the bulbs were wired in parallel and additional bulbs were added.

c Each bulb is rated at 3 V, 6 W. A 13 A fuse is placed immediately after the 3 V power supply. Calculate the maximum number of bulbs in parallel that can be used so that the fuse doesn't melt.

d Describe what would happen to the total resistance if the bulbs are wired in series.

e Predict what would happen if a series combination of bulbs was wired to the same 3 V supply in conjunction with the 13 A fuse. Justify your answer.

12 A piece of copper wire and a piece of plastic are placed across two terminals side by side, and a current is passed through them.

a It is noticed that the wire gets hot if the current is left on for any length of time, but the plastic does not. Explain why this is so.

b Using the wire and plastic as an example, define 'electrical resistance'.

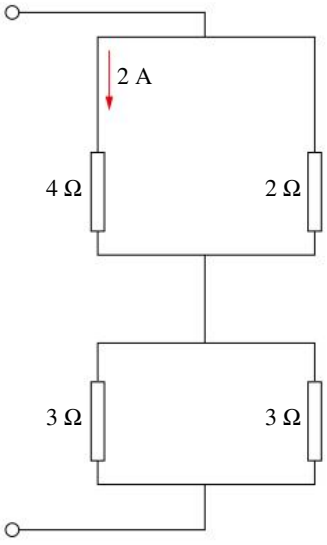
c Design a method that could be used to determine the resistance of the copper wire. Include safe working practices.

d Another student in your class obtained the following results in order to predict the current that will be used when 24 V is applied across the copper wire.

Voltage (V)	Current (A)
0.5	8
1.0	10
1.5	25

Give the student two pieces of advice to improve their results.

13 A circuit is created using a 4 Ω resistor, two 3 Ω resistors and a 2 Ω resistor, as shown below. When connected to a power supply, 2 A of current flow through the 4 Ω resistor.



a Calculate the total current that is supplied to the circuit.

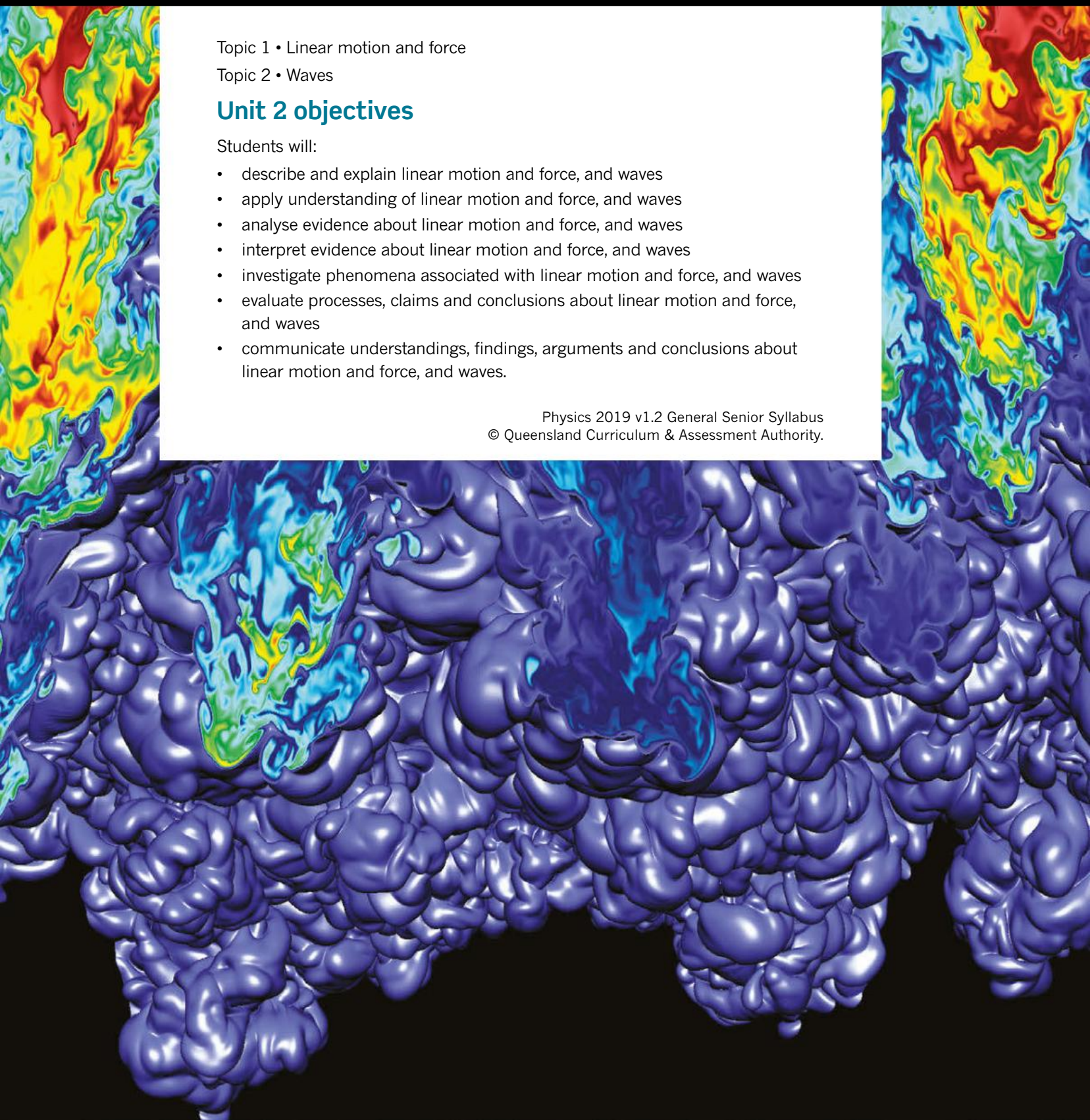
b Calculate the equivalent resistance of this circuit.

c Calculate the voltage supplied to the circuit.

d With the same resistors and power supply, design a circuit that has the minimum current in the circuit going through the 2 Ω resistor.

UNIT 2

Linear motion and waves



Topic 1 • Linear motion and force

Topic 2 • Waves

Unit 2 objectives

Students will:

- describe and explain linear motion and force, and waves
- apply understanding of linear motion and force, and waves
- analyse evidence about linear motion and force, and waves
- interpret evidence about linear motion and force, and waves
- investigate phenomena associated with linear motion and force, and waves
- evaluate processes, claims and conclusions about linear motion and force, and waves
- communicate understandings, findings, arguments and conclusions about linear motion and force, and waves.

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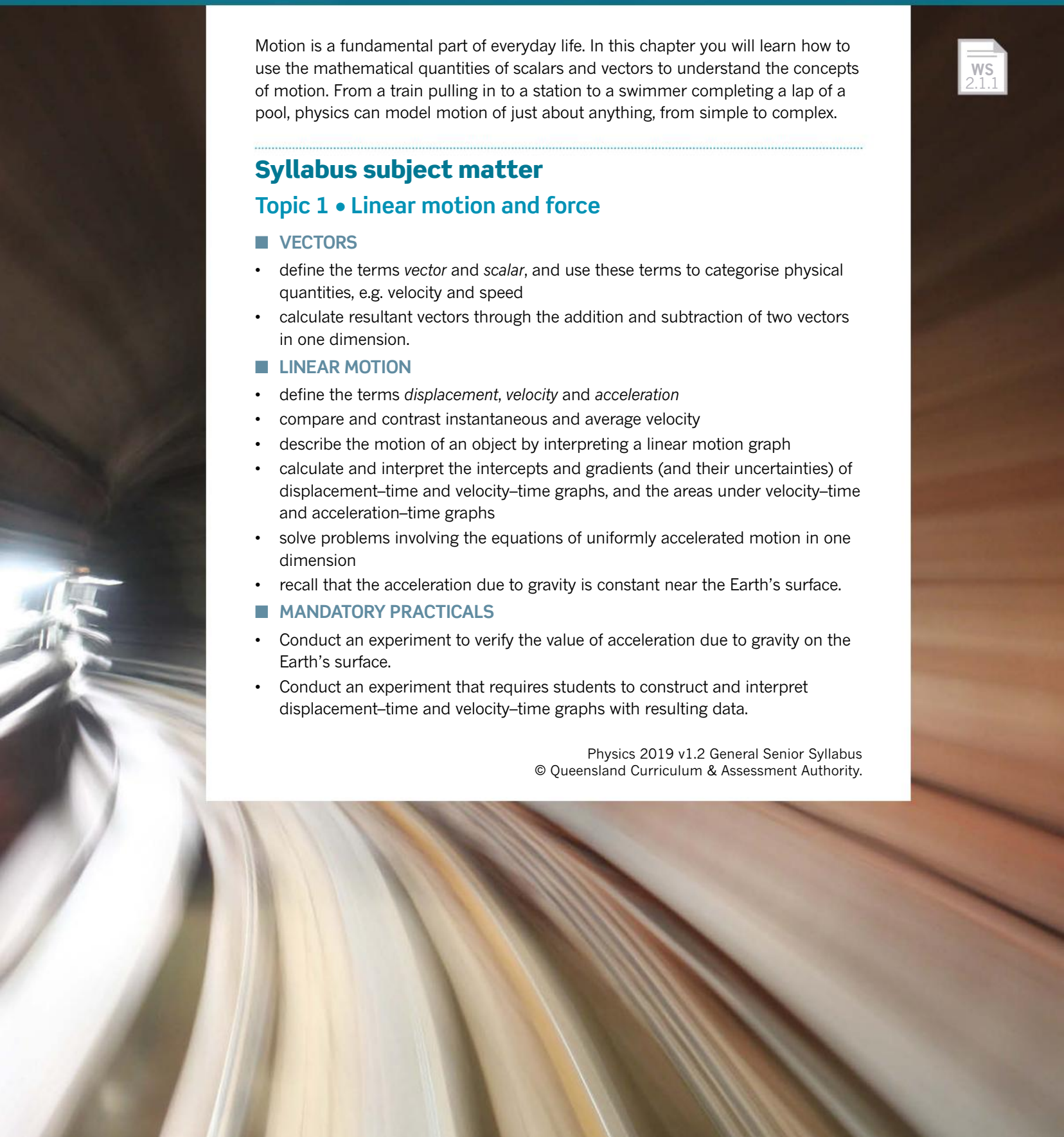
CHAPTER

06 Vectors and linear motion



Motion is a fundamental part of everyday life. In this chapter you will learn how to use the mathematical quantities of scalars and vectors to understand the concepts of motion. From a train pulling in to a station to a swimmer completing a lap of a pool, physics can model motion of just about anything, from simple to complex.

WS 2.1.1

Syllabus subject matter

Topic 1 • Linear motion and force

VECTORS

- define the terms *vector* and *scalar*, and use these terms to categorise physical quantities, e.g. velocity and speed
- calculate resultant vectors through the addition and subtraction of two vectors in one dimension.

LINEAR MOTION

- define the terms *displacement*, *velocity* and *acceleration*
- compare and contrast instantaneous and average velocity
- describe the motion of an object by interpreting a linear motion graph
- calculate and interpret the intercepts and gradients (and their uncertainties) of displacement–time and velocity–time graphs, and the areas under velocity–time and acceleration–time graphs
- solve problems involving the equations of uniformly accelerated motion in one dimension
- recall that the acceleration due to gravity is constant near the Earth's surface.

MANDATORY PRACTICALS

- Conduct an experiment to verify the value of acceleration due to gravity on the Earth's surface.
- Conduct an experiment that requires students to construct and interpret displacement–time and velocity–time graphs with resulting data.

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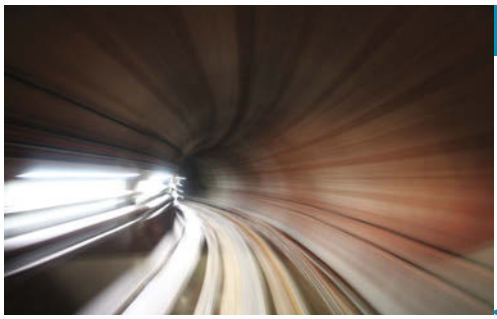
6.1 Vectors



BY THE END OF THIS MODULE, YOU SHOULD BE ABLE TO:

- understand the concepts of scalars and vectors, and the difference between them
- write vectors using appropriate notation and sign conventions
- draw diagrams of vectors
- add and subtract vectors in one dimension using graphical and algebraic methods.

You will come into contact with many physical quantities in the natural everyday world. For example, time, mass and distance are all physical quantities. These quantities are measured in the units seconds, kilograms and metres respectively.

Some measurements only make sense when a direction is included. For example, a GPS system tells you when to turn and in which direction. Without both of these two instructions, the information is incomplete. All physical quantities can be divided into two broad groups, scalars and vectors, on the basis of what information is required for the quantity to make sense.

SCALARS

Scalar measurements only require a magnitude. A number of properties in nature can be measured or described using only a number and unit. For example, if the time taken for a student to travel to school is measured, you need the **magnitude** (size) and the **units** in order to understand the journey. It might say it takes 60 minutes or 1 hour, as long as you give a number and a corresponding unit. Quantities that require magnitude and units are called scalar quantities. Scalars do not need direction. Examples of scalar quantities are:

- time
- distance
- volume
- speed.

VECTORS

Vector measurements require magnitude, units and direction in order to make sense. Quantities that require magnitude, units and direction are called vector quantities. Examples of vector quantities are:

- position
- displacement
- velocity
- acceleration
- force.

These measures are discussed in more detail in the coming chapters.

Scalars are represented by symbols, such as *t* for time and *d* for distance. Vectors are often represented in the same way—it is usually clear from the context whether a scalar or vector is meant.

A number of different types of vector notation are used in books and journals. For example, force can be written as **F** or ***F*** and velocity can be written as **v** or ***v***.

This book uses italics to represent vectors; for example, force is written as *F* and velocity as *v*.

Vectors as arrows

Vector measurements require both a magnitude and a direction. A vector can be visually represented as an arrow. Figure 6.1.1 shows two vector diagrams. In a **vector diagram**, the length of the arrow indicates the magnitude of the vector. The arrowhead shows the direction of the vector, which is always from its tail to its head.

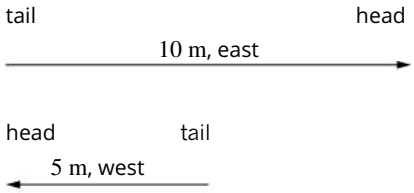


FIGURE 6.1.1 Two vector diagrams. The top vector is twice as long as the bottom vector, so it represents a measure twice the magnitude of the bottom vector. The arrowheads indicate that the vectors are in opposite directions.

Recall that a force is a push or a pull and the unit of measure for force is the **newton** (N). If you push a book to the right, it will respond differently from the way it will respond if you push the book to the left. Therefore, a force is only described properly if a direction is included, and so force is considered to be a vector. Force is an important concept to understand in physics, so many of the examples in this chapter refer to forces.

In some vector diagrams, the length of the arrow is drawn to scale so that it accurately represents the magnitude of the vector.

In the scaled vector diagram in Figure 6.1.2, a force $F = 4\,\text{N}$ left acting on the toy car is drawn as a 2 cm arrow. In this example a scale of 1 cm = 2 N force is used.

FIGURE 6.1.2 A force of 4 N to the left acts on a toy car.

An exact scale for magnitude is not always used. However, it is important that vectors are drawn relative to one another. For example, a vector of 50 m north should be about half as long as a vector of 100 m north.

Point of application of arrows

Vector diagrams may be drawn differently, depending on what they are depicting.

- Force vectors have the tail end of the arrow drawn at the point where the force is applied to the object.
- Displacement vectors have the tail of the arrow at the starting position of the object.
- Friction vectors are drawn at the point where the friction is applied between an object and a surface.

Figure 6.1.3 shows a force applied by a foot to a ball (95 N east) and an opposing friction force (20 N west).

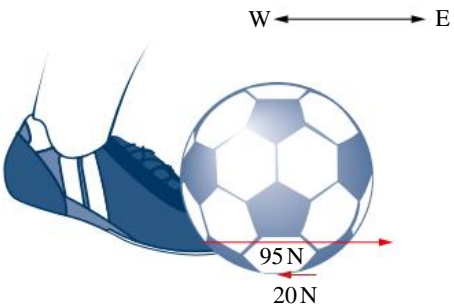


FIGURE 6.1.3 The force on the ball acts at the point of contact between the ball and the foot. The friction force acts between the ball and the ground. The kicking force, as indicated by the length of the arrow, is larger than the friction force.

VECTORS IN ONE DIMENSION

Vectors need a direction in order to make sense. However, for any description of a vector quantity to be useful, the direction should be described using a convention that everyone understands. For vector problems in one **dimension**, a number of **direction conventions** can be used. For example:

- forwards or backwards
- up or down
- left or right
- north or south
- east or west.

As you can see, for vectors in one dimension there are only two directions possible. The two directions must be in the same dimension or along the same line. The direction convention used should be presented graphically in all vector problems. This is shown in Figure 6.1.4. Arrows like these are placed near the vector diagram so it is clear which convention is being used.

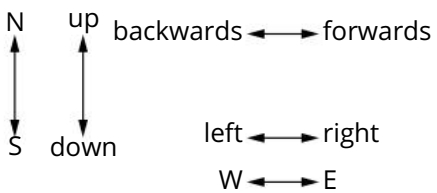


FIGURE 6.1.4 Some common one-dimensional direction conventions

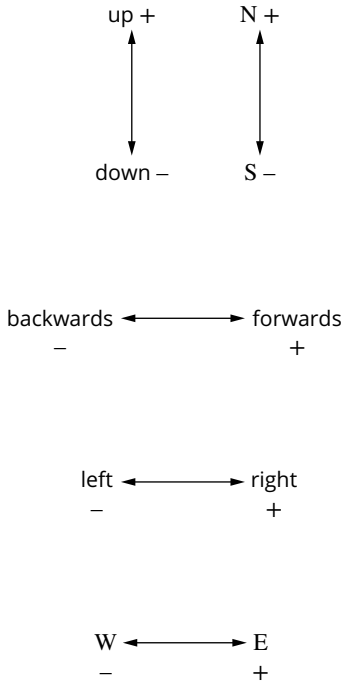


FIGURE 6.1.5 One-dimensional direction conventions can also be expressed as sign conventions.

Sign conventions

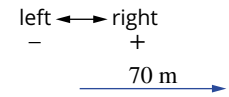
In calculations involving one-dimensional vectors, a sign convention can be used to represent physical directions as positive and negative values. For example, forwards can be positive and backwards can be negative, or right can be positive and left can be negative. A vector of 100 m up can be described as +100 m. The relationship between sign and direction conventions must be clearly indicated in a legend or key. Some examples are provided in Figure 6.1.5.

The advantage of using a sign convention is that the signs of positive and negative can be entered into a calculator, but the words 'up' and 'right' cannot. This will be useful when adding vectors together.

Worked example 6.1.1

DESCRIBING VECTORS IN ONE DIMENSION

Consider the vector below.



a Describe the vector using direction convention shown.

Thinking	Working
Identify the direction convention used in the vector.	The vector is pointing to the right according to the direction convention.
Note the magnitude, unit and direction of the vector.	The vector is 70 m right.

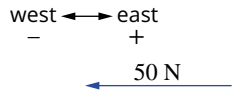
b Describe the vector using an appropriate sign convention.

Thinking	Working
Convert the physical direction to the corresponding mathematical sign. The direction of right is positive and left is negative.	The arrow is pointing right, so the sign is +.
Represent the vector with a mathematical sign, magnitude and unit.	This vector is +70 m.

➤ Try yourself 6.1.1

DESCRIBING VECTORS IN ONE DIMENSION

Consider the vector below.



a Describe the vector using the direction convention shown.

b Describe the vector using an appropriate sign convention.

ADDING VECTORS IN ONE DIMENSION

In reality, more than one vector may act on an object. If this is the case, it is helpful to analyse the associated vector diagrams to find out the overall or combined effect of the vectors. When two or more vectors are in the same dimension, it means that the vectors are either pointing in the same direction or in the opposite direction. They are **collinear** (in line with each other). For example, the vector measurements 10 m west, 15 m east and 25 m west are all in one dimension. They are all in the same or opposite direction to each other. When vectors are combined, it is called adding vectors.

Graphical method of adding vectors

Vector diagrams, as shown in Figure 6.1.6, are convenient for adding vectors. To combine vectors in one dimension, draw the first vector, and then start the second vector with its tail at the head of the first vector. Continue adding arrows 'head to tail' until the last vector is drawn. The sum of the vectors, or the **resultant** vector, is drawn from the tail of the first vector to the head of the last vector.

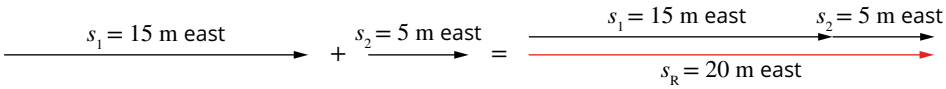


FIGURE 6.1.6 Adding vectors head to tail. This particular diagram represents the addition of 15 m east and 5 m east. The resultant vector, shown in red, is 20 m east.

In Figure 6.1.6, the two vectors s_1 (15 m east) and s_2 (5 m east) are drawn separately. The two vectors are then drawn with s_1 and s_2 connected head to tail. The resultant vector s_R is drawn from the tail of s_1 to the head of s_2. The magnitude (size) of the resultant vector can be deduced from the magnitudes of the separate vectors: 15 m + 5 m = 20 m.

Alternatively, vectors can be drawn to scale such as 1 m = 1 cm. The resultant vector is then directly measured from the scale diagram. The direction of the resultant vector is the same as the direction from the tail of the first vector to the head of the last vector.

Algebraic method of adding vectors

To add vectors in one dimension algebraically, a sign convention is used to represent the direction of the vectors, as shown in Figure 6.1.5. When applying a sign convention, it is important to provide a key explaining the convention used.

The sign convention allows you to enter the signs and magnitudes of vectors into a calculator. The sign of the final magnitude gives the direction of the resultant vector.

Vectors are added head to tail. The resultant vector is drawn from the tail of the first vector to the head of the last vector.

Worked example 6.1.2

ADDING VECTORS IN ONE DIMENSION USING ALGEBRA

Use the sign and direction conventions shown in Figure 6.1.5 to determine the resultant vector of a student who walks 25 m west, 16 m east, 44 m west and then 12 m east.

Thinking	Working
Apply the sign conventions to change each of the directions to signs.	25 m west = –25 m 16 m east = +16 m 44 m west = –44 m 12 m east = +12 m
Add the magnitudes and their signs together.	Resultant vector = (–25) + (+16) + (–44) + (+12) = –41 m
Refer to the sign and direction conventions to determine the direction of the resultant vector.	Negative is west. ∴ Resultant vector = 41 m west.

➤ Try yourself 6.1.2

ADDING VECTORS IN ONE DIMENSION USING ALGEBRA

Use the sign and direction conventions shown in Figure 6.1.5 to determine the resultant vector of a box that has the following forces acting on it: 16 N up, 22 N down, 4 N up and 17 N down.

SUBTRACTING VECTORS IN ONE DIMENSION

The previous module discussed combining or adding vectors. In physics there are times when the difference between two vectors has to be determined. For example, to find a change in velocity you subtract the initial velocity from the final velocity. One way to subtract one vector from another is to add the opposite vector.

To find the difference between two vectors, you must subtract the initial vector from the final vector. To do this, work out which is the initial vector, then reverse its direction. These two vectors are then added: the final vector and the opposite of the initial vector.

This technique can be applied both graphically and algebraically.

Double negatives

When a negative number is multiplied by another negative number, the result is a positive number. It is also illustrated when a negative number is subtracted from another number. The effect is to add the two numbers together. For example: (5) – (–2) = 7.

It is important to differentiate between the terms 'subtract', 'minus', 'take away' or 'difference between' and the term 'negative'. The terms 'subtract', 'minus', 'take away' and 'difference between' are processes, such as add, multiply and divide. They are grouped together on your calculator. The term 'negative' is a property of a number that means that it is the opposite of positive. There is a separate button on your calculator for this property.

FIGURE 6.1.7 As velocity is a vector, direction is important. The tennis ball has a different velocity when it leaves the racquet from when it travelled towards the racquet.

Graphical method of subtracting vectors

Velocity is a quantity that gives an indication of how fast an object is moving. It is a vector because the direction is important when stating the velocity of an object. For example, the velocity of the tennis ball moving towards the racquet in Figure 6.1.7 is different from the velocity of the tennis ball as it leaves the racquet. The concept of velocity is covered in more detail in Module 6.2, but it is useful to use the example of velocity now when discussing the subtraction of vectors. The processes applied to the subtraction of velocity vectors works for all other vectors.

To subtract velocity vectors in one dimension using a graphical method, determine which vector is the initial velocity and which is the final velocity. The final velocity is drawn first. The initial velocity is then drawn, but in the opposite direction to its original form. The sum of these vectors, or the resultant vector, is drawn from the tail of the final velocity to the head of the reversed initial velocity. This resultant vector is the difference between the two velocities, or Δv.

In Figure 6.1.8, the two velocity vectors, v_1 (9 m s^{-1} east) and v_2 (3 m s^{-1} east) are drawn separately. The vectors have the same direction (east). To find the difference between the vectors, subtract the initial velocity from the final velocity. To do this, draw v_2. Then draw v_1 below v_2 in the opposite direction, $-v_1$ (9 m s^{-1} west), with the tail of $-v_1$ in line with the head of v_2 as shown in Fig. 6.1.9. The resultant vector, Δv, is drawn from the tail of v_2 to the head of $-v_1$. In Figure 6.1.9 the resultant vector is shown in red. The resultant vector is 6 m s^{-1} west.

$$\Delta v = (+3) + (-9) = -6 \text{ m s}^{-1}$$

Alternatively, you could draw the vectors to scale and then measure the resultant vector against that scale, for example 1 m s^{-1} = 1 cm.

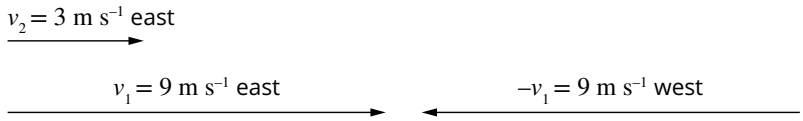


FIGURE 6.1.8 For vectors, $v_2 - v_1$ involves adding the opposite direction of v_1; $-v_1$ as shown.

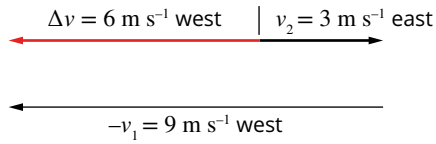


FIGURE 6.1.9 The resultant of $v_2 + (-v_1)$ is given by Δv in red.

The symbol Δ (delta) is used to describe the change in some variable. For example, Δv means the change in velocity.

To find the difference between or a change in vectors, subtract the initial vector from the final vector. Vectors are subtracted by adding the negative of a vector.

Algebraic method of subtracting vectors

To subtract velocity vectors in one dimension algebraically, a sign convention is used to represent the direction of the velocities. Some examples of one-dimensional directions include east and west, north and south and up and down. These options are replaced by positive (+) or negative (–) signs when calculations are performed. To change the direction of the initial velocity, simply change the sign from positive to negative or from negative to positive. The equation for finding the change in velocity is:

Change in velocity = final velocity – initial velocity

$$v = v_2 - v_1$$

Change in velocity = final velocity + the opposite of the initial velocity

$$v = v_2 + (-v_1)$$

The final velocity is added to the opposite of the initial velocity. The change in velocity is a vector, so it will consist of a sign and a magnitude. The sign of the answer can be compared with the sign and direction convention (Figure 6.1.5, page 206) to determine the direction of the change in velocity.

Worked example 6.1.3

SUBTRACTING VECTORS IN ONE DIMENSION USING ALGEBRA

Determine the change in velocity of an aeroplane as it changes from 255 $m\,s^{-1}$ west to 160.0 $m\,s^{-1}$ east, using the sign and direction conventions shown in Figure 6.1.5.

Thinking	Working
Apply the sign and direction conventions to change the directions to signs.	$v_1 = 255\,m\,s^{-1}$ west $= -255\,m\,s^{-1}$ $v_2 = 160.0\,m\,s^{-1}$ east $= +160.0\,m\,s^{-1}$
Reverse the direction of the initial velocity, v_1, by reversing the sign.	$-v_1 = 255\,m\,s^{-1}$ east $= +255\,m\,s^{-1}$
Use the formula for change in velocity to calculate the magnitude and the sign of Δv.	$v = v_2 + (-v_1)$ $= (+160.0) + (+255)$ $= +415\,m\,s^{-1}$
Refer to the sign and direction conventions to determine the direction of the change in velocity. Positive is east.	$\Delta v = 415\,m\,s^{-1}$ east

➤ Try yourself 6.1.3

SUBTRACTING VECTORS IN ONE DIMENSION USING ALGEBRA

Determine the change in velocity of a rocket as it changes from 212.0 $m\,s^{-1}$ up to 2200.0 $m\,s^{-1}$ up, using the sign and direction conventions shown in Figure 6.1.5.

6.1 Review

SUMMARY

- Scalar quantities can be measured or described using a unit.
- Vector quantities will have a magnitude and a direction. They are written using vector notation with an arrow above the variable.
- Combining vectors is known as adding vectors.
- Adding vectors in one dimension can be done graphically by using vector diagrams. After adding vectors head to tail, the resultant vector can be drawn from the tail of the first vector to the head of the last vector.
- Adding vectors in one dimension can be done algebraically by applying a sign convention. Vectors with direction become vectors with either positive or negative signs.
- To find the difference between, or change in vectors, subtract the initial vector from the final vector.
- Vectors are subtracted by adding the negative, or opposite, of a vector.
- Vector subtraction can be determined graphically using a scale.
- Vector subtraction in one dimension can be determined algebraically.

KEY QUESTIONS

Retrieval

1 As well as magnitude and units, identify the quantity needed to describe a vector correctly.

2 For each of the following quantities, state whether they are scalar or a vector.

a velocity
b position
c distance
d force
e time
f speed
g acceleration

3 List the symbols for the following quantities in vector notation:

a force
b velocity

Comprehension

4 Draw vector diagrams for the following forces using a scale of 1 cm = 2 N.

a 4 N right
b 10 N left
c 8 N right

Analysis

5 Determine the resultant vector when the following are combined: 2 m west, 5 m east and 7 m west.

6 Add the following vectors to determine the resultant vector: 3 m up, 2 m down and 3 m down.

7 Determine the resultant vector of a toy train that is made to move in these directions: 23 m forwards, 16 m backwards, 7.0 m forwards and 3.0 m backwards.

8 When adding vector B to vector A using the head-to-tail method, determine the points between which the resultant vector is drawn.

9 A car that was initially travelling at a velocity of $3\,m\,s^{-1}$ west is later travelling at $5\,m\,s^{-1}$ east. Determine the difference between the two vectors.

10 Determine the change in velocity of a runner who changes from running at $4\,m\,s^{-1}$ to the right on grass to running $2\,m\,s^{-1}$ to the right on sand.

11 A student throws a ball up into the air at $4\,m\,s^{-1}$. A short time later the ball is travelling back downwards to hit the ground at $3\,m\,s^{-1}$. Determine the change in velocity of the ball during this time.

12 Jamelia applies the brakes on her car and changes her velocity from $22.2\,m\,s^{-1}$ forwards to $8.20\,m\,s^{-1}$ forwards. Calculate the change in velocity of Jamelia's car.

6.2 Distance and displacement

BY THE END OF THIS MODULE, YOU SHOULD BE ABLE TO:

- understand that the motion of an object can be simplified by considering its centre of mass
- understand the difference between position, distance and displacement
- calculate the distance travelled by and the displacement of an object.

In order to analyse and communicate ideas about motion, it is important to understand the terms used to describe motion, even in its simplest form. In this module you will learn about some of the terms used to describe **rectilinear** motion, or straight-line motion, such as position, distance, displacement, speed and velocity.

CENTRE OF MASS

When analysing motion, many real-life examples are complex, so you might need to simplify the situation. For example, as a freestyle swimmer travels at a constant speed of $2\,m\,s^{-1}$, their head and torso move forwards at this speed. The motion of their arms, however, is more complex. At times their arms move forwards through the air faster than $2\,m\,s^{-1}$, and at other times they are actually moving backwards through the water.

It is beyond the scope of this course to analyse such a complex motion. However, the motion of the swimmer can be simplified by treating the swimmer as a simple object located at a single point called the **centre of mass**. The centre of mass is the balance point of an object. For a person, the centre of mass is located near the waist. The centres of mass of some everyday objects are shown in Figure 6.2.1.

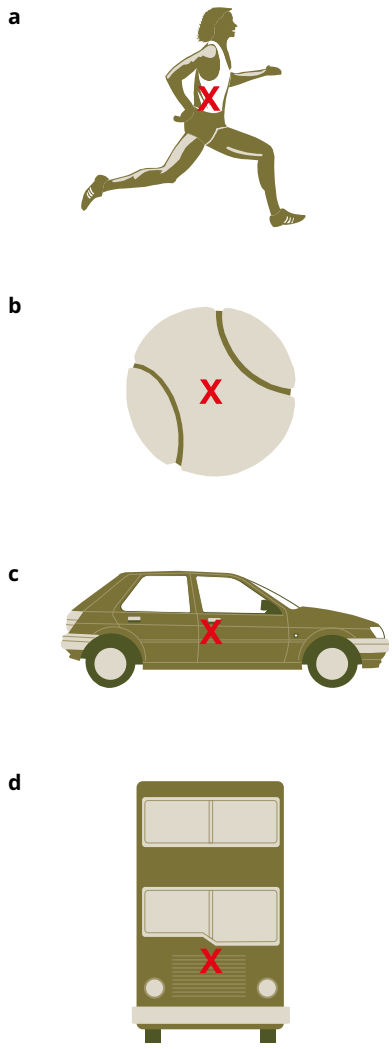


FIGURE 6.2.1 The centre of mass of each object is indicated by a cross.

POSITION, DISTANCE AND DISPLACEMENT

Position

One important term to understand when analysing straight line motion is **position**.

- Position describes the location of an object at a certain point in time with respect to the origin.
- Position is a vector quantity and therefore requires a direction.

Consider a swimmer, Sophie, doing laps in a 50 m pool, as shown in Figure 6.2.2. To simplify her motion, Sophie is treated as a simple point object. The pool can be treated as a one-dimensional number line, with the starting block as the origin. The direction to the right of the starting block is taken to be positive.

In Figure 6.2.2a, Sophie's position as she is warming up behind the starting block is −10 m. The negative sign indicates the direction from the origin, which is to the left. Her position could also be given as 10 m to the left of the starting block.

In Figure 6.2.2b, Sophie's position at the starting block is 0 m.

In Figure 6.2.2c, Sophie's position after swimming half a length of the pool is +25 m or 25 m to the right of the origin.

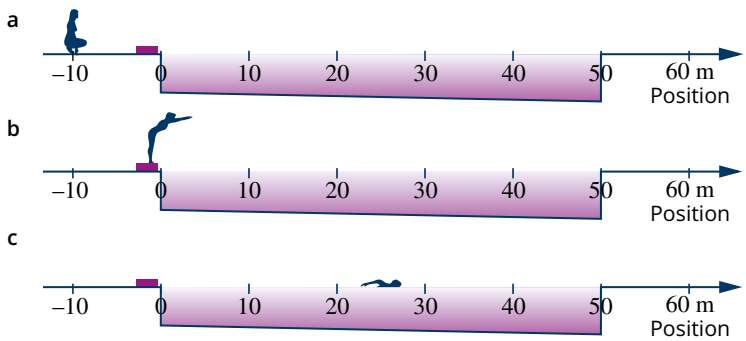


FIGURE 6.2.2 The position of the swimmer is given with reference to the starting block. (a) While warming up, Sophie is at −10 m. (b) When she is on the starting block, her position is zero. (c) After swimming for a short time, she is at a position of +25 m.

Distance travelled

- Distance travelled, *d*, describes the length of the path covered during an object's entire journey.
- Distance travelled is a scalar quantity and is measured in metres (m).

Position describes where an object is at a certain point in time. However, **distance travelled** is how far a body travels during a journey.

In Figure 6.2.2, if Sophie completes three lengths of the pool, the distance travelled during her swim will be:

$$50 + 50 + 50 = 150\,\text{m}$$

The distance travelled is not affected by the direction of the motion. That is, the distance travelled by an object always increases as it moves, regardless of its direction. The tripmeter or odometer of a car or bike measures distance travelled.

Displacement

Displacement is the change in position of an object in a given direction.

Displacement is a vector quantity and is measured in metres (m).

s = final position – initial position

Displacement, *s*, is defined as the change in position of an object. Displacement takes into account only where the motion starts and finishes. The route taken between these points has no effect on displacement. The sign of the displacement indicates the direction in which the position has changed from the start to the end.

Consider the example of Sophie completing one length of the pool. After one lap, the distance travelled is 50 m. Her final position is +50 m and her initial position is 0 m. Her displacement is:

s = final position – initial position
= 50 – 0
= +50 m

Sophie's displacement is 50 m in a positive direction.

Recall that magnitude, units and direction are required for a vector quantity. The distance will be equal to the magnitude of the displacement only if the body is moving in a straight line and does not change direction. If Sophie swims two lengths, her distance travelled will be 100 m: 50 m out and 50 m back. However, her displacement during this swim will be:

s = final position – initial position
= 0 – 0
= 0 m

Even though Sophie has swum 100 m, her displacement is zero because the initial and final positions are the same.

The above formula for displacement is useful if you already know the initial and final positions of a body's motion. An alternative method to determine total displacement, if you know the displacement of each section of the motion, is to add up the individual displacements for each section of motion.

Total displacement = sum of individual displacements

It is important to remember that displacement is a vector and so, when adding displacements, you must obey the rules of vector addition (discussed in Module 6.1).

If Sophie completed two laps, her overall displacement could have been calculated by adding the displacement of each lap:

s = sum of displacements for each lap
= 50 m in the positive direction + 50 m in the negative direction
= 50 + (–50)
= 0 m

6.2 Review

SUMMARY

- The motion of an object travelling in a straight line is known as rectilinear motion.
- Position defines the location of an object with respect to a defined origin.
- Distance travelled, *d*, tells us how far an object has actually travelled. Distance travelled is a scalar.
- Displacement, *s*, is a vector and is defined as the change in position of an object in a given direction:

  s = final position – initial position
- The centre of mass is a single balance point of an object. This point can be used to simplify the motion of an object.

KEY QUESTIONS

Retrieval

1 Define 'displacement' and explain how it differs from distance travelled.

Comprehension

2 A person's distance travelled is 400 m but their displacement is 0 m. Recall an example of how this could happen.

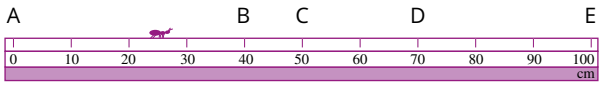
3 A girl swims 10 lengths of a 25 m pool. Determine:

a her distance travelled

b her displacement.

Analysis

4 A somewhat confused ant is walking back and forth along a metre ruler, as show in the figure below. Determine both the size of the displacement and the distance travelled by the ant as it travels on the following paths, taking the right as positive.



a A to B

b C to B

c C to D

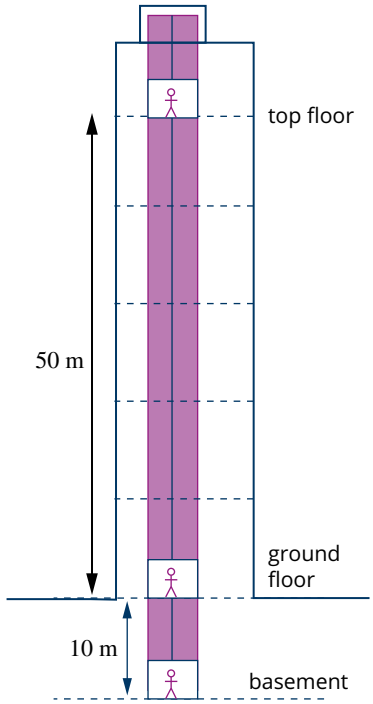
d C to E and then to D

5 During a training ride, a cyclist rides 50.0 km north then 30.0 km south.

a Calculate the distance travelled by the cyclist during the ride.

b Calculate the displacement of the cyclist for this ride.

6 A lift in a city building, shown below, carries a passenger from the ground floor down to the basement, then up to the top floor.



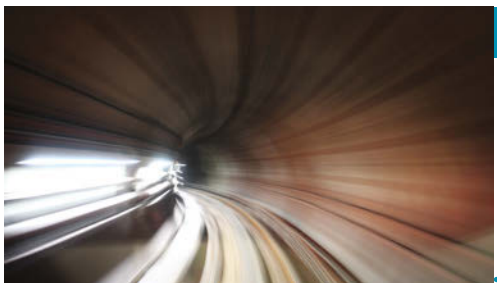
a Calculate the displacement of the lift as it travels from the ground floor to the basement.

b Calculate the displacement of the lift as it travels from the basement to the top floor.

c Calculate the distance travelled by the lift during this entire trip.

d Calculate the displacement of the lift during this entire trip.

6.3 Speed and velocity



BY THE END OF THIS MODULE, YOU SHOULD BE ABLE TO:

- understand the difference between speed and velocity
- understand the difference between instantaneous velocity and average velocity
- calculate the average velocity of an object
- convert between $km\,h^{-1}$ and $m\,s^{-1}$.

For thousands of years, humans have tried to travel at ever greater speeds. This desire has contributed to the development of all sorts of competitive activities, as well as major advances in engineering and design. World records for some of these pursuits are given in Table 6.3.1.

TABLE 6.3.1 World record speeds for a variety of sports or modes of transport

Activity	World record speed ($m\,s^{-1}$)	World record speed ($km\,h^{-1}$)
racehorse	19.7	71
luge	43	140
cricket delivery	44.7	161
waterskiing (barefoot)	68.3	246
tennis serve	73.1	263
train	161	575

- Speed is defined in terms of the rate at which the distance is travelled. Like distance, speed is a scalar. A direction is not required when describing the speed of an object.
- Velocity is defined in terms of the rate at which displacement changes, and so is a vector quantity. A direction should always be given with a velocity.
- The SI unit for speed and velocity is metres per second ($m\,s^{-1}$); kilometres per hour ($km\,h^{-1}$) is also commonly used, so always check the units. See the Skillbuilder on page 215 for practice in converting between the two units.

Speed and velocity are both quantities that give an indication of how quickly the position of an object is changing. Both terms are in common use and are often assumed to have the same meaning. In physics, however, these two terms have different definitions.

Instantaneous speed and velocity

Instantaneous speed and instantaneous velocity give a measure of how fast something is moving at a particular point in time. The speedometer on a car or bike indicates instantaneous speed.

If a speeding car is travelling north and is detected on a police radar gun at $150\,km\,h^{-1}$, it indicates that this car's instantaneous speed is $150\,km\,h^{-1}$, while its instantaneous velocity is $150\,km\,h^{-1}$ north. Notice that the instantaneous speed is equal to the magnitude of the instantaneous velocity, however, the quantity for instantaneous velocity also includes a direction. This is always the case for instantaneous speed and velocity.

Average speed and velocity

Average speed and average velocity both give an indication of how fast an object is moving over a time interval.

Average speed $v_{av} = \frac{\text{total distance}}{\text{time taken}} = \frac{d}{t}$

Average velocity $v_{av} = \frac{\text{displacement}}{\text{time taken}} = \frac{s}{t}$

Average speed is equal to instantaneous speed only when a body is moving in uniform motion (that is, if it moves at a constant speed).

The average speed of a car that takes 30 minutes to travel 20 km from the University of Queensland to Brisbane Airport is 40 km h^{-1}. However, this does not mean that the car travelled the whole distance at this speed. In fact it is more likely that the car was mainly moving at 60 km h^{-1}, but then for some of the time the car would not be moving at all.

A direction (such as north, south, up, down, left, right, positive, negative) must be given when describing a velocity. The direction will always be the same as that of the displacement. Similar to the relationship between distance and displacement, average speed will be equal to the magnitude of average velocity only if the body is moving in a straight line and does not change direction.

For example, in a complete lap of a circular track such as the velodrome shown in Figure 6.3.1, regardless of the average speed, the magnitude of the average velocity will be zero, because the displacement is zero.

FIGURE 6.3.1 Anna Meares won the UCI world championship in 2013. She rode 500 m in a world record time of 32.836 s. Her average speed was 55.6 km h^{-1} but her average velocity was zero.

SKILLBUILDER

Converting units

The SI unit for velocity is m s^{-1}, but km h^{-1} is often used, so it is important to understand how to convert between the two units.

Converting km h^{-1} to m s^{-1}

You should be familiar with 100 km h^{-1}, as it is the speed limit for most freeways and country roads in Australia. Cars that maintain this speed would travel 100 km in 1 hour. There are 1000 metres in 1 kilometre and 3600 seconds in 1 hour (60 s × 60 min), which is the same as travelling 100 000 m in 3600 s.

$$100\,\text{km h}^{-1} = 100 \times 1000\,\text{m h}^{-1}$$
$$= 100000\,\text{m h}^{-1}$$
$$= \frac{100000}{3600}\,\text{m s}^{-1}$$
$$= 27.8\,\text{m s}^{-1}$$

So km h^{-1} can be converted to m s^{-1} by multiplying by $\frac{1000}{3600}$ (or dividing by 3.6).

Converting m s^{-1} to km h^{-1}

A champion Olympic sprinter can run at an average speed of close to 10 m s^{-1}. Each second, the athlete will travel approximately 10 m. At this rate, in 1 hour the athlete would travel:

$10 \times 3600 = 36000\,\text{m} = 36\,\text{km}$

To convert 10 m s^{-1} into km h^{-1}:

$$10\,\text{m s}^{-1} = 10 \times 3600\,\text{m h}^{-1}$$
$$= 36000\,\text{m h}^{-1}$$
$$= \frac{36000}{1000}\,\text{km h}^{-1}$$
$$= 36\,\text{km h}^{-1}$$

So m s^{-1} can be converted to km h^{-1} by multiplying by $\frac{3600}{1000}$ or 3.6.

When converting a speed from one unit to another, it is important to think about the speeds to ensure that your answers make sense. The diagram in Figure 6.3.2 summarises the conversion between units for speed.

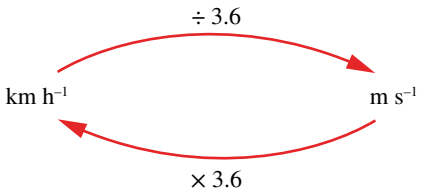


FIGURE 6.3.2 Rules for converting between m s^{-1} and km h^{-1}.

FIGURE 6.3.3 Modern fighter aeroplanes are able to fly at speeds above Mach 1.

Alternative units for speed and distance

Metres per second is the standard unit for measuring speed because it is derived from the standard unit for distance (metres) and the standard unit for time (seconds). However, alternative units are often used to better suit a certain application.

The speed of a boat is usually measured in knots, where 1 knot = 0.51 m s^{-1}. This unit originated in the 17th century, when the speed of sailing vessels would be measured by allowing a rope, with knots tied at regular intervals, to be dragged by the water through a sailor's hands. The speed of the boat could be estimated by counting the number of knots that passed through the sailor's hands, while measuring the time taken for this to happen, and then applying the average speed formula.

The speed of very fast aeroplanes, as shown in Figure 6.3.3, can be measured in Mach numbers. One Mach (referred to as Mach 1) is equal to the speed of sound, which is 340 m s^{-1}. Mach 2 is equal to 680 m s^{-1}, or twice the speed of sound.

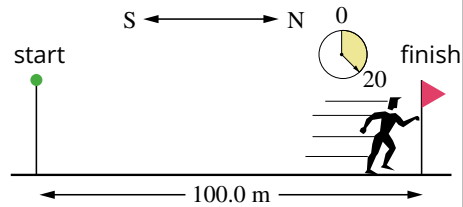
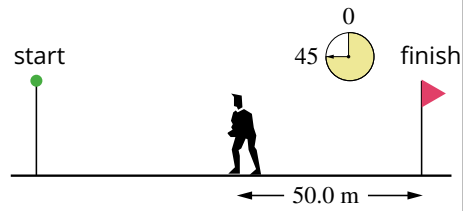
The light-year is an alternative unit for measuring distance. The speed of light in a vacuum is nearly 300 000 km s^{-1}. One light-year is the distance that light travels in one year, which is approximately 9.5×10^{12} km. Because distances between objects in the universe are so large, astronomers use the light-year to measure distances. It takes more than 4 years for light to travel from our nearest star (Alpha Centauri) to Earth. That means the distance from Earth to our nearest star is more than 4 light-years. Light takes approximately 8.5 minutes to travel from the Sun to Earth, so it could be said that the Sun is 8.5 light-minutes away.

Worked example 6.3.1

AVERAGE VELOCITY AND CONVERTING UNITS

Sam is an athlete performing a training routine by running back and forth along a straight stretch of running track. He jogs 100.0 m north in 20.0 s, then turns and walks 50.0 m south for a further 25 s before stopping.

a Calculate Sam's average velocity in m s^{-1}.

Thinking	Working
Calculate the displacement. Remember total displacement is the sum of individual displacements. Sam's total journey consists of two displacements: 100.0 north and then 50.0 m south.	s = sum of displacements = 100.0 m north + 50.0 m south = 100.0 + (–50.0) = +50.0 m or 50.0 m north  
Work out the total time taken for the journey.	20.0 + 25 = 45 s

Substitute the values into the velocity equation. Displacement is 50.0 m north. Time taken is 45 s.	$v_{av} = \frac{s}{t}$ $= \frac{50.0}{45}$ $= 1.1\,m\,s^{-1}$
Velocity is a vector, so a direction must be given.	$1.1\,m\,s^{-1}$ north

b Calculate the magnitude of Sam's average velocity in $km\,h^{-1}$.

Thinking	Working
Convert from $m\,s^{-1}$ to $km\,h^{-1}$ by multiplying by 3.6.	$v_{av} = 1.1\,m\,s^{-1}$ $= 1.1 \times 3.6$ $= 4.0\,km\,h^{-1}$ north
As the magnitude of velocity is needed, direction is not required in this answer.	Magnitude of $v_{av} = 4.0\,km\,h^{-1}$

c Calculate Sam's average speed in $m\,s^{-1}$.

Thinking	Working
Calculate the distance. Remember distance is the length of the path covered in the entire journey. The direction does not matter. Sam travels 100.0 m in one direction and then 50.0 m in the other direction.	$d = 100.0 + 50.0$ $= 150.0$
Work out the total time taken for the journey.	$20.0 + 25 = 45\,s$
Substitute the values into the speed equation. Distance is 150.0 m. Time taken is 45 s.	$v_{av} = \frac{d}{t}$ $= \frac{150.0}{45}$ $= 3.3\,m\,s^{-1}$

d Calculate Sam's average speed in $km\,h^{-1}$.

Thinking	Working
Convert from $m\,s^{-1}$ to $km\,h^{-1}$ by multiplying by 3.6.	$v_{av} = 3.3\,m\,s^{-1}$ $= 3.3 \times 3.6$ $= 12\,km\,h^{-1}$
Speed is not a vector, so a direction is not given.	$12\,km\,h^{-1}$

➤ Try yourself 6.3.1

AVERAGE VELOCITY AND CONVERTING UNITS

Sally is an athlete performing a training routine by running back and forth along a straight stretch of running track. She jogs 100.0 m west in 20.0 s, then turns and walks 160.0 m east in a further 45 s before stopping.

a Calculate Sally's average velocity in $m\,s^{-1}$.

b Calculate the magnitude of Sally's average velocity in $km\,h^{-1}$.

c Calculate Sally's average speed in $m\,s^{-1}$.

d Calculate Sally's average speed in $km\,h^{-1}$.

6.3 Review

SUMMARY

- The average speed of a body, v_{av}, is defined as the rate of change of distance and is a scalar quantity:

$$\text{average speed } v_{av} = \frac{\text{total distance}}{\text{time taken}} = \frac{d}{t}$$

- The average velocity of a body, v_{av}, is defined as the rate of change of displacement and is a vector quantity:

$$\text{average velocity } v_{av} = \frac{\text{displacement}}{\text{time taken}} = \frac{s}{t}$$

- The SI unit for both speed and velocity is metres per second ($m\,s^{-1}$).
- To convert from $m\,s^{-1}$ to $km\,h^{-1}$, multiply by 3.6.
- To convert from $km\,h^{-1}$ to $m\,s^{-1}$, divide by 3.6.
- The instantaneous velocity of an object relates to the position of the object at a particular point in time.
- The average velocity of an object relates to the total displacement of the object over a set period of time.

KEY QUESTIONS

Retrieval

1 State the formula for:
- **a** average speed
- **b** average velocity.

Comprehension

2 Explain the difference between speed and velocity.

Analysis

3 A car travelling at a constant speed was timed over 400.0 m and was found to cover the distance in 12 s.
- **a** Calculate the average speed of the car.
- **b** The driver was distracted and his reaction time was 0.75 s before applying the brakes. Calculate how far the car travelled in this time.

4 A cyclist travels 25 km in 90.0 minutes.
- **a** Calculate her average speed in $km\,h^{-1}$.
- **b** Calculate her average speed in $m\,s^{-1}$.

5 Liam pushes his toy truck 5.0 m east, then stops it and pushes it 4.0 m west. The entire motion takes 10.0 s.
- **a** Calculate the average speed of the truck.
- **b** Calculate the average velocity of the truck.

6 An athlete in training for a marathon runs 10.0 km north along a straight road before realising that she has dropped her drink bottle. She turns around and runs back 3.0 km to find her bottle, then resumes running in the original direction. After running for 1.5 h, the athlete reaches 15.0 km from her starting position and stops.
- **a** Calculate the distance travelled by the athlete during the run.
- **b** Calculate the athlete's displacement during the run.
- **c** Calculate the average speed of the athlete in $km\,h^{-1}$.
- **d** Calculate the athlete's average velocity in $km\,h^{-1}$.

6.4 Acceleration

BY THE END OF THIS MODULE, YOU SHOULD BE ABLE TO:

- understand acceleration as a change in velocity over a particular time period
- calculate the acceleration of an object.

If you have been on a train as it pulled out of the station, you have experienced acceleration. If you have been in an aircraft as it's taken off from a runway, you will have experienced a much greater acceleration. Astronauts and fighter pilots experience enormous accelerations that would make an untrained person lose consciousness. **Acceleration**, which is a measure of how quickly velocity changes, will be discussed in this module.

FINDING THE CHANGE IN VELOCITY AND SPEED

A car speeding away as the traffic lights turn green, a runner stopping at the end of a race, a bouncing tennis ball and a rollercoaster carriage on a ride, all involve changing velocities. If the initial velocity and final velocity of an object are known, then the change in velocity can be calculated.

To find the change, Δ, in any physical quantity, including speed and velocity, the initial value is taken away from the final value. Vector subtraction was covered in detail in Module 6.2.

Change in speed is the final speed minus the initial speed:

$\Delta v = v - u$

where

u is the initial speed ($m\,s^{-1}$)

v is the final speed ($m\,s^{-1}$)

Δv is the change in speed ($m\,s^{-1}$)

Speed is a scalar, so direction is not required.

Change in velocity is the final velocity minus the initial velocity:

$v = v - u$

where

u is the initial velocity ($m\,s^{-1}$)

v is the final velocity ($m\,s^{-1}$)

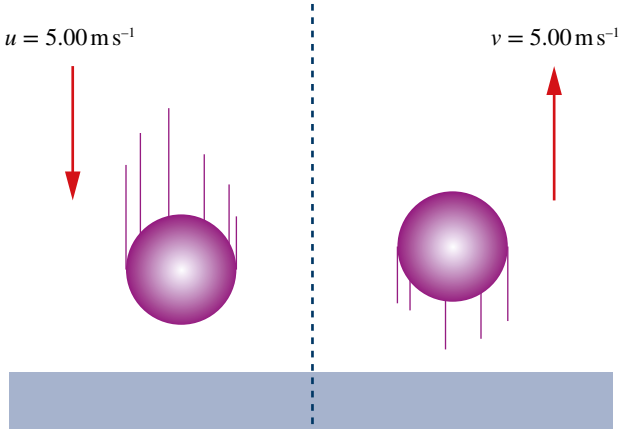
Δv is the change in velocity ($m\,s^{-1}$)

Velocity is a vector, so perform a vector subtraction. As for all vectors, direction is required.

Worked example 6.4.1

CHANGE IN SPEED AND VELOCITY 1

A golf ball is dropped onto a concrete floor and strikes the floor at $5.00\,m\,s^{-1}$. It then rebounds at $5.00\,m\,s^{-1}$.



a Calculate the change in speed of the ball.

Thinking	Working
Find the values for the initial speed and the final speed of the ball.	$u = 5.00\,m\,s^{-1}$ $v = 5.00\,m\,s^{-1}$
Substitute the values into the change in speed equation: $\Delta v = v - u$	$\Delta v = v - u$ $= (5.00) - (5.00)$ $= 0\,m\,s^{-1}$

b Calculate the change in velocity of the ball.

Thinking	Working
Velocity is a vector. Apply the sign convention to replace the directions.	$u = 5.00\,m\,s^{-1}$ down $= -5.00\,m\,s^{-1}$ $v = 5.00\,m\,s^{-1}$ up $= +5.00\,m\,s^{-1}$
As this is a vector subtraction, reverse the direction of u to get $-u$.	$u = -5.00\,m\,s^{-1}$ $-u = +5.00\,m\,s^{-1}$
Substitute the values into the change in velocity equation: $v = v + (-u)$	$v = v + (-u)$ $= (+5.00) + (+5.00)$ $= +10.0\,m\,s^{-1}$
Apply the sign convention to describe the direction.	$v = 10.0\,m\,s^{-1}$ up

➤ Try yourself 6.4.1

CHANGE IN SPEED AND VELOCITY 1

A golf ball is dropped onto a concrete floor and strikes the floor at $9.00\,m\,s^{-1}$. It then rebounds at $7.00\,m\,s^{-1}$.

a Calculate the change in speed of the ball.

b Calculate the change in velocity of the ball.

ACCELERATION

Consider the following information about the velocity of a car that starts from rest, as shown in the Figure 6.4.1. The velocity of the car (Figure 6.4.1) increases by $10\,km\,h^{-1}$ each second. In other words, its velocity changes by $+10\,km\,h^{-1}$ per second. This is stated as an acceleration of +10 kilometres per hour per second or $+10\,km\,h^{-1}s^{-1}$. More commonly in physics, velocity information is given in metres per second.

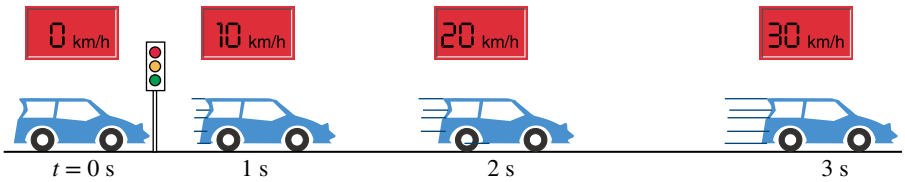


FIGURE 6.4.1 The car increases in velocity from $0\,km\,h^{-1}$ to $30\,km\,h^{-1}$.

The athlete in Figure 6.4.2 below takes 3 seconds to come to a stop at the end of a race.

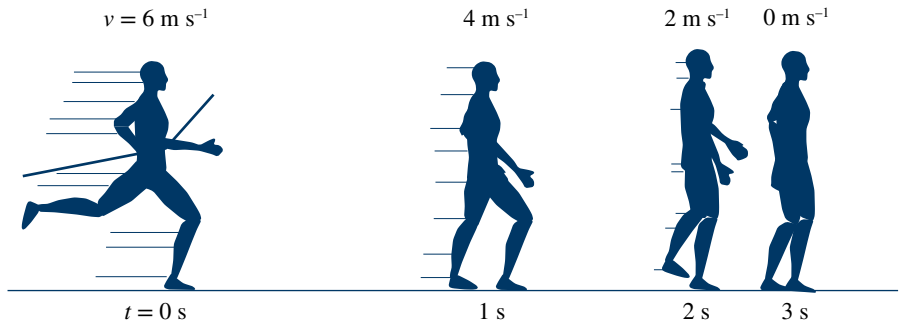


FIGURE 6.4.2 The velocity of the athlete changes by $-2\,m\,s^{-1}$ each second. The acceleration is $-2\,m\,s^{-2}$.

The velocity of the athlete changes by $-2\,m\,s^{-1}$ each second, so the acceleration is –2 metres per second per second. This is usually expressed as –2 metres per second squared or $-2\,m\,s^{-2}$.

A negative acceleration can mean that the object is slowing down in the direction of travel, as is the case with the athlete in Figure 6.4.2. A negative acceleration can also mean speeding up but in the opposite direction.

Acceleration is a vector quantity, so vector diagrams can be used to calculate resultant accelerations of an object.

Average acceleration

As with speed and velocity, the average acceleration of an object can also be calculated.

Average acceleration, a_{av}, is the rate of change of velocity:

$$a_{av} = \frac{\text{change in velocity}}{\text{time taken}}$$
$$= \frac{v}{t}$$
$$= \frac{v-u}{t}$$

where

v is the final velocity ($m\,s^{-1}$)

u is the initial velocity ($m\,s^{-1}$)

Δt is the time interval (s).

Worked example 6.4.2

CHANGE IN SPEED AND VELOCITY 2

A golf ball is dropped onto a concrete floor and strikes the floor at $5.0\,m\,s^{-1}$. It then rebounds at $5.0\,m\,s^{-1}$. The contact with the floor lasts for a time of 25 ms.
Calculate the average acceleration of the ball during its contact with the floor.

Thinking	Working
Note the values you will need in order to find the average acceleration (initial velocity, final velocity and time). Let up be the positive direction. Convert ms into s by dividing by 1000.	$u = -5.0\,m\,s^{-1}$ $-u = 5.0\,m\,s^{-1}$ $v = 5.0\,m\,s^{-1}$ $v = v + (-u)$ $= (+5.0) + (+5.0)$ $= +10.0\,m\,s^{-1}$ $\Delta t = 25\,ms$ $= 0.025\,s$
Substitute the values into the average acceleration equation.	$a_{av} = \frac{v}{t}$ $= \frac{10.0}{0.025}$ $= 4.0 \times 10^2\,m\,s^{-2}$
Acceleration is a vector, so you must include a direction in your answer.	$a_{av} = 4.0 \times 10^2\,m\,s^{-2}$ up

➤ Try yourself 6.4.2

CHANGE IN SPEED AND VELOCITY 2

A golf ball is dropped onto a concrete floor and strikes the floor at $9.0\,m\,s^{-1}$. It then rebounds at $7.0\,m\,s^{-1}$. The contact time with the floor is 35 ms.
Calculate the average acceleration of the ball during its contact with the floor.

6.4 Review

SUMMARY

- Change in speed is a scalar calculation:
  Δv = final speed – initial speed = $v - u$
- Change in velocity is a vector calculation:
  Δv = final velocity – initial velocity = $v - u$
- Acceleration is a vector. The average acceleration of a body, a_{av}, is defined as the rate of change of velocity:

$$a_{av} = \frac{\text{change in velocity}}{\text{time taken}}$$
$$= \frac{v}{t}$$
$$= \frac{v-u}{t}$$

- Acceleration is measured in metres per second per second ($m\,s^{-2}$) or metres per second squared.

KEY QUESTIONS

Retrieval

1 State an expression for the average acceleration of an object:
- **a** in words
- **b** in terms of its change in velocity
- **c** in terms of its initial and final velocity, and time.

Comprehension

2 A radio-controlled car is travelling east at $10.0\,km\,h^{-1}$. It hits some sand and slows down to $3.0\,km\,h^{-1}$ east. Describe its change in speed.

Analysis

3 A lump of putty falls vertically at $5.0\,m\,s^{-1}$ and stops dead when it hits the floor it. Calculate its change in velocity during the collision.

4 A ping-pong ball falls vertically at $5.0\,m\,s^{-1}$. When it hits the floor, it rebounds at $3.0\,m\,s^{-1}$ up. Calculate the change in velocity during the bounce.

5 Ashley runs north on a soccer field at $7.5\,m\,s^{-1}$. He slides along the ground and stops in 1.5 s. Calculate his average acceleration as he slides to a stop.

6 Olivia launches a model rocket vertically and it reaches a speed of $150\,km\,h^{-1}$ after 3.5 s. Calculate the magnitude of its average acceleration in $km\,h^{-1}\,s^{-1}$.

7 A squash ball travelling east at $25\,m\,s^{-1}$ strikes the front wall of the court and rebounds at $15\,m\,s^{-1}$ west. The contact time between the wall and the ball is 0.050 s. Use vector diagrams, where appropriate, to help you with your calculations.
- **a** Calculate the change in speed of the ball.
- **b** Calculate the change in velocity of the ball.
- **c** Calculate the magnitude of the average acceleration of the ball during its contact with the wall.

8 A greyhound starts from rest and accelerates uniformly. Its velocity after 1.2 s is $8.0\,m\,s^{-1}$ south.
- **a** Calculate the change in speed of the greyhound.
- **b** Calculate the change in velocity of the greyhound.
- **c** Calculate the magnitude of the acceleration of the greyhound.

6.5 Equations of motion

BY THE END OF THIS MODULE, YOU SHOULD BE ABLE TO:

- understand, derive and apply equations of motion for objects travelling in a straight line with uniform acceleration
- select the correct equation of motion to use for the known variables
- understand and analyse vertical motion of an object.

A graph is an excellent way of representing motion because it provides a great deal of information that is easy to interpret. However, a graph is time-consuming to draw and sometimes values have to be estimated rather than precisely calculated.

In the previous module, graphs of motion were used to determine quantities such as displacement, velocity and acceleration. This module examines a more powerful and precise method of solving problems involving constant or uniform acceleration. This method involves the use of a series of equations that can be derived from the basic definitions developed earlier.

DERIVING THE EQUATIONS

Consider an object moving in a straight line with an initial velocity, u, and a uniform acceleration, a, for a time interval, Δt. As u, v and a are vectors, and the motion is limited to one dimension, the sign and direction convention of right as positive and left as negative can be used. After a period of time, Δt, the object has changed its velocity from an initial velocity of u and is now travelling with a final velocity of v. Its acceleration will be given by:

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

If the initial time is 0 s and the final time is t s, then $\Delta t = t$. The above equation can then be rearranged as:

$$v = u + at$$

The average velocity of the object is:

$$v_{av} = \frac{\text{displacement}}{\text{time taken}} = \frac{s}{t}$$

When acceleration is uniform, average velocity, v_{av}, can also be found as the average of the initial and final velocities:

$$v_{av} = \frac{1}{2}(u+v)$$

This relationship is shown graphically in Figure 6.5.1.

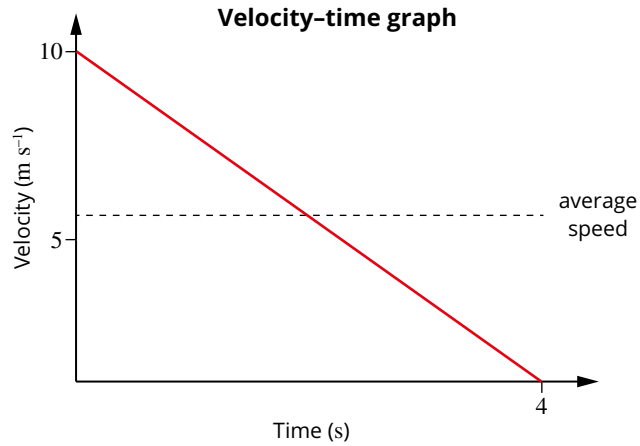


FIGURE 6.5.1 Uniform acceleration as displayed by a v–t graph.

So equating $v_{av} = \frac{s}{t}$ and $v_{av} = \frac{1}{2}(u+v)$:

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

This can be simplified to give:

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

A graph describing motion with constant acceleration is shown in Figure 6.5.2. For constant acceleration, the velocity is increasing by the same amount in each time interval, so the gradient of the v–t graph is constant.

The displacement, s, of the body is given by the area under the velocity–time graph. The area under the velocity–time graph, as shown in Figure 6.5.2, is given by the combined area of the rectangle and the triangle:

$$\text{Area} = s = ut + \frac{1}{2} \times (v-u) \times t$$

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

then $v - u = at$, and this can be substituted for $v - u$:

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

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

Rewriting $v = u + at$ with u as the subject gives:

$$u = v - at$$

Rewriting $v = u + at$ with t as the subject gives:

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

Now, if this is substituted into $s = \frac{1}{2}(u+v)t$:

$$s = \frac{u+v}{2} \times \frac{v-u}{a}$$

$$= \frac{v^2 - u^2}{2a}$$

Finally, transposing this gives:

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

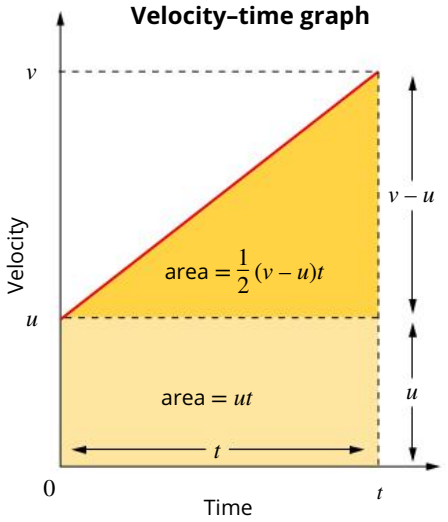


FIGURE 6.5.2 The area under a v–t graph broken up into a rectangle and a triangle

These equations are commonly used to solve problems in which acceleration is constant (or uniform).

$v = u + at$

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

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

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

where

- s is the displacement (m)
- u is the initial velocity ($m\,s^{-1}$)
- v is the final velocity ($m\,s^{-1}$)
- a is the acceleration ($m\,s^{-1}$)
- t is the time taken (s)

SOLVING PROBLEMS USING EQUATIONS

When solving problems using these equations, it is important to think about the problem and try to visualise what is happening. Follow the steps below.

1 Draw a simple diagram of the situation.
2 Write down the information that has been given in the question. You might like to use the word 'suvat' as a memory trick to help you remember to list the variables in the order s, u, v, a and t. Use a sign convention to assign positive and negative values to indicate directions. Convert all units to SI form.
3 Select the equation that matches your data. It should include three values that you know, and the one value that you want to solve.
4 Use the appropriate number of significant figures in your answer.
5 Include units with the answer and specify a direction if the quantity is a vector.

Worked example 6.5.1

USING THE EQUATIONS OF MOTION

A snowboarder in a race is travelling $10.0\,m\,s^{-1}$ north as he crosses the finishing line. He then decelerates uniformly, coming to a stop over a distance of 20.0 m.

a Calculate the acceleration of the snowboarder as he comes to a stop.

Thinking	Working
Write down the known quantities as well as the quantity you are finding. Apply the sign convention that north is positive and south is negative. Take all the information from the question. 'Coming to a stop' means that the final velocity is zero. Use equations for constant acceleration.	$s = +20.0\,m$ $u = +10.0\,m\,s^{-1}$ $v = 0\,m\,s^{-1}$ $a = ?$
Identify the correct equation to use.	$v^2 = u^2 + 2as$
Substitute known values into the equation and solve for a. Include units with the answer.	$0^2 = 10.0^2 + 2 \times a \times 20.0$ $0 = 100.0 + 40.0a$ $-100.0 = 40.0a$ $a = \frac{-100.0}{40.0}$ $= -2.5\,m\,s^{-2}$
Use the sign convention to state the answer with its direction.	$a = 2.5\,m\,s^{-2}$ south

b Determine how long he takes to come to a stop.

Thinking	Working
Write down the known quantities as well as the quantity you are finding. Apply the sign convention that north is positive and south is negative. Take all the information from the question. 'Coming to a stop' means that the final velocity is zero. Use equations for constant acceleration.	$s = +20.0\,m$ $u = +10.0\,m\,s^{-1}$ $v = 0\,m\,s^{-1}$ $a = -2.5\,m\,s^{-2}$ $t = ?$

Identify the correct equation to use. You now know four values, so any equation involving t will work.	$v = u + at$
Substitute known values into the equation and solve for t. Include units with the answer.	$v = u + at$ $0 = 10.0 + (-2.5) \times t$ $-10.0 = -2.5t$ $t = \frac{-10.0}{-2.5}$ $= 4.0\,\text{s}$

c What is the average velocity of the snowboarder as he comes to a stop?

Thinking	**Working**
Write down the known quantities as well as the quantity that you are finding. Apply the sign convention that north is positive and south is negative. The acceleration is constant, so you only need to find the average of the final and initial speeds.	$u = +10.0\,\text{m s}^{-1}$ $v = 0\,\text{m s}^{-1}$ $v_{av} = ?$
Identify the correct equation to use.	$v_{av} = \frac{1}{2}(u+v)$
Substitute known values into the equation and solve for v_{av}. Include units with the answer.	$v_{av} = \frac{1}{2}(u+v)$ $= \frac{1}{2}(0+10.0)$ $= 5.0\,\text{m s}^{-1}$
Use the sign convention to state the answer with its direction.	$v_{av} = 5.0\,\text{m s}^{-1}$ north

➤ Try yourself 6.5.1

USING THE EQUATIONS OF MOTION

A snowboarder in a race is travelling $15\,\text{m s}^{-1}$ east as she crosses the finishing line. She then decelerates uniformly until coming to a stop over a distance of 30.0 m.

a Calculate the acceleration of the snowboarder as she comes to a stop.

b Determine how long she takes to come to a stop.

c Calculate the average velocity of the snowboarder as she comes to a stop.

FIGURE 6.5.3 The time elapsed between each image of the free-falling apple is the same but the distance it travels increases, which shows the apple is accelerating. Without air resistance, this rate of acceleration is the same for all objects.

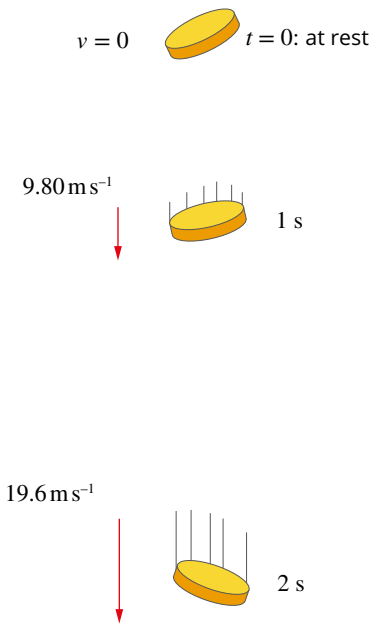


FIGURE 6.5.4 A falling coin

VERTICAL MOTION

Until 500 years ago, it was widely believed that the heavier the object, the faster it would fall. This was the theory of Aristotle, and it lasted for 2000 years until the end of the Middle Ages. In the 17th century, the Italian scientist Galileo conducted experiments that showed that the mass of the object did not affect the rate at which it fell, as long as **air resistance** was not a factor.

It is now known that falling objects speed up because of gravity. Many people still think that heavier objects fall faster than light objects. This is not the case, but the confusion arises because of the effects of air resistance. This module examines the motion of falling objects.

Analysing vertical motion

Air resistance affects some falling objects to a large extent, such as feathers and balloons. This is why these objects do not speed up much as they fall. However, if air resistance can be ignored, all **free-falling** bodies near the Earth's surface will move with an equal downwards acceleration. The image in Figure 6.5.3 shows that the apple is accelerating as it falls, because the distance travelled by the apple between each photograph increases. In a vacuum, this rate of acceleration would be the same for a feather, a bowling ball, or any other object; the mass of the object does not matter.

At the Earth's surface, the acceleration due to gravity, g, is $9.80\,m\,s^{-2}$ down and does not depend on whether the body has been thrown upwards or is falling down.

For example, a coin that is dropped from rest will be moving at $9.80\,m\,s^{-1}$ after 1 s, at $19.6\,m\,s^{-1}$ after 2 s and so on. Each second its speed increases by $9.80\,m\,s^{-1}$. The motion of a falling coin is illustrated in Figure 6.5.4.

However, if the coin was launched straight up at $19.6\,m\,s^{-1}$, then after 1 s its speed would be $9.80\,m\,s^{-1}$, and after 2 s it would be stationary. In other words, each second it would slow down by $9.80\,m\,s^{-1}$. The motion of a coin thrown vertically upwards is shown in Figure 6.5.5.

So, regardless of whether the coin is falling or has been tossed, its speed changes at the same rate. The speed of the falling coin increases by $9.80\,m\,s^{-1}$ each second and the speed of the rising coin decreases by $9.80\,m\,s^{-1}$ each second. That means that the acceleration of the coin due to gravity is $9.80\,m\,s^{-2}$ downwards in both cases.

The acceleration of a free-falling body is constant, so it is appropriate to use the equations for uniform acceleration. It is necessary to specify whether up or down is positive when doing these problems. You can simply follow the mathematical convention of regarding up as positive, which would mean the acceleration due to gravity would always be $-9.80\,m\,s^{-2}$.

Worked example 6.5.2

VERTICAL MOTION

A construction worker accidentally knocks a brick from a building so that it falls vertically a distance of 50.0 m to the ground.
Use $g = -9.80\,m\,s^{-2}$ and ignore air resistance when answering these questions.

a Calculate how long it takes for the brick to fall halfway, to 25 m.

Thinking	Working
Write down the values of the quantities that are known and what you are finding. Apply the sign convention that up is positive and down is negative.	The brick starts at rest so $u = 0$. To fall halfway: $s = -25\,m$ $u = 0\,m\,s^{-1}$ $a = -9.80\,m\,s^{-2}$ $t = ?$

Select the equation for uniform acceleration that best fits the data you have.	$s = ut + \frac{1}{2}at^2$
Substitute known values into the equation and solve for t. Think about whether the value seems reasonable.	$-25 = 0 \times t + \frac{1}{2} \times (-9.80) \times t^2$ $= -4.90t^2$ $t = \sqrt{\frac{-25}{-4.90}}$ $= 2.3\,\text{s}$

b Calculate how long it takes the brick to fall all the way to the ground.

Thinking	Working
Write down the values of the quantities that are known and what you are finding. Apply the sign convention that up is positive and down is negative.	To fall the whole way: $s = -50.0\,\text{m}$ $u = 0\,\text{m s}^{-1}$ $a = -9.80\,\text{m s}^{-1}$ $t = ?$
Identify the correct equation of uniform acceleration to use.	$s = ut + \frac{1}{2}at^2$
Substitute known values into the equation and solve for t. Think about whether the value seems reasonable. Notice that the brick takes 2.3 s to travel the first 25 m and only 0.9 s to travel the final 25 m. This is because it is accelerating.	$-50 = 0 \times t + \frac{1}{2} \times (-9.80) \times t^2$ $-50 = -4.9t^2$ $t = \sqrt{\frac{-50}{-4.9}}$ $= 3.2\,\text{s}$

c Calculate the speed of the brick as it hits the ground.

Thinking	Working
Write down the values of the quantities that are known and what you are finding. Apply the sign convention that up is positive and down is negative	$s = -50.0\,\text{m}$ $u = 0\,\text{m s}^{-1}$ $v = ?$ $a = -9.80\,\text{m s}^{-1}$ $t = 3.2\,\text{s}$
Identify the correct equation to use. You now know four values, so any equation involving v will work.	$v = u + at$
Substitute known values into the equation and solve for v. Think about whether the value seems reasonable.	$v = 0 + (-9.80) \times 3.2$ $= -31\,\text{m s}^{-1}$
Use the sign and direction convention to describe the direction of the final velocity.	$v = -31\,\text{m s}^{-1}$ or $31\,\text{m s}^{-1}$ downwards

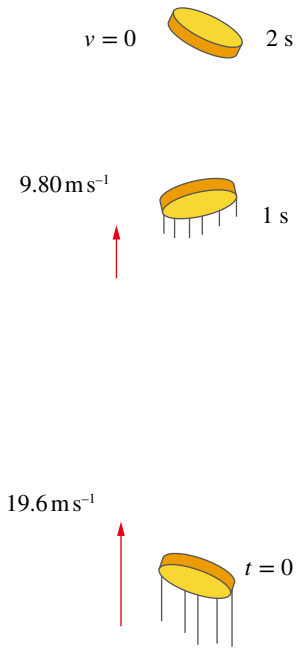


FIGURE 6.5.5 A coin thrown vertically upwards

➤ Try yourself 6.5.2

VERTICAL MOTION

A construction worker accidentally knocks a hammer from a building so that it falls vertically a distance of 60.0 m to the ground. Use $g = -9.80\,m\,s^{-2}$ and ignore air resistance when answering these questions.

a Calculate how long it takes the hammer to fall halfway, to 30.0 m.

b Calculate how long it takes the hammer to fall all the way to the ground.

c Determine the speed of the hammer as it hits the ground.

When an object is thrown vertically up into the air, it will eventually reach a point where it stops momentarily before returning back down. So the velocity of the object decreases as the object rises, becomes zero at the maximum height, and then increases again as the object falls. Throughout this motion, however, the object is still in the same gravitational field, so g remains at $-9.80\,m\,s^{-2}$ throughout the journey. Knowing that the velocity of an object thrown in the air is zero at the top of its flight allows you to calculate the maximum height reached.

6.5 Review

SUMMARY

- The following equations can be used for situations with constant acceleration:
- $v = u + at$
- $s = \frac{1}{2}(u + v)t$
- $s = ut + \frac{1}{2}at^2$
- $v^2 = u^2 + 2as$
- A sign and direction convention for motion in one dimension needs to be used with these equations.
- If air resistance can be ignored, all bodies falling freely near the Earth will move with the same constant acceleration.
- The acceleration due to gravity is represented by g and is equal to $9.80\,m\,s^{-2}$ in the direction towards the centre of Earth.
- The equations for uniform acceleration can be used to solve vertical motion problems. It is necessary to specify whether up or down is positive.

KEY QUESTIONS

Retrieval

1 Recall an equation of motion in terms of the following variables:

a displacement, final velocity, acceleration and time

b displacement, initial velocity, final velocity and time

c final velocity, initial velocity, acceleration and time

e time, acceleration, initial velocity and displacement

f displacement, initial velocity, final velocity, acceleration.

Comprehension

2 A cyclist has a uniform acceleration as he rolls down a hill. His initial speed is $5.00\,m\,s^{-1}$, he travels a distance of 30.0 m and his final speed is $18.0\,m\,s^{-1}$. Identify the equation of motion that should be used to determine his acceleration.

For the remaining questions, ignore the effects of air resistance and assume that the acceleration due to gravity is $9.80\,m\,s^{-2}$ unless instructed otherwise.

3 Maryanne leans over the edge of the Eiffel Tower and knocks her sunglasses off. Describe the acceleration of her sunglasses as they fall.

Analysis

4 A window cleaner working on the Infinity tower accidentally drops her mobile phone. The phone falls vertically towards the ground with an acceleration of $9.80\,m\,s^{-2}$

a Determine the speed of the phone after 3.0 s.

b Calculate how fast the phone is moving after it has fallen 30.0 m.

c Calculate the average velocity of the phone during a fall of 30.0 m.

5 A super ball is bounced so that it travels straight up into the air, reaching its highest point after 1.5 s.
- **a** Calculate the velocity of the ball as it reaches its highest point.
- **b** Calculate the initial speed of the ball just as it leaves the ground.
- **c** Determine the maximum height reached by the ball.

6 A book is knocked off a bench and falls vertically to the floor. It takes 0.40 s to fall to the floor.
- **a** Determine the book's speed as it lands.
- **b** Determine the height from which the book fell.
- **c** Calculate how far the book fell during the first 0.20 s.
- **d** Calculate how far the book fell during the final 0.20 s.

7 While celebrating her birthday, Bindi pops a party popper. The lid travels vertically into the air. Bindi is a keen physics student and notices that the lid takes 4.0 s to return to its starting position.
- **a** Calculate how long it takes the lid to reach its maximum height.
- **b** Calculate how fast the lid was travelling initially.
- **c** Determine the maximum height reached by the lid.
- **d** Determine the velocity of the lid as it returned to its starting point.

8 A new-model Subaru car travels with a uniform acceleration on a racetrack. It starts from rest and covers 400.0 m in 16 s.
- **a** Calculate the magnitude of its average acceleration during this time.
- **b** Calculate the final speed of the car in $m\,s^{-1}$.
- **c** Determine the car's final speed in $km\,h^{-1}$.

9 A hybrid car starts from rest and accelerates uniformly in a positive direction for 8.0 s. It reaches a final speed of $16\,m\,s^{-1}$.
- **a** Calculate the magnitude of the acceleration of the car.
- **b** Calculate the magnitude of the average velocity of the car.
- **c** Calculate the distance travelled by the car.

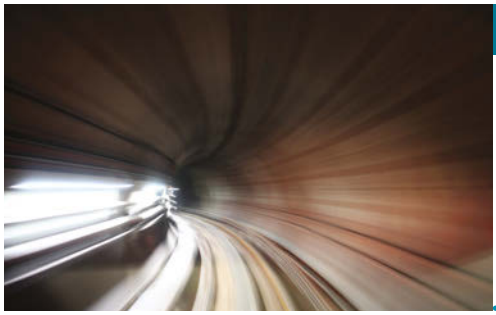
10 During its launch phase, a space rocket accelerates uniformly from rest to $160\,m\,s^{-1}$ upwards in 4.0 s, then travels with a constant speed of $160\,m\,s^{-1}$ for the next 5.0 s.
- **a** Calculate the initial acceleration of the rocket.
- **b** Calculate how far (in km) the rocket travels in this 9.0 s period.
- **c** Calculate the final speed of the rocket in $km\,h^{-1}$.
- **d** Calculate the average speed of the rocket during the first 4.0 s.
- **e** Calculate the average speed of the rocket during the 9.0 s motion.

11 While overtaking another cyclist, Ben increases his speed uniformly from $4.2\,m\,s^{-1}$ to $6.7\,m\,s^{-1}$ east over a time interval of 0.50 s.
- **a** Calculate the magnitude of Ben's average acceleration during this time.
- **b** Determine how far Ben travels while overtaking.
- **c** Determine Ben's average speed during this time.

12 A diver plunges headfirst into a diving pool while travelling at $28\,m\,s^{-1}$ downwards. The diver enters the water and stops after a distance of 4.0 m. Consider the diver to be a single point located at her centre of mass and assume her acceleration through the water to be uniform.
- **a** Calculate the magnitude of the average acceleration of the diver as she travels through the water.
- **b** Calculate how long the diver takes to come to a stop.
- **c** Calculate the speed of the diver after she has dived through 2.0 m of water.

13 A car is travelling along a straight road at $75\,km\,h^{-1}$ east. In an attempt to avoid an accident, the motorist has to brake suddenly and stop the car.
- **a** Calculate the car's initial speed in $m\,s^{-1}$.
- **b** Determine the distance the car travels while the driver is reacting to apply the brakes, if the reaction time of the motorist is 0.25 s.
- **c** Once the brakes are applied, the car has an acceleration of $-6.0\,m\,s^{-2}$. Determine how far the car travels while coming to a stop.
- **d** Calculate the total distance the car travels from the time the driver first notices the danger to when the car comes to a stop.

6.6 Graphs of motion



BY THE END OF THIS MODULE, YOU SHOULD BE ABLE TO:

- interpret position–time graphs to describe an object's motion and its velocity
- interpret velocity–time graphs to describe an object's motion, its acceleration, and its displacement and distance travelled
- interpret acceleration–time graphs to describe an object's motion and its average velocity.

At times, even the motion of an object travelling in a straight line can be complicated. The object may travel forwards or backwards, speed up or slow down, or even stop. This information can be presented in graphical form.

The main advantage of a graph compared with a table is that it allows the nature of the motion to be seen clearly. Information that is contained in a table is not as readily accessible or as easy to interpret as information presented graphically. This module examines position–time, velocity–time and acceleration–time graphs.

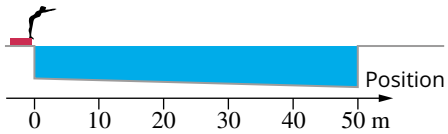


FIGURE 6.6.1 The swimmer stands at the end of a 50 m swimming pool.

POSITION–TIME (x–t) GRAPHS

A position–time graph indicates the position, x, of an object at any time, t, for motion that occurs over an extended time interval. However, the graph can also provide additional information.

Consider Sophie, shown in Figure 6.6.1, as she swims laps in a 50 m pool. Her position–time data are shown in Table 6.6.1. The starting point is treated as the origin for this motion.

TABLE 6.6.1 Positions and times of a swimmer completing 1.5 lengths of a pool

Time (s)	0	5	10	15	20	25	30	35	40	45	50	55	60
Position (m)	0	10	20	30	40	50	50	50	45	40	35	30	25

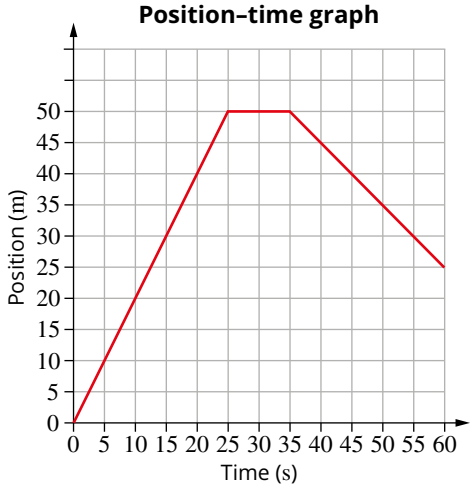


FIGURE 6.6.2 This position–time graph represents the motion of a swimmer travelling 50 m along a pool, then resting and swimming back towards the starting position. The swimmer finishes halfway along the pool.

Analysis of Table 6.6.1 reveals several features of Sophie's swim.

- For the first 25 s, she swims at a constant rate. Every 5 s she travels 10 m in a positive direction, i.e. her velocity is $+2\,\text{m s}^{-1}$.
- From 25 s to 35 s, her position does not change. She seems to be resting, as she is stationary for this 10 s interval.
- From 35 s to 60 s, she swims back towards the starting point, in a negative direction. On this return lap, she maintains a more leisurely rate of 5 m every 5 s, so her velocity is $-1\,\text{m s}^{-1}$. However, Sophie does not complete this lap but ends 25 m from the start.

This data is shown more conveniently on the position–time graph in Figure 6.6.2.

The displacement, s, of the swimmer can be determined by comparing the initial and final positions. For example, her displacement between 20 s and 60 s is:

$s = \Delta x$
$= \text{final position} - \text{initial position}$
$= 25 - 40$
$= -15\,\text{m}$

From the graph in Figure 6.6.2, it can be seen that during the first 25 s, the swimmer has a displacement of +50 m. Her average velocity is $+2\,\text{m s}^{-1}$ or $2\,\text{m s}^{-1}$ to the right, during this time. This value can also be obtained by finding the gradient of this section of the graph.

$$\begin{aligned}\text{Gradient} &= \frac{\text{rise}}{\text{run}} \\ &= \frac{50-0}{25-0} \\ &= 2\,\text{m s}^{-1}\end{aligned}$$

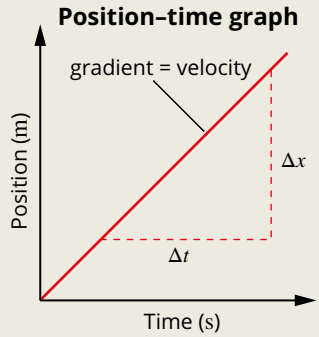
A positive velocity indicates that the object is moving in a positive direction and negative velocity indicates motion in a negative direction, as would be found when taking a gradient from 35 s to 60 s in Figure 6.6.2.

To confirm that the gradient of a position–time graph is a measure of velocity you can use **dimensional analysis**:

$$\text{Gradient of } x\text{–}t \text{ graph} = \frac{\text{rise}}{\text{run}} = \frac{x\ (\text{m})}{t\ (\text{s})} = v\ (\text{m s}^{-1})$$

The units of this gradient will be metres per second (m s^{-1}) so gradient is a measure of velocity. Note that the rise in the graph is the change in position, which is the definition of displacement $\Delta x = s$.

Gradient of x–t graph = velocity



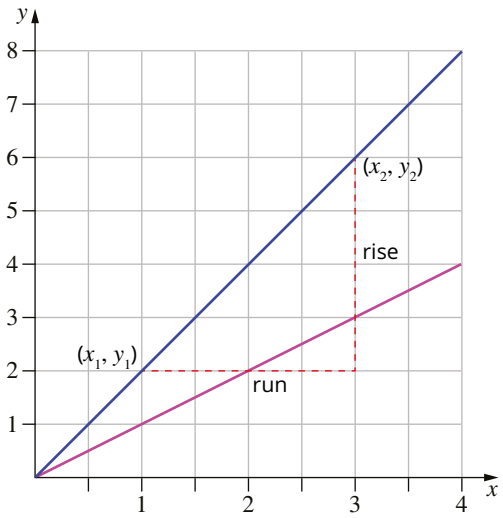
Position–time graph with gradient. Note that the change in position, Δx, is the same as the displacement, s.

SKILLBUILDER

Interpreting the slope of a linear graph

Scientists often represent a relationship between two variables as a graph. For directly proportional relationships, the variables are connected by a straight line that passes through the origin, where the slope (or gradient) of the line represents the constant of proportionality between the two variables. The slope or gradient of the line is defined as the ratio of change between two points in the vertical axis (rise) $y_2 - y_1$, divided by the change between two points in the horizontal axis (run) $x_2 - x_1$. In other words, it measures the rate at which one variable (the dependent variable) changes with respect to the other (the independent variable): gradient = $\frac{y_2 - y_1}{x_2 - x_1}$.

The graph shown has two straight lines with different slopes. The steeper slope (blue line) indicates that the rate of change is faster. This means the change is happening more quickly. The flatter slope (red line) indicates that the rate of change is slower. This means the change is happening more slowly.



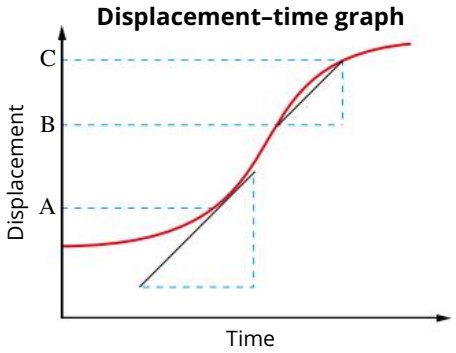


FIGURE 6.6.3 The instantaneous velocity at point *A* is the gradient of the tangent at that point. The average velocity between points *B* and *C* is the gradient of the chord between these points on the graph.

Non-uniform velocity

For motion with uniform (constant) velocity, the position–time graph will be a straight line, but if the velocity is non-uniform the graph will be curved.

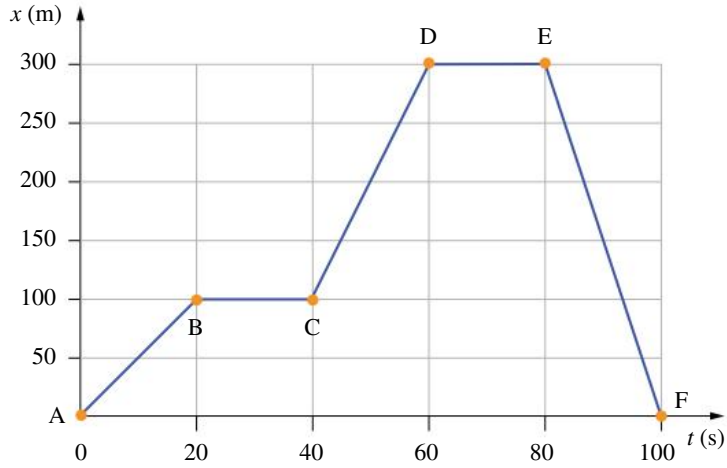
If the position–time graph is curved:

- the instantaneous velocity will be the gradient of the tangent to the line at that point.
- the average velocity will be the gradient of the chord between two points. This is illustrated in Figure 6.6.3.

Worked example 6.6.1

ANALYSING A POSITION–TIME GRAPH

The motion of a cyclist is represented by the position–time graph below, with important features of the motion labelled A, B, C, D, E and F.



a Calculate the velocity of the cyclist between A and B.

Thinking	Working
Determine the change in position (displacement) of the cyclist between A and B using: s = final position – initial position	At A, $x = 0$ m At B, $x = 100$ m $s = 100 - 0$ $= +100$ m or 100 m forwards (i.e. away from the starting point)
Determine the time taken to travel from A to B.	$\Delta t = 20 - 0 = 20$ s
Calculate the gradient of the graph between A and B using: Gradient of x–t graph $= \frac{\text{rise}}{\text{run}} = \frac{x}{t}$ Remember that $\Delta x = s$.	Gradient $= \frac{100}{20} = 5$
State the velocity, using: gradient of x–t graph = velocity Velocity is a vector so direction must be given.	The gradient is 5, so the velocity is $+5\,\text{m s}^{-1}$ or $5\,\text{m s}^{-1}$ forwards.

b Describe the motion of the cyclist between B and C.	
Thinking	**Working**
Interpret the shape of the graph between B and C.	The graph is flat between B and C, indicating that the cyclist's position is not changing for this time. So the cyclist is not moving. If the cyclist is not moving, the velocity is $0\,m\,s^{-1}$.
Confirm the result by calculating the gradient between B and C using: Gradient of x–t graph $= \frac{rise}{run} = \frac{x}{t}$ Remember that $\Delta x = s$.	Gradient $= \frac{0}{20} = 0$

➤ Try yourself 6.6.1

ANALYSING A POSITION–TIME GRAPH

Use the graph shown in Worked example 6.6.1 to answer the following questions.

a Calculate the velocity of the cyclist between E and F.

b Describe the motion of the cyclist between D and E.

VELOCITY–TIME (V–T) GRAPHS

A graph of velocity, v, against time, t, shows how the velocity of an object changes with time. This type of graph is useful for analysing the motion of an object moving in a complex manner.

Analysing motion

Consider the example of the girl in Figure 6.6.4. Aliyah is running back and forth along an aisle in a supermarket. A study of the velocity–time graph in Figure 6.6.4 shows that Aliyah has a positive velocity (runs in a positive direction) for the first 6 s. Between the 6 s and 7 s she is stationary, and then for the final 3 s she has a negative velocity (runs in the opposite direction).

The graph in Figure 6.6.4 shows Aliyah's velocity at each instant in time.

- For the first 4 s, she moves in a positive direction with a constant speed of $3\,m\,s^{-1}$.
- From 4 s to 6 s, she continues moving in a positive direction but slows down.
- At 6 s, she comes to a stop for 1 second.
- For the final 3 s, she accelerates in the negative direction for 1 s then travels at a constant velocity of $-1\,m\,s^{-1}$ for 1 s. She then slows down and comes to a stop at 10 s.

Remember that whenever the graph is below the time axis, velocity is negative, which indicates travel in the opposite direction. So she is travelling in the opposite direction for the last 3 s of her journey.

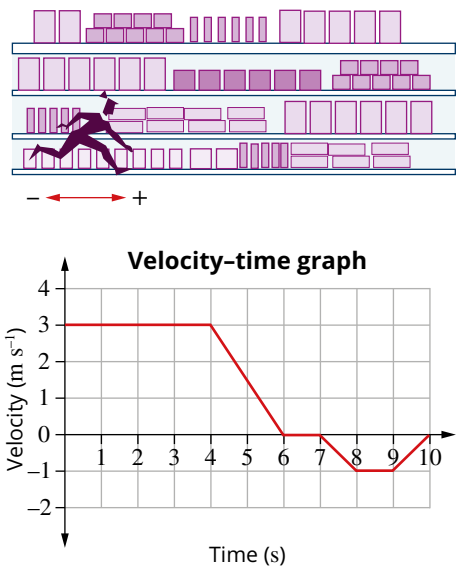


FIGURE 6.6.4 Diagram and v–t graph for Aliyah running along an aisle.

Finding displacement

A velocity–time graph can also be used to find the displacement of an object.

It is easier to see why the area under the v–t graph gives the displacement when velocity is constant. For example, the graph in Figure 6.6.5 on page 236 shows that in the first 4 s of motion, Aliyah moves with a constant velocity of $+3\,m\,s^{-1}$. Note that the area under the graph for this period of time is a rectangle. Her displacement, s, during this time can be determined by rearranging the formula for velocity:

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

$$\therefore s = v \times t$$

= height × base

= area under v-t graph

Aliyah then slows from $3\,m\,s^{-1}$ to zero in the next 2 s. To understand why the triangular area under the graph gives the displacement for this period of time, you would need more complicated mathematics, known as calculus, which is beyond the scope of this book.

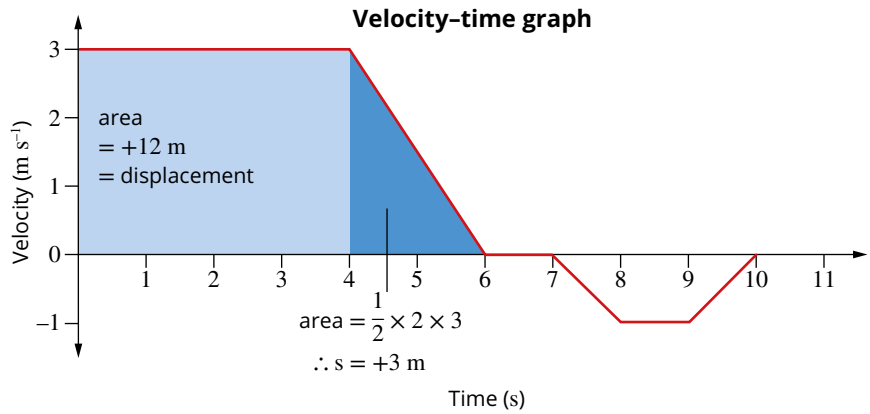


FIGURE 6.6.5 Displacement values shown have been determined from the area between the *v*–*t* curve and the time axis.

The area under the graph in Figure 6.6.5 can be used to find Aliyah's displacement.

For the first 4 s:

$$\text{Area} = l \times w$$
$$= 3 \times 4$$
$$= +12\,\text{m}$$

From 4 s to 6 s:

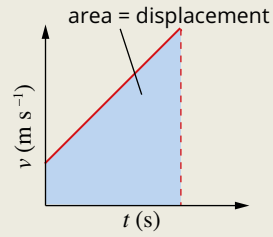
$$\text{Area} = \frac{b \times h}{2}$$
$$= \frac{2 \times 3}{2}$$
$$= +3\,\text{m}$$

The total displacement during the first 6 s

$$= +12\,\text{m} + 3\,\text{m} = +15\,\text{m}$$

Displacement, s, is given by the area under a velocity–time graph. This is the area between the graph and the time axis.

- **An area above the time axis indicates a positive displacement and motion in a positive direction.**
- **An area below the time axis indicates a negative displacement and motion in a negative direction.**

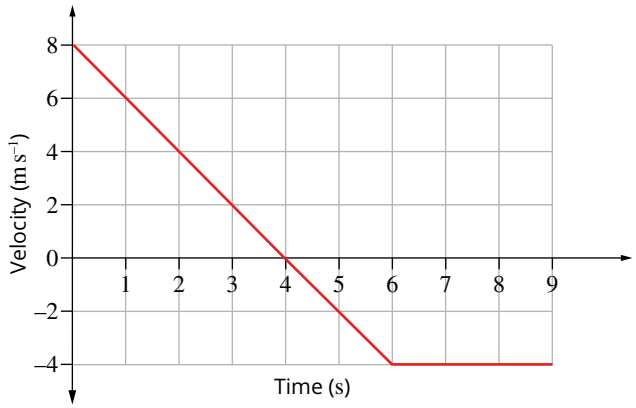


The area under a *v*–*t* graph gives displacement.

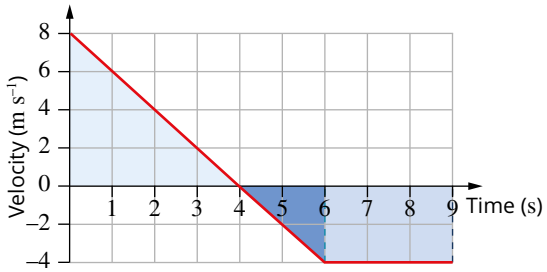
Worked example 6.6.2

ANALYSING A VELOCITY–TIME GRAPH

The motion of a radio-controlled car initially travelling east in a straight line across a driveway is represented by the graph below.



a Calculate the displacement of the car during the first 4 seconds.

Thinking	Working
Displacement is the area under the graph. So, calculate the area under the graph for the time period for which you want to find the displacement. Use displacement = $b \times h$ for squares and rectangles. Use displacement = $\frac{1}{2}(b \times h)$ for triangles.	 The area from 0 to 4 s is a triangle, so: Area = $\frac{1}{2}(b \times h)$ $= \frac{1}{2} \times 4 \times 8$ $= +16\,\text{m}$
Displacement is a vector quantity, so a direction is needed.	Displacement = 16 m east

b Determine the average velocity of the car for the first 4 seconds.

Thinking	Working
Identify the equation and variables, and apply the sign convention.	$v = \frac{s}{t}$ $s = +16\,\text{m}$ $\Delta t = 4\,\text{s}$
Substitute values into the equation: $v = \frac{s}{t}$	$v = \frac{s}{t}$ $= \frac{+16}{4}$ $= +4\,\text{m s}^{-1}$
Velocity is a vector quantity, so a direction is needed.	$v_{av} = 4\,\text{m s}^{-1}$ east

➤ Try yourself 6.6.2

ANALYSING A VELOCITY–TIME GRAPH

Use the graph shown in Worked example 6.6.2 to answer the following questions.

a Calculate is the displacement of the car from 4 to 6 seconds.

b Determine the average velocity of the car from 4 to 6 seconds.

Acceleration from a (*v–t*) graph

The **acceleration** of an object can also be found from a velocity–time graph, as shown in Figure 6.6.6.

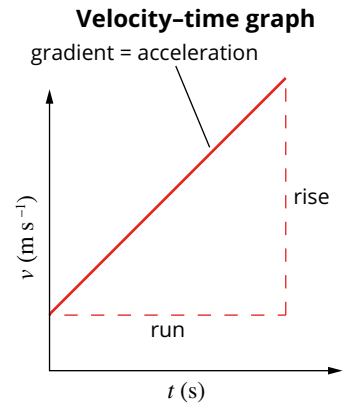


FIGURE 6.6.6 Gradient as displayed in a *v–t* graph

$$\text{Gradient of } v\text{–}t \text{ graph} = \frac{\text{rise}}{\text{run}} = \frac{v\ (\text{m s}^{-1})}{t\ (\text{s})} = a\ (\text{m s}^{-2})$$

Consider the motion of Aliyah in the supermarket. Figure 6.6.7 shows Aliyah's velocity at each instant in time. Acceleration is the change in velocity divided by the time taken, so acceleration can be calculated using the gradient of the *v–t* graph. Aliyah's acceleration for the first 6 seconds is calculated as follows.

- For the first 4 seconds, the line is horizontal, so she is moving at a constant speed of $3\,\text{m s}^{-1}$. Her acceleration is $0\,\text{m s}^{-2}$.
- From 4 to 6 seconds, she is moving in a positive direction but is slowing down from $3\,\text{m s}^{-1}$ to rest. Her acceleration is:

$$a = \frac{v}{t} = \frac{v-u}{t} = \frac{0-3}{2} = -1.5\,\text{m s}^{-2}$$

- The negative sign means that the acceleration is in the opposite direction.

> **i** The gradient of a velocity–time graph gives the average acceleration of the object over the time interval.

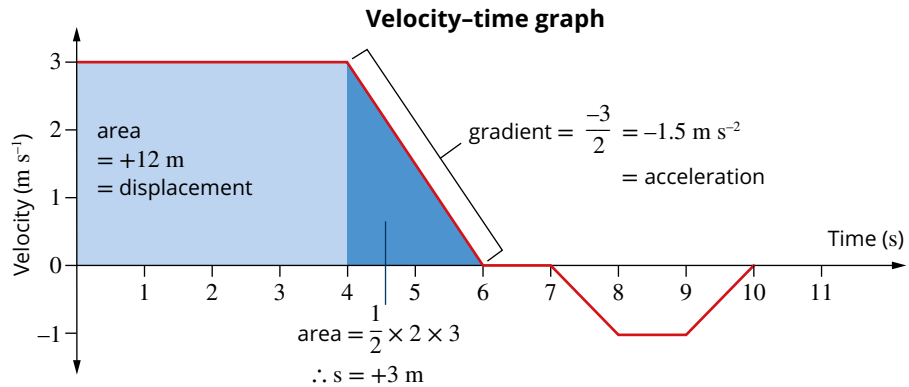
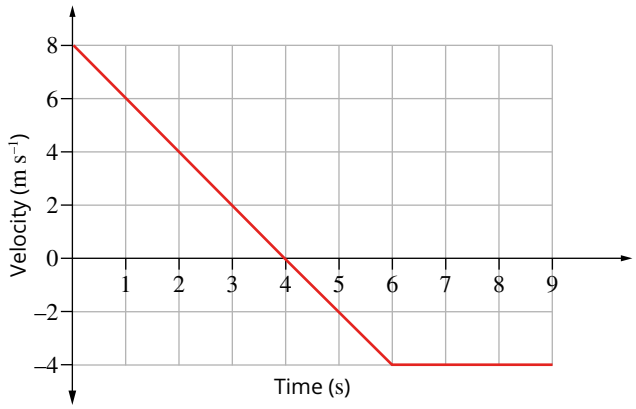


FIGURE 6.6.7 Acceleration as displayed in a *v–t* graph

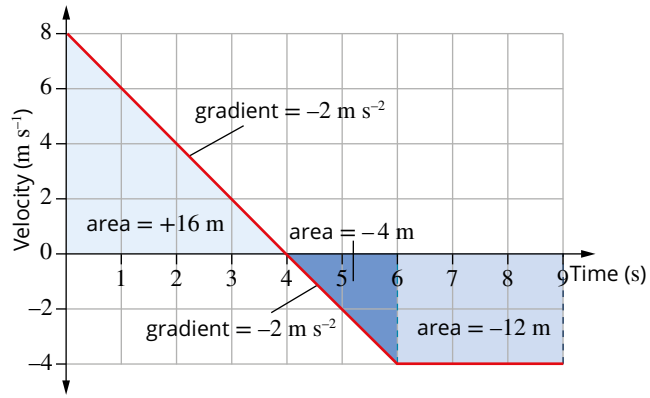
Worked example 6.6.3

ACCELERATION FROM A *V–T* GRAPH

Consider the motion of the radio-controlled car in Worked example 6.6.2, which is initially travelling east in a straight line across a driveway, as shown by the graph below.



Calculate the acceleration of the car during the first 4 s.

Thinking	Working
Acceleration is the gradient of a *v–t* graph. Calculate the gradient from time 0 s to 4 s using: Gradient = $\frac{\text{rise}}{\text{run}}$	 Gradient = $\frac{\text{rise}}{\text{run}}$ = $\frac{-8}{4}$ = –2 m s^{-2}
Acceleration is a vector quantity, so a direction is needed. Note: In this case, although the acceleration is in the westerly direction, the car is still moving in the easterly direction but slowing down.	Acceleration = –2 m s^{-2} east (or 2 m s^{-2} west)

➤ Try yourself 6.6.3

ACCELERATION FROM A *V–T* GRAPH

For the graph shown in Worked example 6.6.3, calculate the acceleration of the car during the period from 4 to 6 seconds.

Distance travelled

A velocity–time graph can also be used to calculate the distance travelled. The process of determining distance requires you to calculate the area under the v–t graph, in the same way as when calculating displacement. However, because the distance travelled by an object always increases as the object moves, regardless of direction, you must add up all the areas between the graph and the time axis, regardless of whether the area is above or below the axis.

For example, Figure 6.6.8 shows the velocity–time graph of the radio-controlled car from Worked example 6.6.3. The area above the time axis, which corresponds to motion in the positive direction, is +16 m. The areas below the axis, which correspond to negative motion, are –4 m and –12 m.

To calculate the total displacement, add up each displacement:

Total displacement

= 16 + (–4) + (–12)

= 16 – 16

= 0 m

To calculate the total distance, add up the magnitude of the areas, and ignore the signs:

Total distance

= 16 + 4 + 12

= 32 m

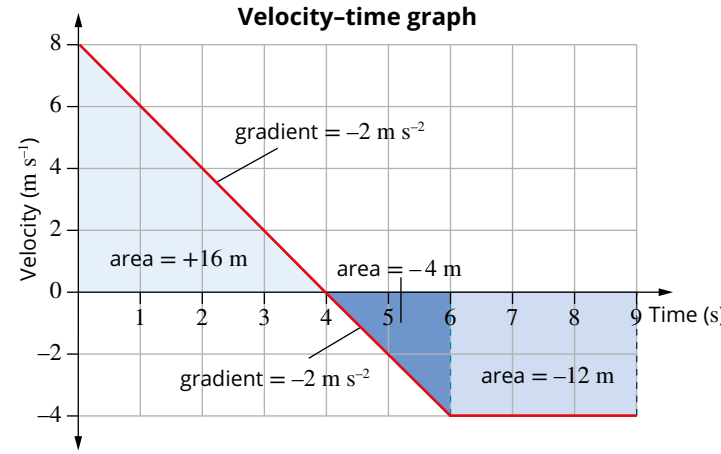


FIGURE 6.6.8 Both distance and displacement can be calculated by using the areas under the velocity–time graph.

Non-uniform acceleration

For motion with uniform (constant) acceleration, the velocity–time graph will be a straight line. For non-uniform acceleration, the velocity–time graph will be curved. If the velocity–time graph is curved:

- the instantaneous acceleration is the gradient of the tangent to the line at that point
- the average acceleration will be the gradient of the chord between two points.

The displacement can still be calculated by finding the area under the graph; however, you will need to make some estimations. Using calculus, the instantaneous acceleration would be determined using differentiation and the displacement using integration or antidifferentiation.

ACCELERATION–TIME (a–t) GRAPHS

An acceleration–time graph simply indicates the acceleration of the object as a function of time. The area under an acceleration–time graph is found by multiplying an acceleration, a, and a period of time, Δt, value. The area gives a change in velocity, Δv, value:

Area = $a \times t = v$

In order to establish the actual velocity of the object, its initial velocity must be known. Figure 6.6.9 shows both Aliyah's velocity versus time (v–t) and acceleration versus time (a–t) graphs.

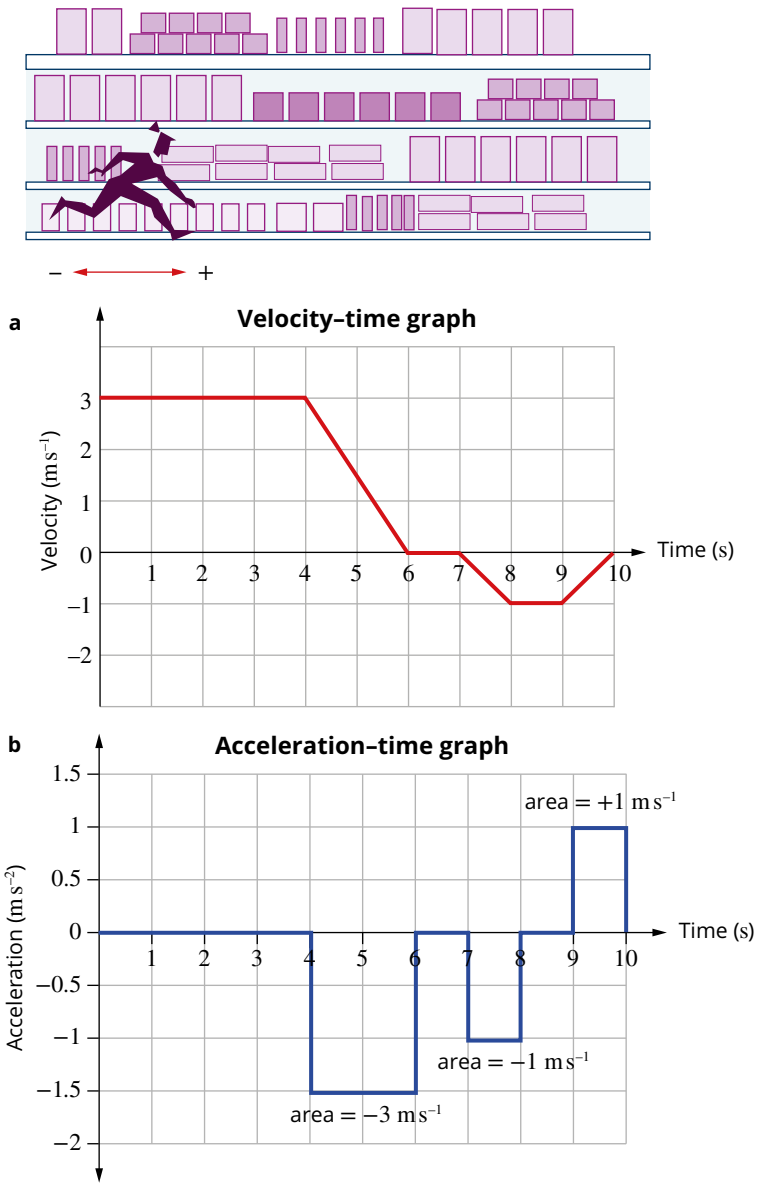


FIGURE 6.6.9 (a) Aliyah's velocity versus time (v–t) graph. (b) Aliyah's acceleration versus time (a–t) graph. The area under the v–t graph gives the value for acceleration, a.

From 0 to 4 s the velocity is constant, so the gradient, and hence the acceleration, is zero. The area under the curve from 4 to 6 s shows a Δv of $-3\,\text{m s}^{-1}$. This indicates that Aliyah has slowed down by $3\,\text{m s}^{-1}$ during this time. The $v-t$ graph confirms this. Her initial speed is $3\,\text{m s}^{-1}$, so she must be stationary ($v = 0$) after 6 s. The v–t graph confirms this.

This calculation could not be made without knowing Aliyah's initial velocity.

PA 2.1.1

6.6 Review

SUMMARY

- A position–time graph can be used to determine the location of an object at any given time. Additional information can also be derived from the graph:
  - Displacement is given by the change in position of an object.
  - The velocity of an object is given by the gradient of the position–time graph.
  - If the position–time graph is curved, the gradient of the tangent at a point gives the instantaneous velocity. The gradient of a chord between two points gives the average velocity between those points.
- The gradient of a velocity–time graph is the acceleration of the object.
- The area under a velocity–time graph is the change in displacement of the object.
- The area under an acceleration–time graph is the change in velocity of the object.

KEY QUESTIONS

Retrieval

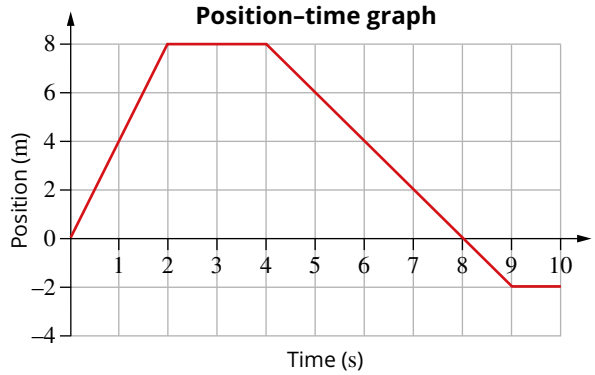
1 Describe the following features of a graph:
- **a** the gradient of a position–time graph
- **b** the gradient of a velocity–time graph
- **c** the area under a velocity–time graph
- **d** the area under an acceleration–time graph.

Comprehension

2 Simon measures the velocity of two cars travelling along a 1.0 km stretch of road. Both cars are at the same displacement at time zero. Car A starts from rest and reaches 100.0 km h^{-1} in 1.0 minute. Car B travels at a constant 60.0 km h^{-1}.
- **a** Draw a velocity–time graph for both cars, using units of m s^{-1}.
- **b** Draw an acceleration–time graph for both cars.
- **c** Using your velocity–time graph, explain whether car A will have passed car B at the end of 1 minute.

Analysis

The following information relates to questions 3–7.
The graph represents the straight-line motion of a radio-controlled toy car.



3 Describe the motion of the car in terms of its position.

4 Determine the position of the toy car at the following times.
- **a** 2.0 s
- **b** 4.0 s
- **c** 6.0 s
- **d** 10.0 s

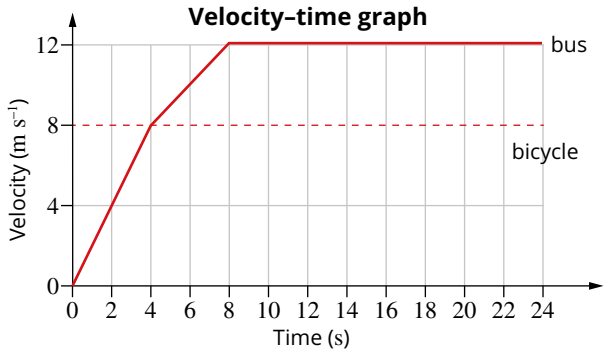
5 Determine the time at which the car returned to its starting point.

6 Calculate the velocity of the toy car at the following times:
- **a** during the first 2.0 s
- **b** at 3.0 s
- **c** from 4.0 s to 8.0 s
- **d** at 8.0 s
- **e** from 8.0 s to 9.0 s.

7 Calculate the following (in metres) for the car's 10.0 s motion:
- **a** distance
- **b** displacement.

The following information relates to questions 8 and 9.

The velocity–time graphs for a bus and a bicycle travelling along the same straight stretch of road are shown below. The bus is initially at rest and starts moving as the bicycle passes it.



8 **a** Calculate the magnitude of the initial acceleration of the bus.

b Calculate the time at which the bus overtakes the bicycle.

c Calculate how far the bicycle has travelled before the bus catches it.

d Calculate the magnitude of the average velocity of the bus during the first 8 s.

9 **a** Draw an acceleration–time graph for the motion of the bus.

b Use your acceleration–time graph to determine the change in velocity of the bus over the first 8.0 s.

Verifying the value of acceleration due to gravity on the Earth's surface

Conduct an experiment to verify the value of acceleration due to gravity on the Earth's surface.

- Write a research question.
- Suggest modifications to the method used in class to improve the outcome.
- Collect sufficient data (five variations of the independent variable and three repetitions of each variation.
- Consider safety.

Research and planning

Aim

- To find a value for the acceleration due to gravity on the Earth's surface.

Rationale (scientific background to the experiment)

The displacement, s, of an object travelling in a straight line can be described by the equation $s = ut + \frac{1}{2}at^2$, where u is its initial velocity, t is time and a is acceleration. For an object falling vertically, from rest, the acceleration of the object will be the acceleration due to gravity, g, near the Earth's surface if the effects of air resistance are ignored. By collecting data of the time taken for the object to hit the ground when it falls from a height s, with an initial velocity of zero, the acceleration due to gravity can be found from the gradient of the line. By graphing s versus t squared, the gradient of the line is $\frac{1}{2}a$.

As mentioned in Module 6.5, air resistance will oppose the motion of a falling object. Therefore, small objects that minimise air resistance, such as a coin or a ball bearing, should be chosen for this experiment.

Timing

45 minutes

Materials

- $2 coin, ball bearing or other small object to drop
- smartphone or tablet with a sound recording app such as Audacity
- long tape measure

Safety

- Be careful that the area is clear when the object is being dropped, especially if it's dropped from a window, stairwell or other large height. Make sure the object isn't too heavy, to avoid damaging the floor.

Method

Risk assessment

Before you commence this practical activity, you must conduct a risk assessment. Complete the template in your Skills and Assessment book or download it from your eBook.

1. Decide on five different heights from which to drop the object. The minimum height should be 1 m; otherwise it will be too difficult to accurately record the time taken for the object to fall. Also try larger heights (e.g. from a stairwell or window) but bear in mind that you need to accurately measure the distance the object falls.
2. Nominate one person to operate the recording software, and another to drop the object. Open a new software document and start recording. The student operating the recording software should count down to the drop ('three, two, one, drop'). Make sure that the instruction to drop the object is louder than the countdown, and can be picked up by the microphone (it should register as a peak on the software). Drop the object.
3. The software should then register another peak when the object hits the ground. Make sure the ground is hard (i.e. not carpet or grass) so that the object will make a sound when it hits it. It's important to limit background noise so the software can detect the sound. Stop recording as soon as the object hits the ground.
4. Note the results in a table for the distance the object has fallen and the time it has taken, with the uncertainty for each measurement. The uncertainty in the measurement for the distance (measured by a tape measure or metre rule) is likely to be ±1 cm; although the tape measure is precise to 1 mm, it's unlikely you'll be able to measure the height that accurately. The uncertainty in the measurement for the time will depend on the software; most can record time to ±0.01 s, so the total uncertainty in the time measurement would be ±0.02 s. Refer to Chapter 1 for a reminder of how to determine uncertainties in measurement.
5. Repeat the same measurements two more times in order to obtain an average.

Variables

i. Independent: height the object is dropped from, s
ii. Dependent: time taken for the object to fall, t
iii. Controlled: starting velocity, mass, volume and shape of object being dropped

Analysing

Raw and processed data

TABLE 1.1 Measured time taken for object to drop from different heights

Measured height (± _____ m)				Measured time (± _____ s)			
Trial 1	**Trial 2**	**Trial 3**	**Average**	**Trial 1**	**Trial 2**	**Trial 3**	**Average**
			±				±
			±				±
			±				±
			±				±
			±				±

TABLE 1.2 Time taken to drop, squared

Measured height (± _____ m)				Time taken squared (t^2) (± _____ s)			
Trial 1	**Trial 2**	**Trial 3**	**Average**	**Trial 1**	**Trial 2**	**Trial 3**	**Average**
			±				±
			±				±
			±				±
			±				±
			±				±

Reflect and check that your data analysis demonstrates these characteristics

- ❑ Effective investigation of phenomena is demonstrated by the collection of sufficient and relevant raw data.
- ❑ Accurate application of algorithms, visual and graphical representations of data is demonstrated by appropriate processing and presentation of data to aid the analysis and interpretation of data.

Analysis

1. Plot the results from Table 1.1 on a graph, with the variable t on the horizontal axis and the variable s on the vertical axis. Include error bars for each point plotted.
2. Plot the results from Table 1.2 on a graph, with t^2 on the horizontal axis, and s on the vertical axis. Include error bars for each point plotted.
3. Draw a line of best fit, and find its gradient. Use your error bars to draw a minimum and a maximum line. As t^2 is on the horizontal axis and s is on the vertical axis, the gradient will be equal to $\frac{1}{2}g$. Use the minimum and maximum lines to find the uncertainty of your value for the gradient to get the uncertainty for your value of the acceleration due to gravity.
4. Are there any points on your graph that do not fit the trend? Explain why this may have been the case.
5. Compare your value for g with the values obtained by other groups. Are they the same? Did other groups use the same values for height?
6. Compare your graph to the graphs drawn by other groups who dropped different objects. What do you notice about the shape of the graphs?
7. Would you expect the graphs to be to same or different? Why?

Reflect and check that your analysis demonstrates these characteristics

- ❑ Systematic and effective analysis of evidence is demonstrated by a thorough and appropriate error analysis.
- ❑ Systematic and effective analysis of evidence is demonstrated by a thorough identification of relevant trends, patterns and relationships.
- ❑ Insightful and valid interpretation of evidence is demonstrated by drawing a valid and defensible conclusion based on the analysis.

Interpreting and communicating

Conclusion

1. The aim of the experiment was to determine the value of the acceleration due to gravity by dropping an object from different heights and measuring the time it took to drop to the ground. Were you able to find a single value for the acceleration due to gravity? (Hint: calculate your percentage error.)
2. Look up the value of acceleration due to gravity at the Earth's surface. How does this compare with your calculated value? Does it lie within your uncertainty range? (Hint: calculate your percentage error.)

Evaluation

3 Why was it useful to draw a graph using t^2 instead of t?

4 Considering your analysis and conclusion, did the experiment provide an effective method of finding the acceleration due to gravity?

5 Was the level of uncertainty that you calculated in your analysis reasonable?

Improvements

6 If you were to repeat the experiment, what would you do differently?

Include in your answer:

- how you would change the methodology and how this might improve the results
- what skills you used to perform the tasks and how your technique could be improved
- how the collection of data could be made more reliable and the uncertainty reduced. What were the sources of uncertainty, and which sources contributed most to the uncertainty in the final value?

Extension

7 Would this experiment work using any object?

8 Identify any limitations to using this method for other objects.

9 Would this experiment work if you threw the object upwards and measured the time it took to return to your hand?

Reflect and check that your evaluation demonstrates these characteristics
❑ Critical evaluation of processes is demonstrated by a discussion of the reliability and validity of the experimental process supported by evidence such as the quality of the data (as quantified in the error analysis).
❑ Critical evaluation of the conclusion is demonstrated by a discussion of the veracity of the conclusions with respect to the error analysis and limitations or sufficiency of the data.
❑ Insightful evaluation of processes and conclusions is demonstrated by a suggestion of improvements or extensions to the experiment that are logically derived from the analysis of the evidence.

MANDATORY PRACTICAL 5

Constructing and interpreting displacement–time and velocity–time graphs

Conduct an experiment that requires you to construct and interpret displacement–time and velocity–time graphs from the resulting data. Use horizontal and vertical error bars when plotting the data to ensure you can determine the uncertainty of the gradient and intercepts.

Research and planning

Aim

- To construct displacement–time and velocity–time graphs for students moving at different speeds along a set distance. To interpret these graphs to find the average velocity and acceleration.

Rationale (scientific background to the experiment)

The following equations describe motion in a straight line with constant acceleration:

- The velocity of an object is the rate at which displacement changes, so the velocity can be found by graphing the displacement of the object against time. The velocity can then be found as the gradient of the line of best fit.
- Similarly, the acceleration of an object can be found as the rate of change of velocity; it is the gradient of a graph of velocity against time.

Timing

45 minutes

Materials

- 50 m running track or 50 m distance marked on sports oval
- 6 stopwatches
- 5 volunteers to run
- video camera, tripod and software (if possible, 5 cameras)
- skateboard/scooter and bicycle

Safety

Make sure there is enough space at the end of the measured distance for the participants to slow down safely.

Method

Risk assessment

Before you commence this practical activity, you must conduct a risk assessment. Complete the template in your Skills and Assessment book or download it from your eBook.

1. Position two people at the end of the track, where the participants will finish. One should have a stopwatch, the other a video camera. The student with the video camera should set it up so that the camera is pointing straight along the finish line. Position other students with stopwatches and video cameras/smartphones at 10 m, 20 m, 30 m and 40 m along the track.
2. Get the person with the stopwatch at the finishing line to give a signal for the walker to start. Each student should start their stopwatch. Stop each stopwatch when the walker crosses each line.
3. Set the video camera running when the walker starts walking. Keep the camera pointing along the finish line so that it will record the walker crossing the line, but not their whole walk.
4. Note the results for distance travelled and time taken in a table, with the uncertainty for each measurement. The stopwatch will typically have a precision of ±0.01 s, but you will need to factor reaction times into your uncertainty—±0.1 s to 0.2 s would be reasonable. The uncertainty in measuring the distances is likely to be ±0.1 m. Refer to Chapter 1 for a reminder of how to determine uncertainties in measurement.
5. Repeat these steps for the student running at a medium jog and a flat-out sprint.
6. Repeat this for a student on a skateboard or scooter, and riding a bicycle. Make sure they start from rest, i.e. so they aren't moving before the signal is given.
7. Repeat each measurement two more times to obtain an average. (You may need to wait for the participants to catch their breath between runs.)

Variables

i. Independent: the distance from the start to the end of the track, *s*
ii. Dependent: time taken to walk/run/ride the distance, *t*
iii. Controlled: starting velocity, *u*

Analysing

Raw and processed data

TABLE 1.1 Measured time taken to walk, run or ride 50 m at 10 m intervals

	Measured time (± ___ s)				
	10 m	**20 m**	**30 m**	**40 m**	**50 m**
walk					
jog					
sprint					
skateboard/ scooter					
bicycle					

Calculate the velocity for each stage of the walk, run or ride. To do this, use:

$$\text{Velocity per stage} = \frac{\text{distance travelled per stage}}{\text{time taken per stage}}$$

For example:

$$\text{Velocity between 10 m and 20 m} = \frac{20\text{ m} - 10\text{ m}}{\text{time taken between 10 and 20 m}}$$

TABLE 1.2 Velocity for each stage

	Velocity (± ___ $m s^{-1}$)				
	0–10 m	**11–20 m**	**21–30 m**	**31–40 m**	**41–50 m**
walk					
jog					
sprint					
skateboard/ scooter					
bicycle					

Reflect and check that your data analysis demonstrates these characteristics

- ❑ Effective investigation of phenomena is demonstrated by the collection of sufficient and relevant raw data.
- ❑ Accurate application of algorithms, visual and graphical representations of data is demonstrated by appropriate processing and presentation of data to aid the analysis and interpretation of data.

Analysis

1. Plot the results for displacement against time on a graph, with the independent variable *t* on the horizontal axis, and the dependent variable *s* on the vertical axis. Include error bars for each point plotted.
2. Draw a line of best fit, and find its gradient. Use your error bars to draw minimum and maximum lines. As *t* is on the horizontal axis and *s* is on the vertical axis, the gradient will be equal to $\frac{s}{t}$, i.e. the average velocity of the walker, runner or rider, v_{av}. Use the minimum and maximum lines to find the uncertainty of your value for the gradient to get the uncertainty for your value of v_{av}. Refer to Chapter 1 for more guidance if necessary.
3. Plot the results for velocity against time on a graph, with *t* on the horizontal axis, and *v* on the vertical axis. Include error bars for each point plotted.
4. Draw a line of best fit, and find its gradient. Use your error bars to draw minimum and maximum lines. As *t* is on the horizontal axis and *v* is on the vertical axis, the gradient will be equal $\frac{v}{t}$, i.e. the average acceleration of the walker, runner or rider, a_{av}. Use the minimum and maximum lines to find the uncertainty of your value for the gradient, in order to get the uncertainty for your value of a_{av}.
5. Are there any points on your graphs that do not fit the trend? Explain why this might be the case.
6. Compare your value for v_{av} and a_{av} with the values obtained by other groups. Are they the same? What does a gradient of zero represent for the velocity versus time graph? What does this mean that the volunteer was doing?
7. Compare your graphs to the graphs drawn by other groups with different participants. What do you notice about the shapes of the graphs?
8. Would you expect them to be to same or different? Why?
9. Where does your line of best fit intercept the horizontal and vertical axes? As your runner started from rest, where would you expect it to cross the axes? What can the intercept tell you about the uncertainties in your measurements?
10. Find the area under the velocity–time graph to calculate the distance travelled. How does this compare with the known length of the track?

Reflect and check that your analysis demonstrates these characteristics

- ❑ Systematic and effective analysis of evidence is demonstrated by a thorough and appropriate error analysis.
- ❑ Systematic and effective analysis of evidence is demonstrated by a thorough identification of relevant trends, patterns and relationships.
- ❑ Insightful and valid interpretation of evidence is demonstrated by drawing a valid and defensible conclusion based on the analysis.

Interpreting and communicating

Conclusion

1. The aim of the experiment was to determine the average velocity and acceleration of a walker, runners and students on a scooter/skateboard and bicycle by analysing displacement–time and velocity–time graphs. Were you able to find a single constant value for the velocity and acceleration?

Evaluation

2. Considering your analysis and conclusion, did the experiment provide an effective method of finding the average velocity and average acceleration?
3. Was the level of uncertainty that you calculated in part 9 of Analysis reasonable?

Improvements

4 If you were to repeat the experiment, what would you do differently?

Include in your answer:

- how you would change the methodology and how this might improve the results
- what skills you used to perform the tasks and how your technique could be improved
- how the collection of data could be made more reliable and the uncertainty reduced. What were the sources of uncertainty, and which ones contributed most to the uncertainty in the final value?

Extension

5 Would this experiment work using any distance or any method of travel?

6 Identify any limitations to using this method for other distances.

7 Would this method work for calculating the average velocity if the runner completed a whole lap of a running track? What might you need to measure instead of displacement? What value would that give you instead of average velocity?

Reflect and check that your evaluation demonstrates these characteristics
❑ Critical evaluation of processes is demonstrated by a discussion of the reliability and validity of the experimental process supported by evidence such as the quality of the data (as quantified in the error analysis).
❑ Critical evaluation of the conclusion is demonstrated by a discussion of the veracity of the conclusions with respect to the error analysis and limitations or sufficiency of the data.
❑ Insightful evaluation of processes and conclusions is demonstrated by a suggestion of improvements or extensions to the experiment that are logically derived from the analysis of the evidence.

Chapter review

06

KEY TERMS

acceleration
air resistance
centre of mass
collinear
dimension
dimensional analysis
direction conventions
displacement
distance travelled
free-fall
magnitude
newton
position
rectilinear
resultant
scalar
speed
units
vector
vector diagram
velocity

KEY QUESTIONS

Retrieval

1 Select the scalar quantities in the list below.
- **A** force
- **B** time
- **C** acceleration
- **D** mass

2 Select the vector quantities in the list below.
- **A** displacement
- **B** distance
- **C** volume
- **D** velocity

3 A car travels 15.0 $m\,s^{-1}$ north and another travels 20.0 $m\,s^{-1}$ south. State why a sign convention is used to describe vectors like these.

4 Vector arrow A is drawn twice the length of vector arrow B. Recall what this means.

Comprehension

5 Angus inadvertently drops an egg while baking a cake and the egg falls vertically towards the ground. Identify which one of the following statements correctly describes how the egg falls.
- **A** The egg's acceleration increases.
- **B** The egg's acceleration is constant.
- **C** The egg's velocity is constant.
- **D** The egg's acceleration decreases.

6 Max is an Olympic trampolinist and is practising some routines. Identify which one or more of the following statements correctly describes Max's motion when he is at the highest point of the bounce. Assume that his motion is vertical.
- **A** He has zero velocity.
- **B** His acceleration is zero.
- **C** His acceleration is upwards.
- **D** His acceleration is downwards.

7 A stone is dropped vertically into a lake. Identify which one of the following statements best describes the motion of the stone at the instant it enters the water.
- **A** Its velocity and acceleration are both downwards.
- **B** It has an upwards velocity and a net downwards acceleration.
- **C** Its velocity and acceleration are both upwards.
- **D** It has a downwards velocity and a net upwards acceleration.

8 A car is moving in a positive direction. It approaches a red light and slows down. Identify which of the following statements correctly describes its acceleration and velocity as it slows down:
- **A** The car has positive acceleration and negative velocity.
- **B** The car has negative acceleration and positive velocity.
- **C** Both the velocity and acceleration of the car are positive.
- **D** Both the velocity and acceleration of the car are negative.

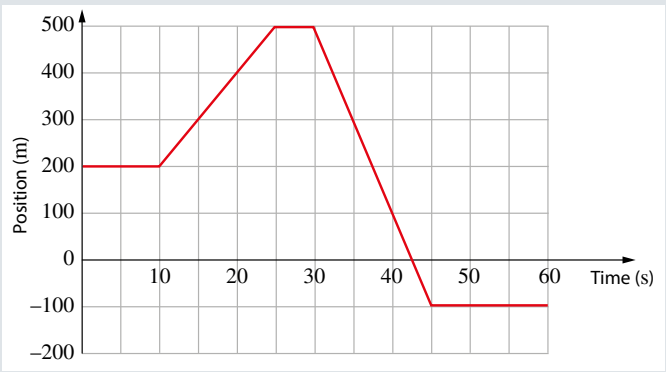
9 A basketballer applies a force with his hand to bounce the ball. Describe how a vector can be drawn to represent this situation.

10 The vector 20.0 N forwards is written as –20.0 N. Show how a vector representing 80.0 N backwards would be written.

11 A car travels at 95 $km\,h^{-1}$ along a freeway. The acceleration due to gravity is 9.80 $m\,s^{-2}$ down and air resistance is considered to be negligible. Calculate the speed of the car in $m\,s^{-1}$.

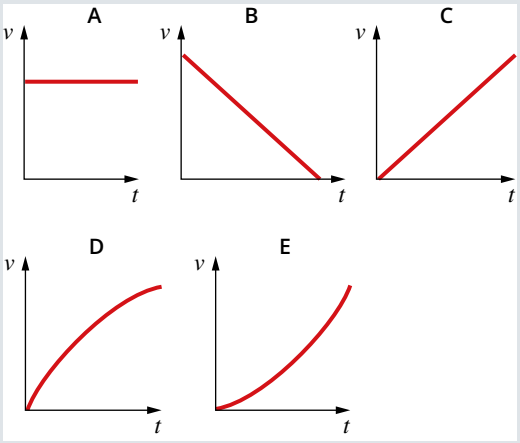
12 A cyclist travels at 15 $m\,s^{-1}$ during a sprint finish. The acceleration due to gravity is 9.80 $m\,s^{-2}$ down and air resistance is considered to be negligible. Calculate the speed of the cyclist in $km\,h^{-1}$.

13 The position–time graph shows the position of a motorbike along a straight stretch of road as a function of time. The motorcyclist starts 200.0 m north of an intersection.



a Determine the time interval in which the motorcyclist is travelling in a northerly direction.
b Determine the time interval in which the motorcyclist is travelling in a southerly direction.
c Determine the time intervals in which the motorcyclist is stationary.
d Determine the time at which the motorcyclist is passing back through the intersection.

14 For each of the activities listed, indicate which of the following velocity–time graphs best represents the motion involved.



a A car slows down to a stop at a red light.
b A swimmer is travelling at a constant speed.
c A motorbike starts from rest with uniform acceleration.

Analysis

15 Add the following force vectors using a number line: 3.0 N left, 2.0 N right, 6.0 N right. Then draw and describe the resultant force vector.

16 Determine the resultant vector of the following combination: 45.0 m forwards, 70.5 m backwards, 34.5 m forwards, 30.0 m backwards.

17 Determine the change in velocity of a bird that changes from flying 3.0 $m s^{-1}$ to the right to flying 3.0 $m s^{-1}$ to the left.

For questions 18–30, the acceleration due to gravity is 9.80 $m s^{-2}$ down and air resistance is considered to be negligible, unless indicated otherwise.

The following information relates to questions 18 and 19. An athlete in training for a marathon runs 15.0 km north along a straight road before realising that she has dropped her drink bottle. She turns around and runs back 5.0 km to find her bottle, then resumes running in the original direction. After running for 2.0 hours, the athlete reaches 20.0 km from her starting position and stops.

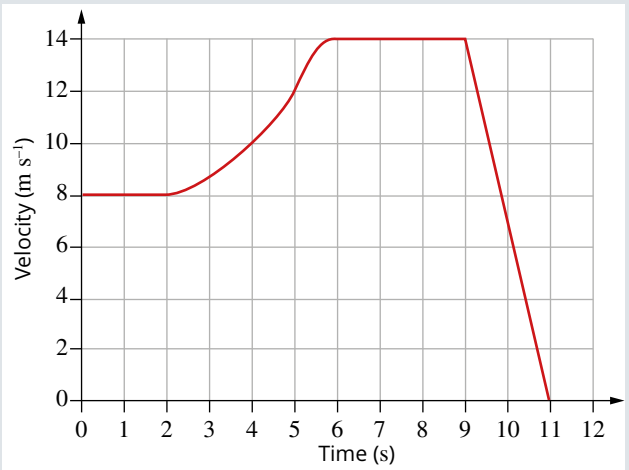
18 Calculate the average speed of the athlete in $km h^{-1}$.

19 Calculate her average velocity in:
a $km h^{-1}$
b $m s^{-1}$.

20 A ping pong ball is falling vertically at 6.0 $m s^{-1}$ as it hits the floor. It rebounds at 4.0 $m s^{-1}$ up. Calculate its change in speed during the bounce.

21 A skier is travelling along a horizontal ski run at a speed of 15 $m s^{-1}$. The skier falls over and takes 2.5 s to come to rest. Calculate the average acceleration of the skier.

22 This velocity–time graph is for a road cyclist as he travels, initially north, along a straight section of track.



a Calculate the displacement of the cyclist during his journey.
b Calculate the magnitude, to three significant figures, of the average velocity of the cyclist during this 11.0 s interval.
c Calculate the acceleration of the cyclist at $t = 1$ s.
d Calculate the acceleration of the cyclist at $t = 10$ s.

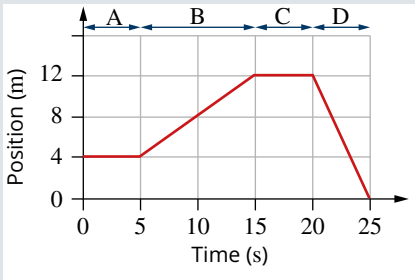
e Determine which one or more of the following statements correctly describes the motion of the cyclist:
- **A** He is always travelling north.
- **B** He travels south during the final 2 s.
- **C** He is stationary at $t = 8$ s.
- **D** He returns to the starting point after 11 s.

23 A car starts from rest and has a constant acceleration of 3.5 m s^{-2} for 4.5 s. Calculate its final speed.

24 A jet-ski starts from rest and accelerates uniformly. If it travels 2.0 m in its first second of motion, calculate:
- **a** its acceleration
- **b** its speed at the end of the first second
- **c** the distance the jet-ski travels in its second second of motion.

25 A skater is travelling along a horizontal skate rink at a speed of 10.0 m s^{-1}. The skater falls over and takes 10.0 m to come to rest.
- **a** Calculate average acceleration of the skater.
- **b** State the time it takes for the skater to come to a stop.

26 The graph shows the position of Candice dancing across a stage.



- **a** Determine Candice's starting position.
- **b** Determine in which of the sections (A–D) Candice is at rest.
- **c** Determine in which of the sections (A–D) Candice is moving in a positive direction, and calculate her velocity.
- **d** Determine in which of the sections (A–D) Candice is moving with a negative velocity and calculate the magnitude of this velocity.
- **e** Calculate Candice's average speed during the 25 s motion.

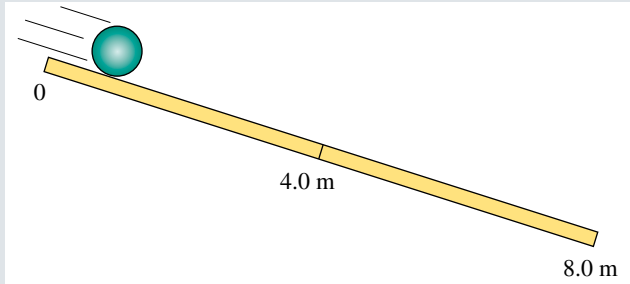
27 A cyclist, Anna, is travelling at a constant speed of 12 m s^{-1} when she passes a stationary bus. The bus starts moving just as Anna passes, and it accelerates uniformly at 1.5 m s^{-2}.
- **a** Determine when the bus reaches the same speed as Anna.
- **b** Determine how long the bus takes to catch Anna.
- **c** Determine the distance Anna has travelled when the bus catches up with her.

Knowledge utilisation

28 Two physics students conduct the following experiment from a very high bridge. Theo drops a 1.5 kg shot-put from a vertical height of 60.0 m. At exactly the same time Benjamin throws a 100 g mass with an initial downwards velocity of 10.0 m s^{-1} from a point 10.0 m above Theo.
- **a** Calculate how long it takes the shot-put to reach the ground.
- **b** Calculate how long it takes the 100 g mass to reach the ground.

29 At the start of an AFL football match, the umpire bounces the ball so that it travels vertically upwards and reaches a height of 15.0 m.
- **a** Calculate how long the ball takes to reach this maximum height.
- **b** One of the ruckmen is able to leap and reach to a height of 4.0 m with his hand. Calculate how long after the bounce the ruckman should try to make contact with the ball.

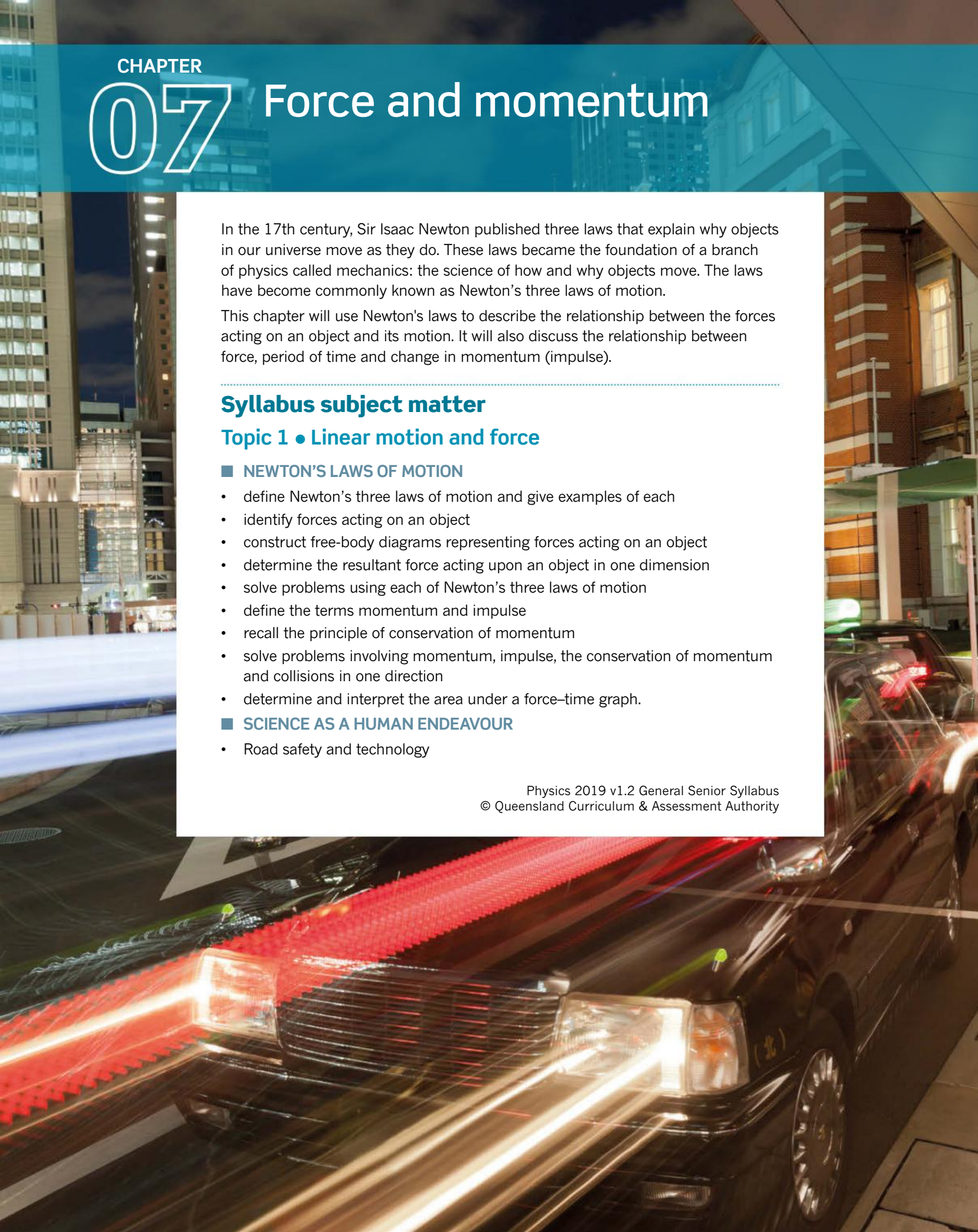
30 A billiard ball that is initially at rest rolls down a smooth ramp that is 8.0 m long. The acceleration of the ball is constant at 2.0 m s^{-2}.



- **a** Calculate the speed of the ball when it is halfway down the ramp.
- **b** Calculate the final speed of the ball.
- **c** Determine how long the ball takes to roll the first 4.0 m.
- **d** Determine how long the ball takes to travel the final 4.0 m.

CHAPTER

07 Force and momentum



In the 17th century, Sir Isaac Newton published three laws that explain why objects in our universe move as they do. These laws became the foundation of a branch of physics called mechanics: the science of how and why objects move. The laws have become commonly known as Newton's three laws of motion.

This chapter will use Newton's laws to describe the relationship between the forces acting on an object and its motion. It will also discuss the relationship between force, period of time and change in momentum (impulse).

Syllabus subject matter

Topic 1 • Linear motion and force

NEWTON'S LAWS OF MOTION

- define Newton's three laws of motion and give examples of each
- identify forces acting on an object
- construct free-body diagrams representing forces acting on an object
- determine the resultant force acting upon an object in one dimension
- solve problems using each of Newton's three laws of motion
- define the terms momentum and impulse
- recall the principle of conservation of momentum
- solve problems involving momentum, impulse, the conservation of momentum and collisions in one direction
- determine and interpret the area under a force–time graph.

SCIENCE AS A HUMAN ENDEAVOUR

- Road safety and technology

Physics 2019 v1.2 General Senior Syllabus
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7.1 Forces

BY THE END OF THIS MODULE, YOU SHOULD BE ABLE TO:

- identify the forces acting on an object, including the force due to gravity, friction and reaction forces
- draw diagrams to show the forces acting on an object
- identify whether the forces acting on an object are balanced or unbalanced
- apply the vector model of forces, including vector addition, to find the net or resultant force acting on an object.

FORCES ACTING ON OBJECTS

A force is a measure of the push or pull on an object, and is measured in newtons (N). Force is a vector and so it requires a magnitude and a direction to describe it fully.

The previous chapter developed the concepts and ideas needed to describe the motion of a moving body. In this chapter, rather than simply describe the motion, you will investigate the forces that cause the motion to occur.

In simple terms, a **force** can be thought of as a push or a pull; but forces exist in a wide variety of situations in everyday life and are fundamental to the nature of matter and the structure of the universe. Consider each of the photographs in Figure 7.1.1. For each situation, a force—a push or a pull—is acting.

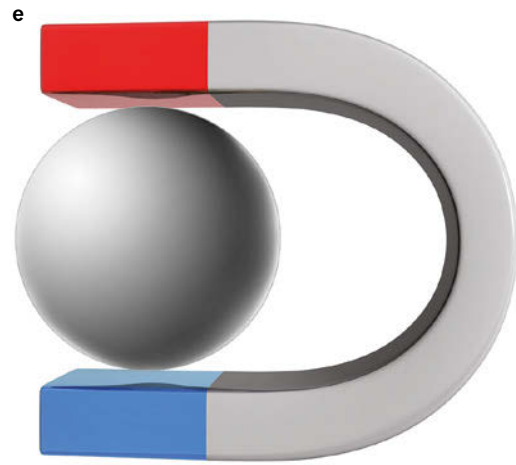


FIGURE 7.1.1 (a) At the moment of impact, both the tennis ball and the racquet strings are distorted by the forces acting at this instant. (b) The rock climber is relying on the frictional force between his hands and feet and the rock face. (c) A continual force causes the clay to deform into the required shape. (d) The gravitational force between the Earth and the Moon is responsible for two high tides each day. (e) The ball is suspended in mid-air because of the magnetic forces of repulsion and attraction.

In Figure 7.1.1, forces are acting in each of the situations. Some are applied directly to an object and some act on a body without touching it. Forces that act directly on a body are called **contact forces**, because the body will only experience the force while contact is maintained. Forces that act on a body at a distance are **non-contact forces**.

Contact forces are the easiest to understand and include the simple pushes and pulls that are experienced daily. Examples of contact forces include the forces between colliding billiard balls and the forces that act between you and your chair as you sit reading this book. Friction and drag forces are also contact forces.

Non-contact forces occur when the object causing the push or pull is physically separated from the object that experiences the force. These forces are said to 'act at a distance'. Examples of non-contact forces include gravitation, magnetic and electric forces.

The amount of force acting on an object can be measured using the SI unit called the newton (N). The unit honours Sir Isaac Newton (1643–1727), who is still considered to be one of the most significant physicists to have lived. A force of one newton, 1 N, is approximately the force you have to exert when holding a 100 g mass against the downwards pull of gravity. In everyday life this is about the same as holding a small apple.

TYPES OF FORCES

Some forces, such as hitting a ball with a bat, or pushing a box, are easy to picture. Other forces are harder to describe, but it is useful to be able to identify them when solving problems. Some of the forces that you might encounter when solving simple force problems are described in Table 7.1.1.

TABLE 7.1.1 Some simple types of forces

Type of force	Description
Applied force	An applied force is perhaps the easiest to imagine. It is a force applied to an object by a person or another object. If you pull or push a cart, these are applied forces.
Gravitational force	If you step on bathroom scales, you might say you weigh 60 kg. If you are cooking, you might weigh out 100 g of flour. However, these measurements (60 kg and 100 g) are masses, not weights. In physics, the weight of an object is the force it experiences due to the gravitational attraction of the Earth and due to its mass. The gravitational force is described in more detail in the next module, and in Units 3 and 4. For simple physics problems on Earth, the gravitational force acts directly downwards.
Normal reaction force	The normal reaction force acts to oppose another force applied to a solid object. For example, a book sitting on a table will experience a force downwards due to gravity, and will also experience a normal reaction force upwards from the table, to oppose its weight. If you push against a wall, the normal reaction force pushes back against your hands.
Frictional force	The frictional force opposes motion. It arises when two surfaces are pressed together, and it depends on the types of surfaces. For example, if you push a book across a table, the frictional force opposes the book's motion.
Tension	Tension is the force that acts along a string or wire when it is pulled tightly by forces at either end. For example, a bob on a pendulum will experience a gravitational force downwards, and a corresponding force upwards due to tension in the string. A tension force acts equally at all points in the string or wire.
Drag	Drag is the force due to air resistance, and it acts to slow motion. Drag can be useful, such as when it slows a parachutist as they fall, or it can be unwanted, such as the air resistance on a large truck. Many problems in Physics Units 1 and 2 will instruct you to ignore air resistance as it can be complicated to model, but it is useful to know that air resistance is acting in some way.

RESULTANT FORCES AND EQUILIBRIUM

If more than one force acts on a body at the same time, the body behaves as if only one force is acting. This force is the vector sum of all the forces and is called the **resultant force** or **net force**, F_{net}.

When the net force is zero, the forces are said to be in **equilibrium**. The forces are balanced.

Free-body or force diagrams

A free-body diagram or force diagram is simply a picture that represents the forces acting upon an object. The forces are drawn to scale. Recall from Module 6.1 how to draw vectors in one dimension, and how to add and subtract them graphically and algebraically.

Consider an object with two forces acting on it: 20 N east and 40 N west. These forces can be illustrated in a simplified diagram, as shown in Figure 7.1.2.

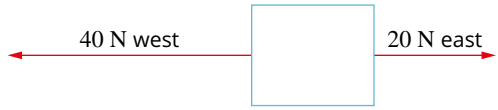


FIGURE 7.1.2 A free-body or force diagram. As the force acting west is twice as large as the force acting east, its arrow is drawn twice as long. The arrowheads indicate that the vectors are in opposite directions.

On Earth, objects will also have the force due to gravity acting on them. Consider the bin sitting on a table shown in Figure 7.1.3. The forces acting are the weight of the object downwards and the normal reaction force from the table upwards. In the figure, these forces are drawn to be the same size but in opposite directions—as the object is at rest the forces must be in equilibrium so they must be equal and opposite. (Note that there is no need to draw a representative picture of the bin for a free-body diagram—a square or a circle will work just as well.)

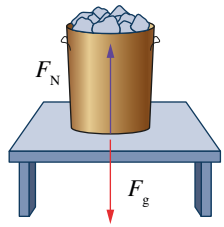


FIGURE 7.1.3 The forces acting on a bin sitting on a table. They are equal in magnitude but opposite in direction.

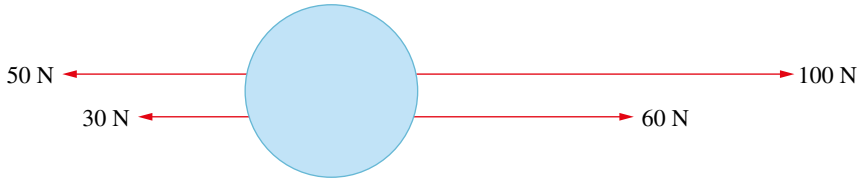
In Units 1 & 2 you will draw free-body diagrams showing forces acting in two dimensions, but will only solve problems mathematically with forces acting in one dimension (as illustrated in the above examples). In Units 3 & 4 you will also consider situations in which forces act in two or three dimensions.

The net force acting on an object can be found using the vector addition and subtraction techniques covered in Module 6.1. This is shown in the following worked example.

Worked example 7.1.1

FREE-BODY DIAGRAMS AND NET FORCE

A ball has four forces acting on it: 50 N left, 100 N right, 30 N left and 60 N right. Construct a free-body diagram, and find the resultant force acting on the ball.

Thinking	Working
Construct a free-body diagram showing all of the given forces.	
Apply a sign convention so that right is positive and left is negative.	The forces acting are: –50 N +100 N –30 N +60 N
Add the forces together.	$F_{net} = (-50) + 100 + (-30) + 60 = 80\,N$
Use the sign convention to describe the resultant force.	$F_{net} = 80\,N$ right

➤ Try yourself 7.1.1

FREE-BODY DIAGRAMS AND NET FORCE

A box is dragged across the floor with a force of 25 N. A frictional force of 10.0 N opposes the motion. Construct a free-body diagram of the box, and determine the net force acting on the box.

7.1 Review

SUMMARY

- A force is a push or a pull.
- A force is a vector quantity and therefore requires a magnitude and direction to describe it fully.
- Forces that act directly on a body are called contact forces. Forces that act on a body at a distance are non-contact forces.
- The forces that act on an object include applied forces (a simple push or pull), as well as gravitational and frictional forces, the normal reaction force, tension and drag.
- The forces acting on an object can be represented by free-body or force diagrams.
- If forces acting on an object are balanced, they are said to be in equilibrium. If forces are not balanced, a net or resultant force will act on the object.
- Forces can be added using vector addition to find the resultant force, F_{net}, acting on an object.

KEY QUESTIONS

Retrieval

1 Name three items that are needed to fully describe a force.

Comprehension

2 A girl is standing still in the queue at the airport, holding a suitcase. Describe the forces acting on the suitcase and determine if they balanced.

3 The girl in Question 2 gets tired, and puts the suitcase on the floor. Describe the forces acting on the suitcase now.

4 A swimmer completes a training drill in which he doesn't use his legs to kick, but only uses his stroke to move down the pool. Identify the force that causes the swimmer to move forwards down the pool.

5 When a magnet touches a paperclip, it can pick the paperclip up. A magnet can also pull a paperclip towards it. If the paperclip is covered with a piece of paper, it can still be picked up when the magnet touches the paper. Indicate whether the force provided by the magnet is a contact force or a non-contact force.

Analysis

6 Explain the difference between contact and non-contact forces.

7 Draw free-body diagrams for the following.

a An apple sits at rest on a table.

b A cat pushes the apple to the right across the table so that it accelerates.

c The apple falls towards the ground at constant velocity.

8 Calculate the net force on a sled pulled by a force of 120 N north when a frictional force of 120 N south acts upon it.

9 A cart experiences forces of 30 N west and 20 N east. Calculate the net force acting on the cart and identify the direction in which the cart will move.

10 A box experiences forces of 10 N up, 20 N down, 40 N up and 30 N down. Calculate the net force acting on the box and identify the direction in which the box will move.

7.2 Newton's laws of motion

BY THE END OF THIS MODULE, YOU SHOULD BE ABLE TO:

- understand Newton's three laws of motion
- use Newton's second law to calculate the force acting on an object for a given acceleration and mass
- be able to identify an action–reaction pair.

Newton's three laws of motion describe how forces can be used to explain the motion of bodies. The first law describes what happens to a body when there is no net force on it. The second law explains acceleration when there is an unbalanced force acting, and the third states that all forces act in action–reaction pairs.

NEWTON'S FIRST LAW

Newton's first law states that every object continues to be at rest, or continues with constant velocity, unless it experiences an unbalanced force. This is also called the law of inertia. Inertia is the tendency of an object to maintain its velocity. An object that is moving at constant velocity will keep moving unless an unbalanced force acts on it.

This is seldom observed in everyday life, due to the presence of forces such as friction and air resistance, which will eventually slow the motion of the object. To maintain constant motion, frictional forces must be balanced with some other force. For example, an object can keep moving at a constant velocity if it is driven by a motor.

Newton's first law is often misunderstood due to a common misconception. People mistakenly think that an object that is moving at constant velocity must have a force causing it to move.

Newton's first law can be stated as:

An object will maintain a constant velocity unless an unbalanced, external force acts on it.

This statement needs to be analysed in more detail by first examining some of the key terms used. The term 'maintain a constant velocity' implies that, if the object is moving, then it will continue to move with a velocity that has the same magnitude and direction. For example, if a car is moving at $12.0\,m\,s^{-1}$ south, then some time later it will still be moving at $12.0\,m\,s^{-1}$ south (Figure 7.2.1). It should also be noted that zero velocity is constant, so if the car is at rest at $0\,m\,s^{-1}$, then some time later it will still be at rest at $0\,m\,s^{-1}$. An object that is stationary will remain stationary, as long as the forces acting on it are balanced. For example, an object will fall due to the force of gravity, but will remain at rest when this force is balanced by the normal reaction force applied by a table.

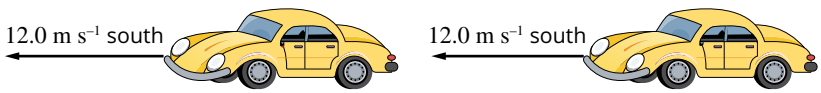


FIGURE 7.2.1 The car maintains a constant velocity.

Newton's first law:
An object will maintain a constant velocity unless an unbalanced, external force acts on it.

The use of the term 'unbalanced' in relation to the acting force implies that there must be a net force acting on the object. If the forces are balanced, then the object's velocity will remain constant. If the forces are unbalanced, then the velocity will change, or will not remain constant. This is illustrated in Figure 7.2.2.

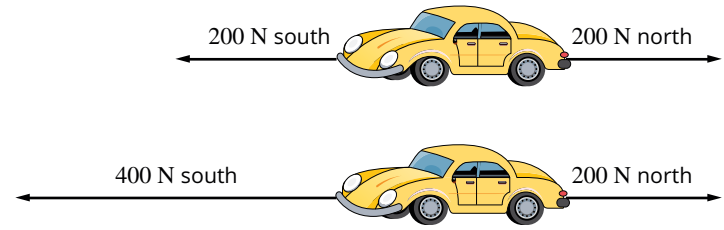


FIGURE 7.2.2 The forces on the top car are balanced, and so it will maintain a constant velocity. The forces on the bottom car are unbalanced: it has a net force in the forwards direction, so its velocity will change.

The term 'external', in relation to forces, implies that the forces are not internal. When forces are internal, they will have no effect on the motion of the object. For example, if you are sitting in a car and push forwards on the steering wheel then the car will not move forwards due to this force. In order for you to push forwards on the steering wheel, you must push backwards on the seat. Both the steering wheel and the seat are attached to the car; therefore, there are two forces acting on the car that are equal and in the opposite direction to each other, as shown in Figure 7.2.3. All internal forces must result in balanced forces on the object and therefore they will not change the velocity of the object.

FIGURE 7.2.3 This driver is applying internal forces on a car. These internal forces will balance and cancel each other.

The effects of forces

In Module 7.1, you found the resultant or net force acting on an object. Applying a net force can cause an object to speed up, to slow down, to start moving, to stop moving or to change its direction. The effect depends on the direction of the force in relation to the direction of the velocity vector of the object experiencing the force (Figure 7.2.4). The effect of external forces is summarised in Table 7.2.1.

TABLE 7.2.1 The effect of the application of a force and the relationship between the direction of the force and the velocity

Relationship between velocity and force	Effect of force
force applied to object at rest	object starts moving
force in same direction as velocity	magnitude of velocity increases (object speeds up)
force in opposite direction to velocity	magnitude of velocity decreases (object slows down)
force perpendicular to velocity	direction of velocity changes (object turns); more on this in Units 3 and 4

In all cases, the effect of a force is to change the velocity of an object. A force can change the magnitude of the velocity, the direction of the velocity, or both the magnitude and the direction of the velocity.

FIGURE 7.2.4 The upwards thrust force on a rocket has the effect of speeding it up, whereas the upwards drag force on a parachute has the effect of slowing the descent of a parachutist.

Stating Newton's first law in different ways

Ludwig Wittgenstein, an Austrian–British philosopher, stated that 'understanding means seeing that the same thing said different ways is the same thing'. To truly understand Newton's first law, you should be able to state it in different ways yet still recognise it as being consistent with Newton's first law.

All of these statements are consistent with Newton's first law:

- An object will maintain a constant velocity unless an unbalanced, external force acts on it.
- An object will continue with its motion unless an unbalanced, external force is applied.
- An object will not continue with its velocity if an unbalanced, external force is applied.
- A body will either remain at rest or continue with constant speed in a straight line (i.e. constant velocity) unless it is acted on by a net force.
- If an unbalanced, external force is applied, then an object's velocity will change.
- If a net force is applied, then an object's velocity will change.
- If no net force is applied, an object will not accelerate.
- If a net force is applied, an acceleration will result.
- Net forces cause acceleration.
- No force, no acceleration.
- Constant velocity means no net force is applied.

Inertia

Inertia is resistance to a change in motion of an object. It is related to the mass of the object. As the mass of the object increases, the inertia increases and therefore it becomes more difficult:

- to start it moving if it is stationary
- to stop it moving
- to change its direction of motion.

You can experience the effect of inertia when you push a trolley in a supermarket. If the trolley is empty, it is relatively easy to start pushing it, or to pull it to a stop when it is already moving. It is also easy to turn a corner. If you fill the trolley with heavy groceries, you notice that it becomes more difficult to move. It requires more force to make the trolley start moving when it is at rest, and it becomes more difficult to pull it to a stop if it is already moving. It also requires more force to change the trolley's direction.

It is important to note that the effect of inertia is independent of gravity. Inertia depends on mass, and weight force due to gravity also depends on mass, so it is a common misunderstanding to think that the effects of inertia only apply in the presence of gravity. However, it would be just as difficult to change the state of motion of the trolley in space as it is in the supermarket aisle.

Newton's first law and inertia are related. Due to inertia, an object will continue with its motion unless a net force acts on it. You could experience the connection between Newton's first law and inertia when standing up on public transport. Imagine standing up in a bus that is initially at rest and then starts moving forwards. If you are not holding on to anything, you might stumble backwards as though you have been pushed backwards. However, you have not been pushed backwards; the bus has started moving forwards and, because you have inertia, your mass resists the change in motion. According to Newton's first law, your body is simply maintaining its original state of being motionless until an unbalanced force acts to accelerate it. When the bus comes to a sudden stop, your body again resists the change by continuing to move forwards until an unbalanced force acts to bring it to a stop.

Frictional forces

A mathematical analysis of frictional forces is beyond the scope of this course. However, an understanding of how friction acts is useful when analysing the forces acting on an object. Friction is a force that opposes movement. Suppose you want to push your textbook along the table. As you start to push the book, you find that the book does not move at first. You then increase the force that you apply. Suddenly, at a certain critical value, the book starts to move.

There is a maximum frictional force that resists the start of the slide. This force is called the static friction force, F_s. Once the book begins to slide, a much lower force than F_s is needed to keep the book moving. This force is called the kinetic friction force and is represented by F_k. The graph in Figure 7.2.5 shows how the force required to move an object changes as static friction is overcome.

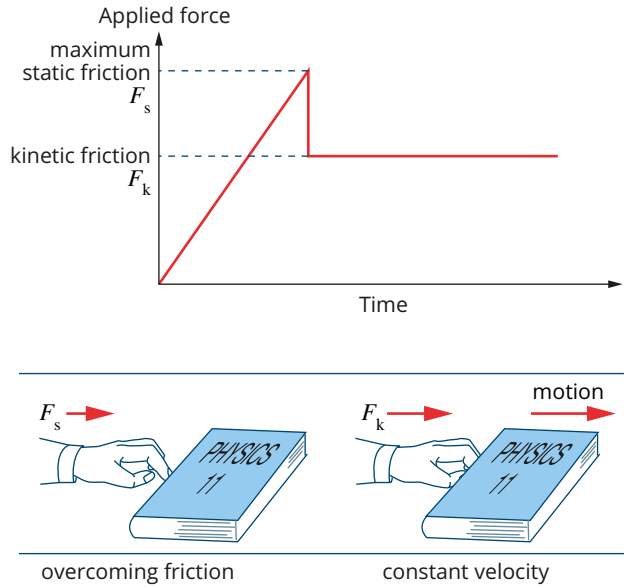


FIGURE 7.2.5 To get things moving, the static friction between an object and the surface must be overcome. This requires a larger force than is needed to maintain constant velocity.

Friction can be understood when you consider that even the smoothest surfaces are quite jagged at the microscopic level. When the book is resting on the table, the jagged points of its bottom surface have settled into the valleys of the surface of the table and this helps to resist attempts to slide the book. Once the book is moving, the surfaces do not have any time to settle into each other, so less force is required to keep the book moving.

Another fact that helps to explain friction arises from the forces of attraction between the atoms and molecules of the two different surfaces that are in contact. These surfaces produce weak bonding between their respective particles, so before one surface can move across the other, these bonds must be broken. This extra effort adds to the static friction force. Once there is relative motion between the surfaces, the bonds cannot re-form.

In everyday life, there are situations in which friction is desirable (e.g. walking) and others in which it is a definite problem. Consider the moving parts within the engine of a car. Friction can rob an engine of its fuel economy and cause it to wear out. Special oils and lubricants are introduced in order to prevent moving metal surfaces from touching. If the moving surfaces actually moved over each other, they would quickly wear, producing metal filings that could damage the engine. Instead, a thin layer of oil separates metal surfaces. The oils are chosen on the basis of their viscosity (thickness). For example, low viscosity oils can be used in the engine, but heavier oils are needed in the gearbox and differential of the car, where greater forces are applied to the moving parts. It is the lack of friction, however, that enables magnetic levitation trains to reach very high speeds (Figure 7.2.6).

FIGURE 7.2.6 This magnetic levitation train in China rides 1 cm above the track, so the frictional forces are negligible. The train is propelled by a magnetic force to a cruising speed of about 430 km h^{-1}.

At other times, friction is essential. For example, if there is any ice on the road when driving to the snowfields, drivers are required to fit chains to their cars. When driving over a patch of ice, the chains break through the ice and the car is able to grip the road. Similarly, friction is definitely required within the car's brakes when the driver wants to slow down. In fact, modern brake pads are specially designed to maximise the friction between them and the brake drum or disc.

Observing Newton's first law

An object in motion will eventually stop. For example, a pen sliding across a table is a good example of Newton's first law. The motion does not continue, so a net force must be acting. In this case, the force is not obvious. Confusion sometimes arises if the force due to friction is overlooked. Friction is a force that always acts in the opposite direction to the motion of objects. Air resistance is also a force that is often overlooked, as is the force due to gravity. By ignoring the effects of these important forces, it can be easy to come to the incorrect conclusion that the natural state of any object is to be at rest. By considering all the external forces acting on an object, it becomes clear that the natural state of any object is to maintain the velocity it currently has.

You can observe Newton's first law in the classroom by trying the following activities.

- Place some objects such as an eraser, a highlighter or a bottle of liquid paper on a piece of paper. Pull the paper slowly and observe what happens. Then pull the paper very quickly and observe what happens. A quick pull demonstrates the principle of inertia and Newton's first law.
- Make a pile of 20c coins on a smooth surface. Place them all tails-up except for the bottom coin. See if you can knock out the bottom coin by flicking it with another tails-up 20c coin.
- Put your right hand on your right shoulder, palm up, and place a coin on your elbow. Fling your arm down and see if you can catch the coin. The coin should remain motionless long enough for you to catch it.

NEWTON'S SECOND LAW

In Module 7.1, you learnt that unbalanced forces acting on an object mean that a net or resultant force is acting on it. The net force can be found using vector addition. The section on Newton's first law states that a net force will produce an acceleration. **Newton's second law** makes the quantitative connection between force, mass and acceleration. It states that the acceleration, a, of a body experiencing an unbalanced or net force, F_{net}, is directly proportional to the net force acting on it and inversely proportional to the mass, m, of the body. This equation is also commonly written as $F_{net} = ma$.

Newton's second law:

$a = \frac{F_{net}}{m}$ or $F_{net} = ma$

where

a is the acceleration of an object ($m\,s^{-2}$)

F_{net} is the net force applied to the object (N)

m is the mass of the object (kg)

By definition, 1 newton is the force needed to accelerate a mass of 1 kg at $1\,m\,s^{-2}$. The unit of force is the units of mass and acceleration combined, or $kg\,m\,s^{-2}$. This unit was renamed the newton (N) in honour of Sir Isaac Newton.

One of the implications of Newton's second law is that, for a given mass, a greater acceleration is achieved by applying a greater force. This is shown in Figure 7.2.7. Doubling the applied force will double the acceleration of the object. In other words, acceleration is proportional to the net force applied. Notice also in Figure 7.2.7 that the acceleration of the object is in the same direction as the net force applied to it.

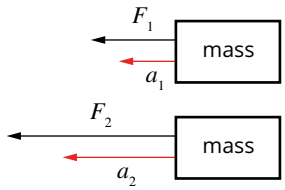


FIGURE 7.2.7 Given the same mass, a larger force will result in a larger acceleration. If the force is doubled, then the acceleration is also doubled.

Newton's second law also explains how acceleration is affected by the mass of an object. For a given force, the acceleration of an object will decrease with increased mass. In other words, acceleration is inversely proportional to the mass of an object. This is shown in Figure 7.2.8.

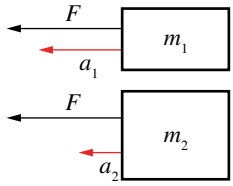


FIGURE 7.2.8 Given the same force, a larger mass will result in a lower acceleration. If the mass is doubled, then the acceleration is halved.

Newton's second law helps you to understand why a motorcycle can accelerate from traffic lights at a greater rate than a car or a truck. Although the engine of a car or truck often has more power than that of a motorcycle, the motorcycle has far less mass. This allows the motorcycle to accelerate more quickly than a car or truck (Figure 7.2.9).

FIGURE 7.2.9 The lower mass of motorcycles enables them to accelerate faster than cars and trucks.

Observing Newton's second law

The equation $F_{net} = ma$ enables you to calculate the force that causes a mass to accelerate. Mass is something that is easily experienced. You can measure the mass of an object on a balance. You can hold two masses in your hands and feel their effect. Similarly, you can observe acceleration, such as when a car accelerates away from the traffic lights. Force, on the other hand, is not something you can see. However, you can see the effect of a force.

Worked example 7.2.1

CALCULATING THE FORCE THAT CAUSES AN ACCELERATION

Calculate the net force causing a 5.50 kg mass to accelerate at 3.75 m s^{-2} west.

Thinking	Working
Ensure that the variables are in their standard units.	$m = 5.50$ kg $a = 3.75$ m s^{-2} west
Apply the equation for force from Newton's second law.	$F_{net} = ma$ $= 5.50 \times 3.75$ $= 20.6$ N
Give the direction of the net force, which is always the same as the direction of the acceleration.	$F_{net} = 20.6$ N west

➤ Try yourself 7.2.1

CALCULATING THE FORCE THAT CAUSES AN ACCELERATION

Calculate the net force causing a 75.8 kg runner to accelerate at 4.05 m s^{-2} south.

The first equation for uniform acceleration, which is discussed in Module 6.4 on page 221, can be combined with Newton's second law to calculate changes in time or velocity.

The first equation for uniform acceleration is:

$$v = u + at$$

This can be rearranged to give:

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

Combining this with $F_{net} = ma$ gives:

$$F_{net} = m\ \frac{v - u}{t}$$

The relationship between net force, mass and the velocity of an object is given by this equation:

$$F_{net} = m\ \frac{v - u}{t}$$

where

- F_{net} **is the force applied to the object (N)**
- m **is the mass of the object (kg)**
- u **is the initial speed (m s^{-1})**
- v **is the final speed in (m s^{-1})**
- t **is the time (s)**

Worked example 7.2.2

CALCULATING THE FINAL VELOCITY OF AN ACCELERATING MASS

Calculate the final velocity of a 225 kg scooter that accelerates for 2.00 s from rest due to a force of 2430 N north.

Thinking	Working
Ensure that the variables are in their standard units.	$m = 225\,\text{kg}$ $t = 2.00\,\text{s}$ $u = 0\,\text{m s}^{-1}$ $F_{net} = 2430\,\text{N north}$
Apply a variation of the equation for force from Newton's second law.	$F_{net} = m\frac{v-u}{t}$ $(v-u) = \frac{F_{net}t}{m}$ $v = \frac{F_{net}t}{m} + u$ $= \frac{2430 \times 2.00}{225} + 0$ $= 21.6\,\text{m s}^{-1}$
Give the direction of the final velocity as being the same as the direction of the force.	$v = 21.6\,\text{m s}^{-1}$ north

➤ Try yourself 7.2.2

CALCULATING THE FINAL VELOCITY OF AN ACCELERATING MASS

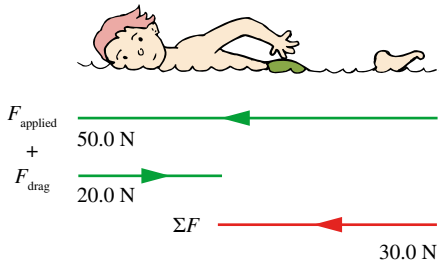
Calculate the final velocity of a 307 g fish that accelerates for 5.20 seconds from rest due to a force of 0.250 N left.

Forces do not always act alone. Mostly, more than one force will act on an object at any time. The overall effect of the forces depends on the direction of each of the forces. For example, some forces act together and some may oppose each other. When using Newton's second law, it is important to use the net, or resultant, force in the calculation. As forces are vectors, they can be added or combined using the techniques discussed in Module 6.1. Consider the following worked examples.

Worked example 7.2.3

ACCELERATION OF AN OBJECT WITH MORE THAN ONE FORCE ACTING ON IT

A swimmer whose mass is 75 kg applies a force of 50.0 N as he starts a lap. The water opposes his efforts to accelerate with a drag force of 20.0 N. Calculate his initial acceleration.

Thinking	Working
Determine the individual forces acting on the swimmer, and apply the vector sign convention.	$F_1 = 50.0\,\text{N forwards} = 50.0\,\text{N}$ $F_2 = 20.0\,\text{N backwards} = -20.0\,\text{N}$
Determine the net force acting on the swimmer.  	$F_{net} = F_1 + F_2$ $= 50.0 + (-20.0)$ $= +30.0\,\text{N or } 30.0\,\text{N forwards}$
Use Newton's second law to determine acceleration.	$a = \frac{F_{net}}{m}$ $= \frac{30.0}{75}$ $= 0.40\,\text{m s}^{-2}$ forwards

PA 2.1.2

➤ Try yourself 7.2.3

ACCELERATION OF AN OBJECT WITH MORE THAN ONE FORCE ACTING ON IT

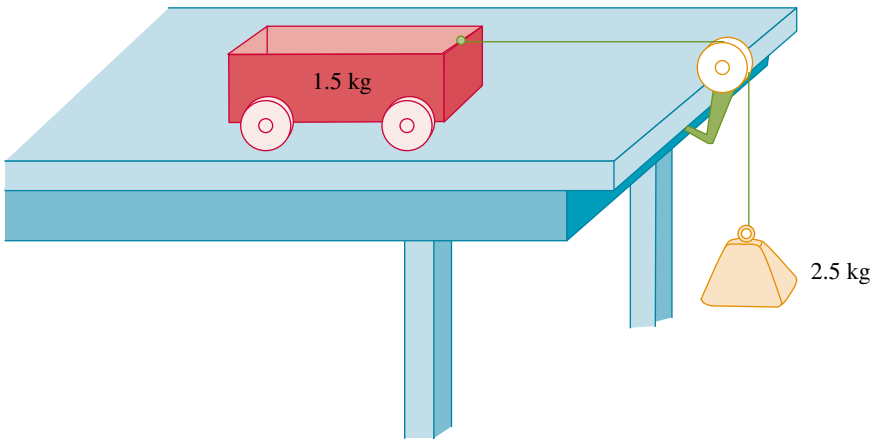
A car with a mass of 900.0 kg applies a driving force of 3000.0 N as it starts moving. Friction and air resistance oppose the motion of the car with a force of 750 N. Calculate the initial acceleration of the car.

If an object is allowed to fall under the influence of gravity, then $F_{net} = F_g = mg$. Remember that acceleration due to gravity is $g = 9.80\,m\,s^{-2}$ downwards.

Worked example 7.2.4

CALCULATING THE ACCELERATION OF A CONNECTED BODY

A 1.5 kg dynamics cart is connected by a cord to a 2.5 kg mass as shown. The cord is placed over a pulley and the mass is allowed to fall under the influence of gravity.



a Calculate the acceleration of the cart, assuming that the cart is unhindered by friction.

Thinking	Working
As the mass falls, the cart will move to the right. Therefore, both the downwards movement of the mass and the rightwards movement of the cart will be considered positive motion. Remember: $g = 9.80\,m\,s^{-2}$ down	$m_1 = 2.5\,kg$ $m_2 = 1.5\,kg$ $g = +9.80\,m\,s^{-2}$
Determine the forces acting on the system. The only force acting on the combined system of the cart and mass is the weight of the falling mass.	$F_{net} = F_g$ $= m_1 g$ $= 2.5 \times 9.80$ $= 24.5$ $= 25\,N$ in the positive direction
Calculate the mass being accelerated. This net force has to accelerate not only the cart but also the falling mass.	$m_1 + m_2$ $= 2.5 + 1.5$ $= 4.0\,kg$
Use Newton's second law to determine acceleration.	$a = \frac{F_{net}}{m}$ $= \frac{24.5}{4.0}$ $= 6.1\,m\,s^{-2}$ to the right

b Calculate the acceleration if a frictional force of 8.5 N acts against the cart.	
Thinking	**Working**
Write down the data that is given. Apply the sign convention to vectors.	$m_1 = 2.5\,\text{kg}$ $m_2 = 1.5\,\text{kg}$ $g = +9.80\,\text{m s}^{-2}$ $F_f = 8.5\,\text{N left} = -8.5\,\text{N}$
Determine the forces acting on the system. There are now two forces acting on the combined system of the cart and mass: the weight of the falling mass and friction.	$F_{net} = F_g + F_f$ $= 24.5 + (-8.5)$ $= 16.0\,\text{N}$
Use Newton's second law to determine acceleration.	$a = \frac{F_{net}}{m}$ $= \frac{16.0}{4.0}$ $= 4.0\,\text{m s}^{-2}$

➤ Try yourself 7.2.4

CALCULATING THE ACCELERATION OF A CONNECTED BODY

A 0.60 kg dynamics cart is connected by a cord to a 1.5 kg mass. The cord is placed over a pulley and the mass is allowed to fall under the influence of gravity.

a Determine the acceleration of the cart, assuming that the cart can move over the table unhindered by friction.

b Calculate the acceleration if a frictional force of 4.2 N acts against the cart.

Air resistance and the feather and hammer experiment

When two objects with different masses fall under the influence of the force due to gravity in the absence of air resistance, they will both fall at the same rate. That is, their accelerations will be the same. They will cover the same displacement in the same time and will hit the ground at the same time if dropped from the same height. This runs counter to our experience, because you are used to seeing the effects of air resistance. If you were to try this experiment on the Moon, you would find that a feather and a hammer would fall at the same rate because there is no atmosphere and, therefore, no air resistance. If you search online, you can find footage of an experiment performed by popular physicist Brian Cox, who uses a bowling ball and a feather in a NASA vacuum chamber to demonstrate this phenomenon.

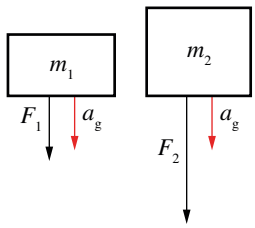


FIGURE 7.2.10 Given the same acceleration, a larger mass must have a larger force acting on it. If the mass is doubled, then the force is doubled.

If you understand that all objects accelerate due to gravity at the same rate in a vacuum, the common misconception is that the force due to gravity is the same on all objects. This is not true. In fact, the force due to gravity is larger on larger objects and smaller on smaller objects. You must not forget that the objects have different masses. A larger mass experiences a greater force due to gravity (weight) than a smaller mass, but it also has more inertia so it requires that greater force in order to achieve the same acceleration. Refer to Figure 7.2.10 to see how this works.

If you consider the relationship between acceleration and mass, and the relationship between acceleration and force, then:

$$a = \frac{F}{m}$$

If m_2 is ten times the mass of m_1, then the force due to gravity on m_2 is ten times the force due to gravity on m_1. Consider the acceleration of both masses:

$$a_1 = \frac{F_1}{m_1}$$

If $F_2 = 10F_1$ and $m_2 = 10m_1$, then:

$$\begin{aligned} a_2 &= \frac{F_2}{m_2} \\ &= \frac{10F_1}{10m_1} \\ &= \frac{F_1}{m_1} \\ &= a_1 \end{aligned}$$

This proof shows that the ratio of force to mass is equal for all combinations of force and mass under the same effects due to gravity. This proves that all masses will experience the same acceleration if air resistance is removed.

Why doesn't this experiment work on Earth?

When you see a feather floating down through the air, you know that it is accelerating at a rate far less than a hammer falling from the same height. From the previous section, you will know that the hammer and the feather have forces due to gravity acting on them that are proportional to their mass. They do not fall at the same rate because of the force of air resistance. Remember, Newton's second law says the acceleration is proportional to the net force acting on an object, which means you must consider all the forces acting on an object to determine the acceleration.

Air resistance is a force that results from air molecules colliding with the object. The faster the object moves, the greater the air resistance. In addition, the greater the surface area perpendicular to the direction of motion, the greater the air resistance. This force, which acts in the opposite direction to the motion of an object, is significant when compared with the weight of the feather, but insignificant when compared with the weight of the hammer. As a result, this force has a noticeable effect on the feather's acceleration but makes no noticeable difference to the hammer's acceleration.

In Figure 7.2.11, the force of air resistance is denoted as F_{AR} and is the same size on both objects. The difference between the two objects is the downwards weight force (due to gravity). Figure 7.2.11 also shows that the acceleration of the thinner object is much less than the acceleration of the thicker object. This is the observation that often causes misconceptions.

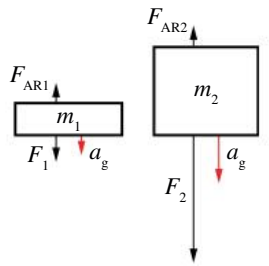


FIGURE 7.2.11 The effect of air resistance on an object depends on the surface area perpendicular to the motion and the speed of the object.

NEWTON'S THIRD LAW

Newton realised that when a body exerts a force on another body, then the forces exist in pairs and that each force in the pair acts on a different object. Figure 7.2.12 shows a hammer hitting a nail on the head. Both the hammer and the nail experience forces during this interaction. The nail experiences a downwards force as the hammer hits it. When the nail is hit it moves a distance into the wood. As it hits the nail, the hammer experiences an upwards force that causes the hammer to stop. These forces are known as an action–reaction pair and are shown in Figure 7.2.13.

FIGURE 7.2.12 A hammer hitting a nail is a good example of an action–reaction pair and Newton's third law.

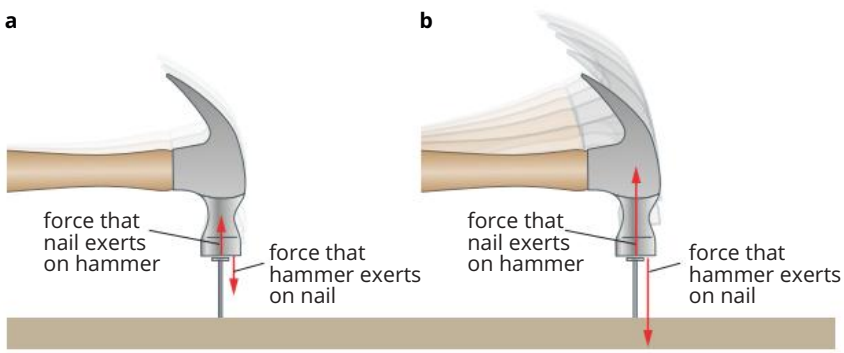


FIGURE 7.2.13 (a) As the hammer gently taps the nail, both the hammer and the nail experience small forces. (b) When the hammer smashes into the nail, both the hammer and the nail experience large forces. In both cases, these forces are designated by $F_{\text{on nail by hammer}}$ and $F_{\text{on hammer by nail}}$.

It is important to note that, regardless of whether the hammer exerts a small or a large force on the nail, the nail will exert exactly the same-size force back on the hammer.

Newton's third law states that when one body exerts a force on another body (an action force), the second body exerts an equal force in the opposite direction on the first (the reaction force):

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

Newton's third law:
For every action (force), there is an equal and opposite reaction (force).

To simplify the notation, the following convention will be used, where the first subscript is the body experiencing the force.

$$F_{AB} = F_{\text{on A by B}}$$

It is important to recognise that the action force and the reaction force in Newton's third law act on *different* objects and so should never be added together; their effect will only be on the object on which they act (Figure 7.2.14). Newton's third law applies not only to forces between objects that are in direct contact, but also to non-contact forces, such as the force due to gravity between objects.

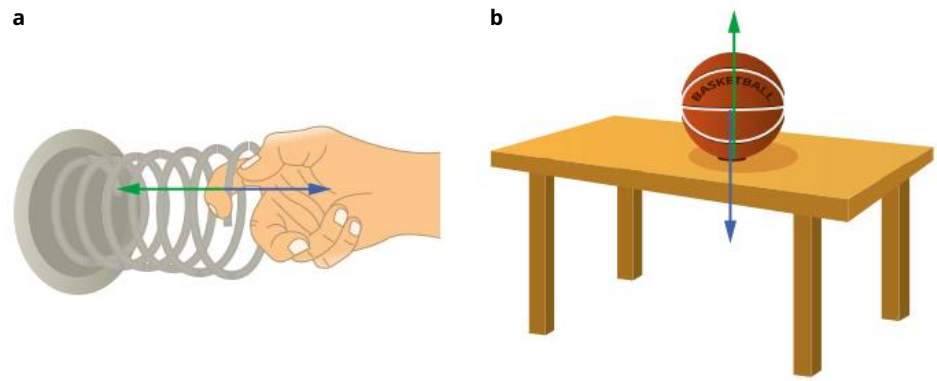


FIGURE 7.2.14 (a) An action–reaction pair. The hand pulls on the spring and the spring pulls back on the hand with an equal and opposite force. (b) Not an action–reaction pair. This is because the force due to gravity and the normal reaction force both act on the same object: the basketball.

The forces in an action–reaction pair:
- are the same magnitude (size)
- act in opposite directions
- are exerted on two different objects.

The main misconception that arises when considering Newton's third law is the belief that, if a large mass collides with a smaller mass, then the larger object exerts a larger force and the smaller object exerts a smaller force. This is not true. If you witnessed the **collision** between the car and the bus in Figure 7.2.15c, you would see the car undergoing a large deceleration, while the bus undergoes only a small acceleration.

Although the force on each object is the same size, the resulting acceleration may not be. This is because the rate of acceleration depends on the mass of the objects concerned (from Newton's second law). Sometimes, when the objects have very different masses, the effect of one force in the pair is much more noticeable. For example, if you stub your toe on a large, heavy rock, the force exerted on your toe by the rock causes your foot to decelerate significantly. The equal and opposite force exerted by your toe on the rock does not cause significant acceleration of the rock, because of its much greater mass.

From Newton's second law, you know that the same force acting on a larger mass will result in a smaller acceleration. This is the effect seen in the situation of the car colliding with the bus. Because of the car's small mass, the force acting on the car will cause the car to undergo a large deceleration. The occupants may be seriously injured as a result of this. The force acting on the bus is equal in size, but is acting on a much larger mass. As a result, the bus will have a relatively small acceleration and the occupants will not be as seriously affected.

Identifying the action and reaction forces

When analysing a situation to determine the action and reaction forces according to Newton's third law, it is helpful to be able to label the force vectors systematically. A good strategy for labelling force vectors is to use the capital letter F to represent the force and then to include a subscript consisting of the word 'on' and the thing on which the force is acting, and then the word 'by' and the thing that is applying the force.

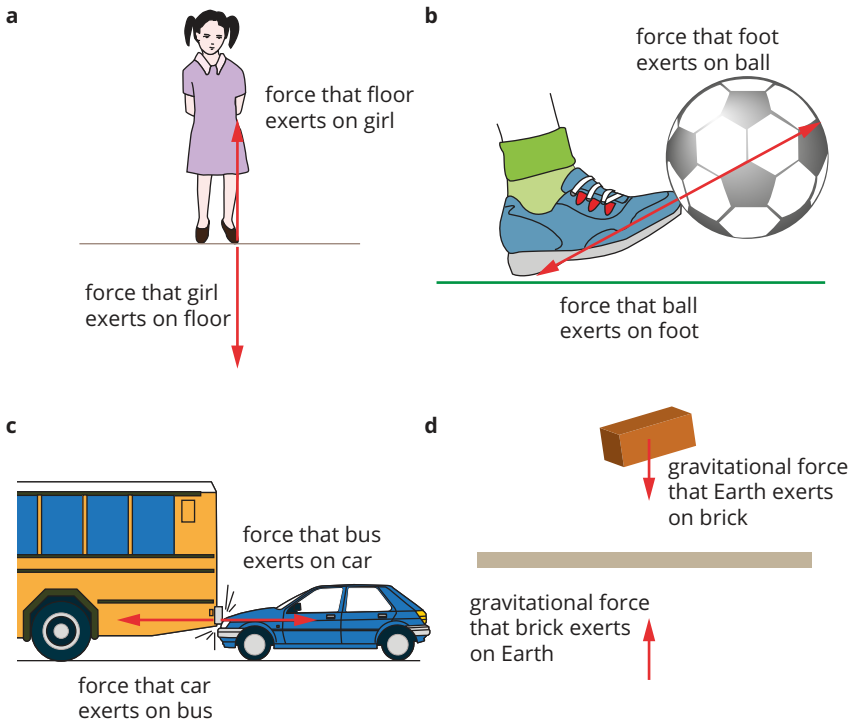


FIGURE 7.2.15 Some action–reaction pairs

The equal and opposite force is then labelled with a capital F and a subscript with the objects in reverse. For example, the action and reaction force vector arrows shown in Figure 7.2.15 can be labelled as shown in Table 7.2.2.

TABLE 7.2.2 Labels of action and reaction force vectors in Figure 7.2.15

	Action vector	Reaction vector
a	$F_{\text{on floor by girl}}$	$F_{\text{on girl by floor}}$
b	$F_{\text{on ball by foot}}$	$F_{\text{on foot by ball}}$
c	$F_{\text{on bus by car}}$	$F_{\text{on car by bus}}$
d	$F_{\text{on Earth by brick}}$	$F_{\text{on brick by Earth}}$

It should be noted that it does not matter which force is considered the action force and which is considered the reaction force. You could consider the force on the girl by the floor to be the action force and the force on the floor by the girl to be the reaction force. It does not matter, as long as you label them clearly. They are always equal in magnitude and opposite in direction.

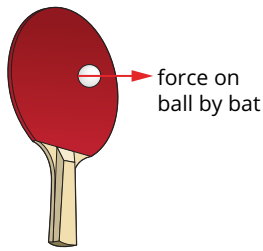
Observing Newton's third law

Newton's second and third laws can be observed in the classroom if you have two dynamics carts with wheels that are free to roll on a smooth surface such as a bench or desk. If the two carts are placed in contact with each other, and the plunger is activated on *one* of the carts, you will observe that both carts roll backwards. This is because of the action–reaction force pair described by Newton's third law. If the two carts have similar masses, you will observe that they accelerate apart at a similar rate. If one cart is heavier than the other, you will observe that the lighter cart accelerates at a faster rate. This is because the forces acting on both carts are equal in magnitude and so, according to Newton's second law, the smaller mass will experience a greater acceleration.

Worked example 7.2.5

APPLYING NEWTON'S THIRD LAW

In the diagram below, a table-tennis bat is in contact with a table-tennis ball and one of the forces is given.



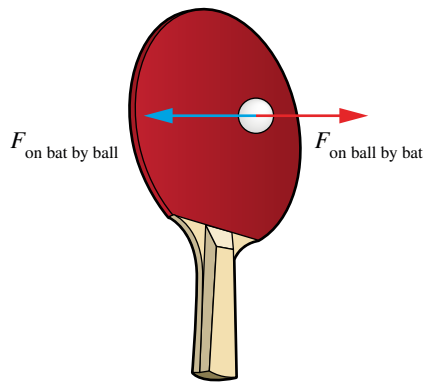
a Label the given force using the system 'F_{on} _____ by _____'.

Thinking	Working
Identify the two objects involved in the action–reaction pair.	The bat and the ball
Identify which object is applying the force and which object is experiencing the force, for the force vector shown.	The force vector shown is a force from the bat on the ball.
Use the system of labelling action and reaction forces 'F_{on} _____ by _____' to label the action force.	$F_{\text{on ball by bat}}$

b Label the reaction force to the given force using the system 'F_{on} _____ by _____'.

Use the system of labelling action and reaction forces 'F_{on} _____ by _____' to label the reaction force.	$F_{\text{on bat by ball}}$

c Draw the reaction force on the diagram, showing its size and location.

Use a ruler to measure the length of the action force and construct a vector arrow in the opposite direction with its tail on the point of application of the reaction force.	

➤ Try yourself 7.2.5

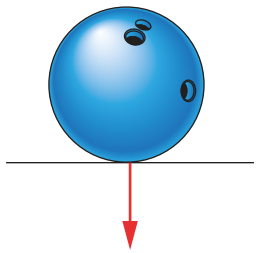
APPLYING NEWTON'S THIRD LAW

In the diagram below, a bowling ball is resting on the floor, and one of the forces is given. Copy the diagram into your book and complete the following.

a Label the given force using the system 'F_{on} _____ by _____'.

b Label the reaction force to the given force using the system 'F_{on} _____ by _____'.

c Draw the reaction force on the diagram, showing its size and location.



Newton's third law and motion

Newton's third law also explains how you are able to move around. In fact, Newton's third law is needed to explain all motion. Consider walking. Your leg pushes backwards on the ground with each step. This is an action force on the ground by the foot. As shown in Figure 7.2.15, a component of the force acts downwards and another component pushes backwards horizontally along the surface of the ground.

The force is transmitted because there is friction between your shoe and the ground. In response, the ground then pushes forwards on you via your foot. This forwards component of the reaction force enables you to move forwards. In other words, it is the ground pushing forwards on you that moves you forwards.

It is important to remember that in Newton's second law, $F_{\text{net}} = ma$, the net force, F_{net}, is the sum of the forces acting on the body. This does not include forces that are exerted by the body on other objects. When you push back on the ground, this force is acting on the ground and may affect the ground's motion. If the ground is firm, this effect is usually not noticed, but if you run along a sandy beach, the sand is clearly pushed back by your feet.

The act of walking relies on there being some friction between your shoe and the ground. Without it, there is no grip and it is impossible to supply the action force to the ground. Consequently, the ground cannot supply the reaction force needed to enable forwards motion. Walking on smooth ice is a good example of this. Mountaineers use crampons (basically, a rack of nails) attached to the soles of their boots in order to gain a better grip in icy conditions.

All motion can be explained in terms of action and reaction force pairs. Table 7.2.3 gives some examples of the action and reaction pairs in familiar motions.

TABLE 7.2.3 Action and reaction force pairs are responsible for all types of motion

Motion	Action force	Reaction force
swimming	hand pushes back on water	water pushes forwards on hand
jumping	legs push down on Earth	Earth pushes up on legs
bicycle or car	tyre pushes back on ground	ground pushes forwards on tyre
rocket	hot gas is forced backwards by the rocket	rocket is forced forwards by the hot gas
skydiving	force of gravitation on the skydiver from Earth	force of gravitation on Earth from skydiver

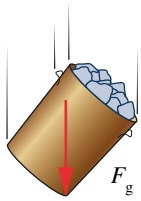


FIGURE 7.2.16 When the bin is in mid-air, there is an unbalanced force due to gravity acting on it so it accelerates towards the ground.

The normal force

When an object is allowed to fall under the influence of gravity, it is easy to see the effect of the force due to gravity. Figure 7.2.16 shows a rubbish bin falling to the ground. The action force is the force due to gravity of the Earth on the bin, so the net force on the bin is equal to the force due to gravity, and the bin therefore accelerates at $-9.80\,\text{m}\,\text{s}^{-2}$.

When the bin is at rest on a table, as shown in Figure 7.2.17(a), the force due to gravity ($F_g = mg$) is still acting between the Earth and the bin. The bin is at rest, so there must be another force acting to balance the force due to gravity on the bin. This upwards force is provided by the table. Because gravity pulls down on the mass of the bin, the bottom of the bin will push down on the surface of the table and the table provides a reaction force on the bin that is equal and opposite, so it will push upwards on the bin as shown in Figure 7.2.17(b).

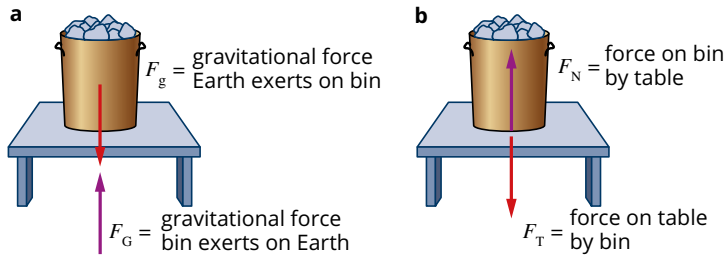


FIGURE 7.2.17 (a) Action–reaction gravitation forces between the bin and the Earth. (b) Action–reaction contact forces between the bin and the table.

The magnitude and direction of the gravitational force on the bin by Earth is equivalent to the magnitude and direction of the force on the table by the bin. Therefore the gravitational force on the bin by Earth is balanced by the upwards contact reaction force on the bin by the table. But it is important to note that these two forces are not the pair of forces described in Newton's third law (Figure 7.2.17). This is because the two forces are both acting on the bin and Newton's third law force pairs all act on *different* objects. The contact force provided by a surface that is perpendicular to another surface is called the normal reaction force. It is often abbreviated to normal force, and represented by F_N or N. The normal reaction force will be discussed in more detail in Units 3 & 4.

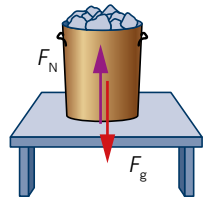


FIGURE 7.2.18 The effect of the two forces on the bin. These are not an action–reaction force pair, even though they are equal in magnitude and opposite in direction.

WS 2.1.5 WS 2.1.6

PA 2.1.3

7.2 Review

SUMMARY

- Newton's first law states that every object continues to be at rest, or continues with constant velocity, unless it experiences an unbalanced force. This is also called the law of inertia.
- Newton's second law states that the acceleration of a body experiencing an unbalanced force is directly proportional to the net force and inversely proportional to the mass of the body: $a = \frac{F_{net}}{m}$ or $F_{net} = ma$.
- Newton's third law states that when one body exerts a force on another body (an action force), the second body exerts an equal force in the opposite direction on the first (the reaction force): $F_{AB} = -F_{BA}$.
- The forces in an action–reaction pair are the same magnitude, act in opposite directions and are exerted on two different objects.
- For an object on a horizontal surface, the normal reaction force, F_N, and the force due to gravity, F_g, have the same magnitude, but act in opposite directions. When the object is stationary, $F_N = F_g$, and they are not an action–reaction force pair.

KEY QUESTIONS

Retrieval

1 State:
- **a** Newton's first law
- **b** Newton's second law
- **c** Newton's third law.

Comprehension

2 A student observes a box sliding across a surface and slowing down to a stop. Discuss the forces acting on the box.

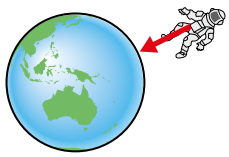
3 Phil is standing inside a tram when it moves off suddenly. Len, who was sitting down, commented that Phil was 'thrown backwards' as the tram started moving. Determine whether this statement is correct. Explain your answer in terms of Newton's laws.

4 A car changes its direction as it turns a bend in the road while maintaining its speed of $16\,m\,s^{-1}$. Explain the effects on the car.

5 A bowling ball rolls along a smooth wooden floor at constant velocity. Ignoring the effects of friction and air resistance, describe what you can deduce about the force acting on the bowling ball.

6 Identify the forces acting on a hammer and a nail when a heavy hammer hits a small nail.

7 In the figure below, an astronaut is orbiting the Earth, and one of the forces acting on him is shown by the red arrow.



- **a** Name the given force using the system '$F_{on\ _____\ by\ _____}$'.
- **b** Name the reaction force using the system '$F_{on\ _____\ by\ _____}$'.

8 When an inflated balloon is released it will fly around the room. Describe the forces acting that cause the balloon to move.

9 Determine the reaction force involved when a ball is hit with a racquet with a force of 100.0 N west.

10 Two students, James and Tania, are discussing the forces acting on a lunchbox that is sitting on the laboratory bench. James states that the weight force and the normal force are acting on the lunchbox and that because these forces are equal in magnitude but opposite in direction, they comprise a Newton's third law action–reaction pair. Tania disagrees, saying that these forces are not an action–reaction pair. Explain who is correct.

Analysis

11 Calculate the horizontal force that has to be applied to a wheelie bin if it is to be wheeled to the street on a horizontal path against a frictional force of 20.0 N at a constant $1.5\,m\,s^{-1}$.

12 A young boy is using a horizontal rope to pull his billycart at a constant velocity. A frictional force of 25 N also acts on the billycart. Calculate the force the boy applies to the rope.

7.2 Review *continued*

13 Passengers on commercial flights are required to be seated and have their seatbelts done up when their aircraft is coming in to land. Describe what would happen to a person who was standing in the aisle as the aircraft travelled along the runway during landing.

14 A magician performs a trick in which a cloth is pulled quickly from under a glass filled with water without causing the glass to fall over or the water to spill out.

- **a** Explain the physics principles underlying this trick.
- **b** Explain whether using a full glass would make the trick easier or more difficult.

15 Explain which of these objects would find it most difficult to come to a stop: a cyclist travelling at $50.0\,km\,h^{-1}$, a car travelling at $50.0\,km\,h^{-1}$ or a fully laden semitrailer travelling at $50.0\,km\,h^{-1}$.

16 A light aircraft flying at constant speed at a constant altitude has a weight of 50.0 kN down, and the thrust produced by its engines is 12 kN to the east. Determine the lift force required by the wings of the aircraft, and calculate the drag force that is acting.

Use $g = 9.80\,m\,s^{-2}$ when answering the questions 17–24.

17 Calculate the acceleration of a 23.9 kg mass when a net force of 158 N north acts on it.

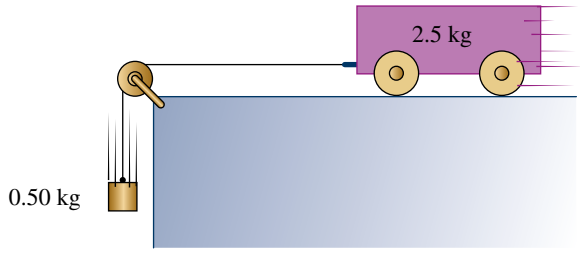
18 Calculate the mass of a train if it accelerates at $7.20\,m\,s^{-2}$ north when a net force of 565 000 N north acts on it.

19 Calculate the final velocity of a stationary 3.00 g marble when a net force of 0.0823 N north acts on it for 0.0105 seconds.

20 Mary is paddling a canoe. The paddles are providing a constant driving force of 45 N south and the drag forces total 25 N north. The mass of the canoe is 15 kg and Mary has a mass of 50.0 kg.

- **a** Calculate Mary's weight.
- **b** Find the net horizontal force acting on the canoe.
- **c** Calculate the magnitude of the acceleration of the canoe.

21 A 0.50 kg metal block is attached by a piece of string to a dynamics cart. The block is allowed to fall from rest, dragging the cart along. The mass of the cart is 2.5 kg.



- **a** If friction is ignored, calculate the acceleration of the block as it falls.
- **b** Determine the speed of the block after 0.50 s.
- **c** If a frictional force of 4.3 N acts on the cart, calculate its acceleration.

22 An empty truck of mass 2000 kg has a top acceleration of $2.0\,m\,s^{-2}$. The mass of one box is 300 kg. Determine the number of boxes that would be loaded on to the truck if the truck's top acceleration decreased to $1.25\,m\,s^{-2}$.

23 A 70.0 kg fisherman is fishing in a 40.0 kg dinghy at rest on a still lake when, suddenly, he is attacked by a swarm of wasps. To escape, he leaps into the water and exerts a horizontal force of 140 N north on the boat.

- **a** Determine the force the boat exerts on the fisherman.
- **b** Calculate the initial acceleration of the boat.
- **c** If the force on the fisherman lasted for 0.50 s, determine the initial speed attained by both the man and the boat.

24 An astronaut becomes untethered during a space walk and drifts away from the spacecraft. To get back to the ship, she decides to throw her tool kit away. Comment on the direction in which she should throw the tool kit.

7.3 Momentum

BY THE END OF THIS MODULE, YOU SHOULD BE ABLE TO:

- understand the concept of momentum
- find the momentum of an object as the product of its mass and velocity
- understand that changes in momentum are caused by the action of a net force.

It is possible to understand some physics concepts intuitively without knowing the physics terms or words that describe them. For example, you may know that once a heavy object gets moving it is difficult to stop it, whereas a lighter object moving at the same speed is easier to stop. In the previous sections of this chapter you have seen how Newton's laws of motion can be used to explain these observations. In this section you will explore how these observations can be related to the concept called momentum.

The **momentum** of an object relates to both its mass and its velocity. The footballers colliding in Figure 7.3.1 have momentum due to their mass, and the faster they run, the more momentum they will have. A slower moving player has less momentum than one who is moving faster. Similarly, a person with greater mass will have more momentum than a smaller, lighter person travelling at the same speed. The more momentum an object has, due to its mass or its velocity, the more momentum it has to lose before it stops.

FIGURE 7.3.1 Momentum is related to mass and velocity. The greater the mass or velocity, the harder it is to stop or start moving.

The momentum of an object is given by:

$p = mv$

where

p is momentum (kg m s^{-1})

m is the mass of the object (kg)

v is the velocity of the object (m s^{-1})

The greater an object's mass or velocity, the larger that object's momentum. As velocity is a vector quantity, momentum is also a vector and so it must have magnitude, units and direction. The direction of a momentum vector will always be the same as the direction of the velocity vector. For calculations of change in momentum in a single dimension, you can use the sign conventions of positive and negative.

Momentum is a vector quantity, so it must have magnitude, units and direction.

Worked example 7.3.1

MOMENTUM

Calculate the momentum of a 60.0 kg student walking at $3.50\ \text{m s}^{-1}$ east.	
Thinking	**Working**
Ensure that the variables are in their standard units.	$m = 60.0\ \text{kg}$ $v = 3.50\ \text{m s}^{-1}$ east
Apply the equation for momentum.	$p = mv$ $= 60.0 \times 3.50$ $= 210\ \text{kg m s}^{-1}$ east

➤ Try yourself 7.3.1

MOMENTUM

Calculate the momentum of a 1230 kg car driving at 16.7 m s^{-1} north.

The change in momentum of an object, Δp, moving in one dimension can be calculated from the mass of the object, m, its initial velocity, u, and its final velocity, v.

$$\Delta p = p_{\text{final}} - p_{\text{initial}}$$
$$= mv - mu$$

The change in momentum of an object is given by:

$\Delta p = mv - mu$

where

Δp **is the change in momentum (kg m s^{-1})**

m **is the mass (kg)**

v **is the final velocity (m s^{-1})**

u **is the initial velocity (m s^{-1})**

Worked example 7.3.2

CHANGE IN MOMENTUM 1

A student rides a bike to school and approaches the bike rack with a velocity of 8.2 m s^{-1} east. The student and the bike have a combined mass of 80.0 kg and the student stops at the rack.

Calculate the change in momentum of the student during the time it takes to stop.

Thinking	Working
Ensure that the variables are in their standard units.	$m = 80$ kg $u = 8.2$ m s^{-1} east $v = 0$ m s^{-1}
Apply the sign convention to the velocity vector.	$m = 80$ kg $u = +8.2$ m s^{-1} $v = 0$ m s^{-1}
Apply the equation for change in momentum.	$\Delta p = mv - mu$ $= (80 \times 0) - (80 \times 8.20)$ $= 0 - 656$ $= -656$ kg m s^{-1}
Apply the sign convention to describe the direction of the change of momentum.	$\Delta p = 660$ kg m s^{-1} west

➤ Try yourself 7.3.2

CHANGE IN MOMENTUM 1

A student hurries to class after lunch, moving with a velocity of 4.55 m s^{-1} north. She suddenly remembers that she has forgotten her laptop and goes back to her locker at a velocity of 6.15 m s^{-1} south. If her mass is 75.0 kg, calculate the change in momentum of the student during the time it takes to turn around.

Worked example 7.3.3

CHANGE IN MOMENTUM 2

A car of mass 1500 kg that is initially travelling at 30.0 m s^{-1} north undergoes a change of momentum of 12 000 kg m s^{-1} south. Calculate the final velocity of the car.

Thinking	Working
Ensure that the variables are in their standard units.	$m = 1500\,\text{kg}$ $u = 30.0\,\text{m s}^{-1}$ north $\Delta p = 12\,000\,\text{kg m s}^{-1}$ south
Apply the sign convention to the velocity vector.	$m = 1500\,\text{kg}$ $u = +30.0\,\text{m s}^{-1}$ $\Delta p = -12\,000\,\text{kg m s}^{-1}$
Apply the equation for change in momentum.	$\Delta p = mv - mu$ $-12\,000 = (1500 \times v) - (1500 \times 30.0)$ $-12\,000 = 1500v - 45\,000$ $33\,000 = 1500v$ $v = +\frac{33\,000}{1500}$ $= +22\,\text{m s}^{-1}$
Apply the sign convention to describe the direction of the change of momentum.	$v = 22\,\text{m s}^{-1}$ north

➤ Try yourself 7.3.3

CHANGE IN MOMENTUM 2

A 2200 kg elephant walking at 2.5 m s^{-1} north suddenly undergoes a change of momentum of 4400 kg m s^{-1} north. Calculate the final velocity of the elephant.

Force is equal to the rate of change of momentum. This can be shown using Newton's second law, $a = \frac{F_{net}}{m}$, and the acceleration equation $a = \frac{v-u}{t}$.

The following derivation shows how Newton's second law relates to momentum. It results with net force, F_{net}, equal to the change in momentum, Δp, divided by the period of time, Δt, which is the rate of change of momentum:

$$\begin{aligned} a &= \frac{F_{net}}{m} \\ F_{net} &= ma \\ &= m\frac{(v-u)}{t} \\ &= \frac{mv-mu}{t} \\ &= \frac{p}{t} \end{aligned}$$

This means that changes in momentum are caused by the action of a net force.

Newton's second law showed that when forces act on an object a change of momentum occurs. When an object changes its velocity, its momentum will also change. An increase in velocity corresponds to an increase in momentum, and a decrease in velocity corresponds to a decrease in momentum. This change often occurs in collisions, so you can also consider this change in momentum as a transfer of momentum.

It is easy to change the velocity of an object. You can either run faster or run slower; you can press a little harder on the pedals of a bike or press a little softer. You can also bounce an object off a surface. For example, the basketball in Figure 7.3.2 experiences a change in velocity when it changes direction during the bounce. The cause of these changes in motion will be discussed in Module 7.4.

FIGURE 7.3.2 A bouncing basketball undergoes a change in momentum when it changes direction as it bounces.

7.3 Review

SUMMARY

- Momentum is the product of an object's mass and velocity.
- Momentum is a vector quantity and is calculated using the equation $p = mv$.
- Change or transfer in momentum, Δp, is also a vector quantity, and is given by $\Delta p = mv - mu$.
- A change or transfer in momentum occurs when an object changes its velocity, i.e. when it accelerates or has a net force acting on it.

KEY QUESTIONS

Retrieval

1 Give an equation for the following:
- **a** the momentum of an object
- **b** the change in momentum of an object.

Comprehension

2 Viggo runs south at $5\,km\,h^{-1}$, and then turns around and runs north at $5\,km\,h^{-1}$. He says that because his speed is the same, his momentum hasn't changed. Explain why he is not correct.

3 Lou is performing an experiment in which she lets a trolley roll down a slope. She wants to double the momentum of the trolley. Describe how she could do this, without pushing the trolley to increase its velocity.

Analysis

4 Calculate the momentum of a 3.50 kg fish swimming at $2.50\,m\,s^{-1}$ south.

5 Calculate the momentum of a 433 kg boat travelling at $22.2\,m\,s^{-1}$ west.

6 Calculate the momentum of a 65.0 g tennis ball being served at $61.0\,m\,s^{-1}$ south.

7 Determine which of these objects has the greater momentum: a medicine ball of mass 4.5 kg travelling at $3.5\,m\,s^{-1}$ or one of mass 2.5 kg travelling at $6.8\,m\,s^{-1}$.

8 Calculate the change of momentum of a 9.50 kg dog that changes its velocity from $2.50\,m\,s^{-1}$ north to $6.25\,m\,s^{-1}$ south.

9 Calculate the change of momentum of a 6050 kg truck as it changes from moving at $22.2\,m\,s^{-1}$ west to $16.7\,m\,s^{-1}$ east.

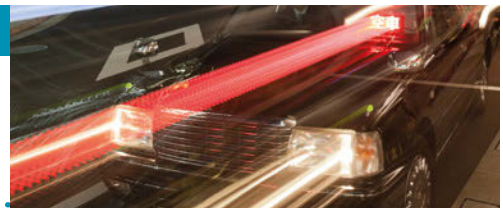
10 The velocity of an 8.00 kg mass changes from $3.00\,m\,s^{-1}$ east to $8.00\,m\,s^{-1}$ east. Calculate the change in momentum.

11 The momentum of a ball of mass 0.125 kg changes by $0.075\,kg\,m\,s^{-1}$ south. If its original velocity was $3.00\,m\,s^{-1}$ north, determine its final velocity.

7.4 Impulse

BY THE END OF THIS MODULE, YOU SHOULD BE ABLE TO:

- understand impulse as the change in momentum of an object
- calculate the impulse and force acting on an object
- calculate the impulse from a force–time graph.



IMPULSE OF A FORCE

In a car crash, it's not only the speed of the car that counts, it's also how quickly it stops!

This is a direct consequence of Newton's second law. If the velocity decreases over a long time, the deceleration is small. Using the formula $F = ma$, if a is small, you can conclude that the force required to bring the car to a stop will also be relatively small. If, however, the car is brought to a halt very rapidly, there will be a large deceleration requiring a large force (Figure 7.4.1). The force determines the damage. Despite the likelihood of injury caused by a large force that acts for a short time, such as in a car crash, a smaller force acting for a longer time has the same effect on the motion of an object. Gradually applying the brakes will also bring the car to rest. One way to quantify the similarity between these situations is to describe the impulse in a collision, which considers both the force and the time over which the force acts.

FIGURE 7.4.1 Rapid deceleration requires a large force and often results in damage and injury.

An **impulse** is a measure of the force on a body and the time over which the force acts. An impulse is calculated as the product of the resultant force, F_{net} (often just written as F), and the change in time, Δt.

$$I = F_{net}\ t$$

From Newton's second law, $F_{net} = \frac{p}{t}$, it can be shown that:

$$I = F_{net}\ t = \ p$$

From the change in momentum equation, $\Delta p = mv - mu$, it can be shown that:

$$I = \ p = mv - mu$$

The impulse, I, of the resultant force is equal to the change in momentum of the object. Impulse is a vector quantity, and so requires direction as well as magnitude. Its units are newton seconds (N s).

The impulse of the resultant force acting on an object is given by:

$I = \Delta p = mv - mu$

where

I is the impulse (N s)

Δp is the change in momentum (kg m s^{-1})

m is the mass (kg)

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

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

Units of momentum

Impulse can be expressed in terms of a momentum change, so the units for momentum ($kg\,m\,s^{-1}$) and impulse (N s) must be equivalent. This can be shown by using Newton's second law.

Given that $1\,N = 1\,kg\,m\,s^{-2}$ (from $F = ma$), it follows that $1\,N\,s = 1\,kg\,m\,s^{-2} \times s$

$$1\,N\,s = 1\,kg\,m\,s^{-1}$$

Even though the units are equivalent, they should be used with the appropriate quantity that is involved.

The newton second (N s) is the product of a force and a time interval and so should be used with impulse. The kilogram metre per second ($kg\,m\,s^{-1}$) is the product of a mass and a velocity and so should be used with momentum. Even so, it is not uncommon to see newton seconds used as the unit of momentum, nor is this incorrect.

Worked example 7.4.1

CALCULATING THE IMPULSE AND FORCE

A 1485 kg sports car is travelling at $93.0\,km\,h^{-1}$ north when the driver loses control of the car on an icy road. The car comes to rest against a tree.

a Calculate the impulse of the tree on the car.

Thinking	Working
Convert $km\,h^{-1}$ to $m\,s^{-1}$.	$93.0\,km\,h^{-1} = \frac{93.0}{3.6}\,m\,s^{-1} = 25.8\,m\,s^{-1}$
Calculate the change in momentum. The negative sign indicates that the change in momentum (the impulse), is in the direction opposite to the car's initial momentum, as would be expected.	$p = mv - mu$ $= (1485 \times 0) - (1485 \times 25.8)$ $= 0 - 38313$ $= -3.83 \times 10^4\,kg\,m\,s^{-1}$
The impulse is the change in momentum of the car. Apply a sign convention to the answer, taking north as positive, and remember to give the units as N s.	$I = 3.83 \times 10^4\,N\,s$ south

b If the car crumples in 40.0 ms, find the force exerted by the tree on the car.

Thinking	Working
Transpose $\Delta p = F_{net}\,\Delta t$ to find the force.	$F_{net} = \frac{p}{t}$ $= \frac{-3.83 \times 10^4}{40.0 \times 10^{-3}}$ $= -9.57 \times 10^5\,N$ $= 9.57 \times 10^5\,N$ south

➤ Try yourself 7.4.1

CALCULATING THE IMPULSE AND FORCE

The driver of a 1485 kg car stops to refuel. The vehicle was travelling at $95.5\,km\,h^{-1}$ north and took 12.5 s to come to a halt at the petrol station.

a Calculate the impulse of the braking system on the car.

b Calculate the average braking force.

Worked example 7.4.2

CALCULATING THE FORCE AND IMPULSE

A student drops a 105 g pool ball onto a concrete floor from a height of 2.00 m. Just before it hits the floor, the velocity of the ball is 6.26 m s^{-1} down. Before it bounces back up, there is an instant in time at which the ball's velocity is zero. The time it takes for the ball to change its velocity to zero is 5.02 ms.

a Calculate the change in momentum of the pool ball.

Thinking	Working
Ensure that the variables are in their standard units.	$m = 0.105\,\text{kg}$ $u = 6.26\,\text{m s}^{-1}$ down $v = 0\,\text{m s}^{-1}$
Apply the sign and direction convention for motion in one dimension. Up is positive and down is negative.	$m = 0.105\,\text{kg}$ $u = -6.26\,\text{m s}^{-1}$ $v = 0\,\text{m s}^{-1}$
Apply the equation for change in momentum.	$\Delta p = mv - mu$ $= (0.105 \times 0) - (0.105 \times -6.26)$ $= 0.657\,\text{kg m s}^{-1}$
Refer to the sign and direction convention to determine the direction of the change in momentum.	$\Delta p = 0.657\,\text{kg m s}^{-1}$ up

b Calculate the impulse of the pool ball.

Thinking	Working
Using the answer to part (a), apply the equation for impulse.	$I = \Delta p$ $= 0.657\,\text{N s}$
Refer to the sign and direction convention to determine the direction of the impulse.	$I = 0.657\,\text{N s}$ up

c Calculate the force that acts to cause the impulse.

Thinking	Working
Use the answer to part (b). Ensure that the variables are in their standard units. $5.02\,\text{ms} = 5.02 \times 10^{-3}\,\text{s}$	$I = 0.657\,\text{N s}$ $\Delta t = 5.02 \times 10^{-3}\,\text{s}$
Apply the equation for force.	$F\Delta t = I$ $F = \frac{I}{t}$ $= \frac{0.657}{5.02 \times 10^{-3}}$ $= 131\,\text{N}$
Refer to the sign and direction convention to determine the direction of the force.	$F = 131\,\text{N}$ up

➤ Try yourself 7.4.2

CALCULATING THE FORCE AND IMPULSE

A student drops a 56.0 g egg onto a table from a height of 60.0 cm. Just before it hits the table, the velocity of the egg is 3.43 m s^{-1} down. The egg's final velocity is zero as it smashes on the table. The time it takes for the egg to change its velocity to zero is 3.55 ms.

a Calculate the change in momentum of the egg.

b Calculate the impulse of the egg.

c Calculate the force that acts to cause the impulse.

Worked example 7.4.3

CALCULATING THE FORCE AND IMPULSE (SOFT LANDING)

A student drops a 105 g pool ball onto a foam mattress from a height of 2.00 m. Just before it hits the foam mattress, the velocity of the ball is 6.26 m s^{-1} down. Before it bounces back up, there is an instant in time at which the ball's velocity is zero. The time it takes for the ball to change its velocity to zero is 0.360 s.

a Calculate the change in momentum of the pool ball.

Thinking	Working
Ensure that the variables are in their standard units.	$m = 0.105\,\text{kg}$ $u = 6.26\,\text{m s}^{-1}$ down $v = 0\,\text{m s}^{-1}$
Apply the sign and direction convention for motion in one dimension. Up is positive and down is negative.	$m = 0.105\,\text{kg}$ $u = -6.26\,\text{m s}^{-1}$ $v = 0\,\text{m s}^{-1}$
Apply the equation for change in momentum.	$\Delta p = mv - mu$ $= (0.105 \times 0) - (0.105 \times -6.26)$ $= 0.657\,\text{kg m s}^{-1}$
Refer to the sign and direction convention to determine the direction of the change in momentum.	$\Delta p = 0.657\,\text{kg m s}^{-1}$ up

b Calculate the impulse of the pool ball.

Thinking	Working
Using the answer to part (a), apply the equation for impulse.	$I = \Delta p$ $= 0.657\,\text{N s}$
Refer to the sign and direction convention to determine the direction of the impulse.	$I = 0.657\,\text{N s}$ up

c Calculate the force that acts to cause the impulse.

Thinking	Working
Using the answer to part (b), ensure that the variables are in their standard units.	$I = 0.657\,\text{N s}$ $\Delta t = 0.360\,\text{s}$
Apply the equation for force.	$F\Delta t = I$ $F = \frac{I}{t}$ $= \frac{0.657}{0.360}$ $= 1.83\,\text{N}$
Refer to the sign and direction convention to determine the direction of the force.	$F = 1.83\,\text{N}$ up

➤ Try yourself 7.4.3

CALCULATING THE FORCE AND IMPULSE (SOFT LANDING)

A student drops a 56.0 g egg into a mound of flour from a height of 60.0 cm. Just before it hits the mound of flour, the velocity of the egg is 3.43 m s^{-1} down. The egg's final velocity is zero as it sinks into the mound of flour. The time it takes for the egg to change its velocity to zero is 0.325 seconds.

a Calculate the change in momentum of the egg.

b Calculate the impulse of the egg.

c Calculate the force that acts to cause the impulse.

From these worked examples you should notice the following:

- The change in momentum and the impulse were always the same.
- Regardless of the surface that the object landed on, the impulse or change in momentum remained the same.
- The period of time was the main difference between the two different surfaces. Hard surfaces resulted in a short time to stop and soft surfaces resulted in a longer time to stop.
- The effect of the period of time on the force was dramatic. A shorter time meant a greater force, whereas a longer time meant a much smaller force.

FORCE VERSUS TIME GRAPHS

In many practical applications, the force applied to an object is not constant. For example, when a tennis player hits a ball, the initial force exerted by the racquet is relatively small. As the strings stretch and the ball deforms, this force builds up to a maximum value before decreasing again as the ball rebounds from the racquet. If the force is measured over time, this data can be represented graphically (Figure 7.4.2).

The impulse of the ball, or the change in momentum, may be found from the product of the average force, F_{av}, and time, Δt:

$$I = F_{av}\Delta t$$

Impulse is simply the area under the force–time graph.

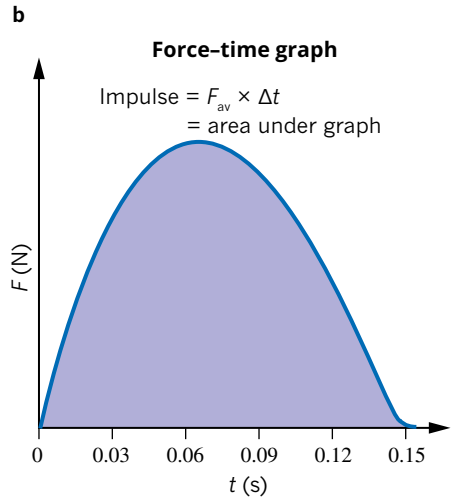
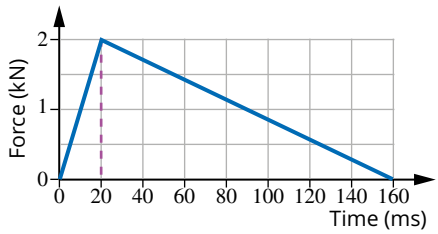


FIGURE 7.4.2 (a) The tennis player hits the ball with a racquet. (b) The force changes with time as the racquet strikes the ball.

Worked example 7.4.4

RUNNING SHOES

A running-shoe company plots the following force–time graph for a running shoe. Use the data to calculate the magnitude of the impulse.

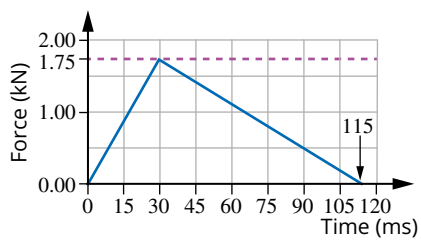


Thinking	Working
Recall that impulse $I = F_{av}\Delta t$. When the force is not constant, impulse is the area under the force–time graph. The area shown is a triangle.	$I = \frac{b \times h}{2}$ $= \frac{160 \times 10^{-3} \times 2 \times 10^{3}}{2}$ $= 160$ N s

➤ Try yourself 7.4.4

RUNNING SHOES

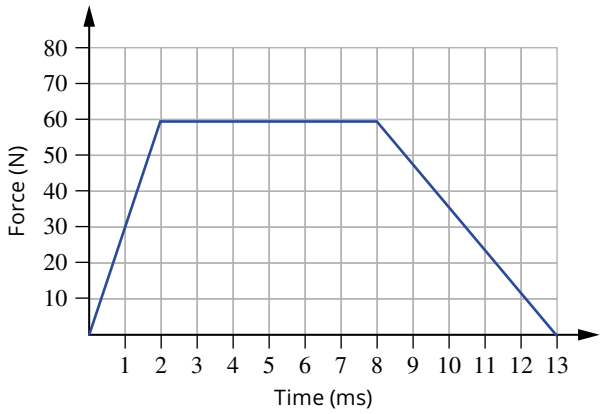
A running-shoe company plots the following force–time graph for an alternative design intended to reduce the peak force on the heel. Calculate the magnitude of the impulse.



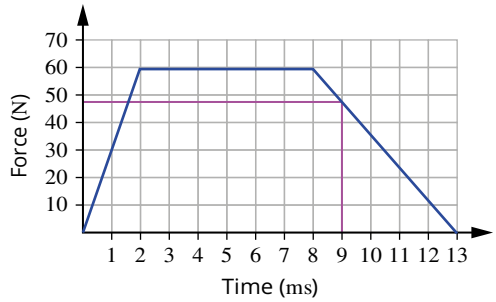
Worked example 7.4.5

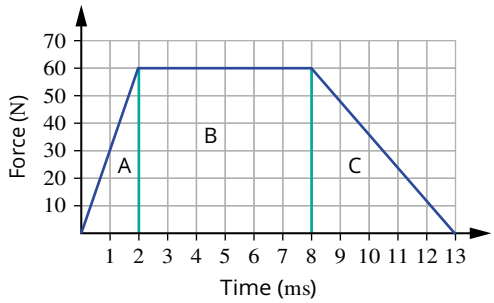
CALCULATING THE TOTAL IMPULSE FROM A CHANGING FORCE

A student records the force acting on a rubber ball as it bounces off a hard concrete floor over a period of time. The graph shows the forces acting on the ball during its collision with the concrete floor.



a Determine the force acting on the ball over a time of 9.0 ms.

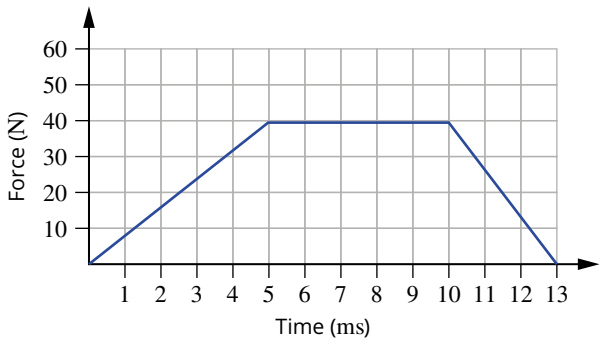
Thinking	Working
From the 9.0 ms point on the horizontal axis, go up to the line of the graph, then across to the vertical axis.	
The force is estimated by reading the intercept of the vertical axis.	$F = 48\,\text{N}$

b Calculate the total impulse of the ball over the 13 ms period of time.	
Thinking	**Working**
Break the area under the graph into sections for which you can calculate the area.	In this case, the graph can be broken into three sections: A, B and C. 
Calculate the area of the three sections A, B and C using the equations for area of a triangle and the area of a rectangle.	Area = area A + area B + area C $= \frac{1}{2}b \times h + (b \times h) + \frac{1}{2}b \times h$ $= \frac{1}{2} \times (2.0 \times 10^{-3}) \times 60 + (6.0 \times 10^{-3}) \times 60$ $+ \frac{1}{2} \times (5.0 \times 10^{-3}) \times 60$ $= 0.060 + 0.36 + 0.15$ $= 0.57$
The total impulse is equal to the area.	$I = 0.57$ Ns
Apply the sign and direction convention for motion in one dimension vertically.	$I = 0.57$ Ns up

➤ Try yourself 7.4.5

CALCULATING THE TOTAL IMPULSE FROM A CHANGING FORCE

A student records the force acting on a tennis ball as it bounces off a hard concrete floor over a period of time. The graph shows the forces acting on the ball during its collision with the concrete floor.



a Determine the force acting on the ball over a time of 4.0 ms.

b Calculate the total impulse of the ball over the 13 ms period of time.

7.4 Review

SUMMARY

- The change in momentum of an object with a net force acting on it is known as the impulse, I (N s). Impulse, $I = F_{av}\Delta t = mv - mu = \Delta p$
- The units for impulse are N s, and for a change in momentum are kg m s^{-1}. These units are equivalent.
- Impulse can be calculated from the area under a force–time graph.
- In many practical applications, measures are taken to increase the time of the interaction in order to reduce the maximum force.

KEY QUESTIONS

Retrieval

1 State an equation for the impulse acting on an object in terms of:
- **a** the mass, and initial and final velocity of the object
- **b** the resultant force acting and the time over which the force acts.

2 Describe how to find the impulse of an object from a force–time graph.

3 State the units for:
- **a** change in momentum
- **b** impulse.

Comprehension

4 Explain why a man fielding in a cricket match cups his hands and then draws them into his body as the ball reaches his hands.

5 Crash helmets have a hard outside layer and foam padding inside. Explain the function of foam padding inside a helmet.

6 A student conducts an experiment with one pile of corrugated cardboard and one pile of non-corrugated cardboard. Discuss what the result would be if he drops two identical raw eggs, one onto each pile.

Analysis

7 Calculate the impulse of a 9.50 kg dog that changes its velocity from 2.50 m s^{-1} north to 6.25 m s^{-1} south.

8 Calculate the impulse of a 6050 kg truck as it changes from moving at 22.2 m s^{-1} west to 16.7 m s^{-1} east.

9 The velocity of an 8.00 kg mass changes from 3.00 m s^{-1} east to 8.00 m s^{-1} east. Calculate the impulse acting on the mass.

10 When a tennis player serves, she hits the 57 g tennis ball at the top if its flight so that the ball is momentarily stationary, and leaves the racquet at 144 km h^{-1}. If the ball and racquet are in contact for 0.060 s, calculate the magnitude of the force exerted by the racquet on the ball.

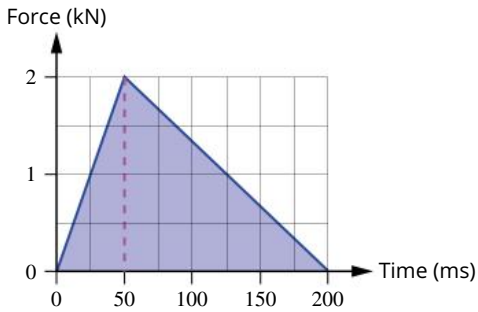
11 A 160 g cricket ball flies past the wicket at 155 km h^{-1} and is stopped by the wicket keeper. Calculate the magnitude of the impulse delivered by the ball to the wicket keeper.

12 A basketball of mass 0.625 kg is bounced against the court at a speed of 32.0 m s^{-1} and it rebounds at 24.5 m s^{-1}. Calculate the force exerted by the court on the ball if the interaction lasts 16.5 ms.

13 **a** Calculate the momentum of a 100.0 tonne train travelling at 50.0 km h^{-1}.
- **b** Calculate the magnitude of the impulse if the train were to collide with a 5.00 tonne truck at a level crossing, and push the truck for 15 m before coming to rest.

14 Jacinta inflates two basketballs to different pressures, and drops them from the same height. The ball with the higher pressure bounces higher. She argues that if each of the two balls were thrown with the same speed at a player, the ball with greater pressure would hurt more. Sarah disagrees, arguing that the balls have essentially the same mass and speed, and so there will not be any difference when they hit the player. Determine who is correct and justify your answer.

The following information relates to questions 15 and 16. The force–time graph below shows a schematic representation of the force exerted by an athlete's foot over the 200.0 ms that his foot is in contact with the ground.



15 Calculate the magnitude of the impulse of the athlete on the ground.

16 Calculate the magnitude of the force exerted by his foot if the force exerted by his foot was constant for the duration of the contact.

17 Compare the momentum of an 800.0 kg bull moving at a slow 0.010 m s^{-1} and that of a 15 g bullet travelling at 350 m s^{-1}. Determine which would require the larger impulse to stop.

7.5 Conservation of momentum

BY THE END OF THIS MODULE, YOU SHOULD BE ABLE TO:

- understand that momentum is conserved in all collisions
- understand mathematically how momentum is conserved when masses combine, and in explosions
- solve problems using the principle of conservation of momentum.

The most significant feature of momentum is that it is **conserved** in any interaction or collision between objects. This means that the total (sum of) momentum in any system before a collision will be equal to the total (sum of) momentum in the system after the collision. This is known as the law of conservation of momentum and can be represented by the following relationship, where Σp is the sum of the momentum of objects in a system.

$$\Sigma p_{\text{before}} = \Sigma p_{\text{after}}$$

To find the total momentum of objects in a system (either before or after a collision), simply find the momentum of each object, considering their masses and velocities, and then add the momenta together.

For collisions in one dimension, apply the sign convention of positive and negative directions to the velocities and then use algebra to determine the answer to the problem.

NEWTON'S THIRD LAW AND MOMENTUM

This law of conservation of momentum is a direct consequence of applying Newton's third law to a situation in which two objects come together in a collision or move apart in an **explosion**. If the words collision or explosion appear in a question, they are signposts that you should consider the conservation of momentum.

Remember, Newton's third law states that for every action (force), there is an equal and opposite reaction (force). This means that when object 1 exerts a force, F_{21}, on object 2, object 2 will exert an equal and opposite force, $-F_{12}$, on object 1. Remember that F_{12} is the same as writing $F_{\text{on 1 by 2}}$. You can write this mathematically as:

$$F_{12} = -F_{21}$$

In a collision between two objects, the time of contact, t, is the same for both objects.

$$F_{12}\Delta t = -F_{21}\Delta t$$

You will recognise this as the equation for impulse from Module 7.4, where $\Delta p = F\Delta t$. In a collision, Newton's third law can be thought of in terms of equal and opposite impulses, or the change in momentum of object 1 must be equal and opposite to the change in momentum of object 2.

$$F_{12}\Delta t = -F_{21}\Delta t$$
$$\Delta p_1 = -\Delta p_2$$

Given that $p = mv$:

$$m_1v_1 - m_1u_1 = -(m_2v_2 - m_2u_2)$$

This can be rearranged as:

$$m_1u_1 + m_2u_2 = m_1v_1 + m_2v_2$$

In other words, the total momentum before is equal to the total momentum after:

$$\Sigma p_{\text{before}} = \Sigma p_{\text{after}}$$

The law of conservation of momentum is a direct result of Newton's laws.

If two objects collide in one dimension, then:

$\Sigma p_{before} = \Sigma p_{after}$

$m_1u_1 + m_2u_2 = m_1v_1 + m_2v_2$

where

m_1 is the mass of object 1 (kg)

m_2 is the mass of object 2 (kg)

u_1 is the initial velocity of object 1 ($m\,s^{-1}$)

u_2 is the initial velocity of object 2 ($m\,s^{-1}$)

v_1 is the final velocity of object 1 ($m\,s^{-1}$)

v_2 is the final velocity of object 2 ($m\,s^{-1}$)

Worked example 7.5.1

CONSERVATION OF MOMENTUM

A 2.50 kg mass is moving at 4.50 $m\,s^{-1}$ west towards a 1.50 kg mass moving at 3.00 $m\,s^{-1}$ east. Calculate the final velocity of the 2.50 kg mass if the 1.50 kg mass rebounds at 5.00 $m\,s^{-1}$ west.

Thinking	Working
Identify the variables using subscripts. Ensure that the variables are in their standard units.	$m_1 = 2.50\,kg$ $u_1 = 4.50\,m\,s^{-1}$ west $v_1 = ?$ $m_2 = 1.50\,kg$ $u_2 = 3.00\,m\,s^{-1}$ east $v_2 = 5.00\,m\,s^{-1}$ west
Apply the sign convention to the variables, using east as positive.	$m_1 = 2.50\,kg$ $u_1 = -4.50\,m\,s^{-1}$ $v_1 = ?$ $m_2 = 1.50\,kg$ $u_2 = +3.00\,m\,s^{-1}$ $v_2 = -5.00\,m\,s^{-1}$
Apply the equation for conservation of momentum.	$\Sigma p_{before} = \Sigma p_{after}$ $m_1u_1 + m_2u_2 = m_1v_1 + m_2v_2$ $(2.50 \times -4.50) + (1.50 \times 3.00)$ $= 2.50v_1 + (1.50 \times -5.00)$ $2.50v_1 = -11.25 + 4.50 - (-7.50)$ $v_1 = \frac{0.75}{2.50}$ $= 0.300\,m\,s^{-1}$
Apply the sign convention to describe the direction of the final velocity.	$v_1 = 0.300\,m\,s^{-1}$ east

➤ Try yourself 7.5.1

CONSERVATION OF MOMENTUM

A 1200 kg wrecking ball is moving at 2.50 $m\,s^{-1}$ north towards a 1500 kg wrecking ball moving at 4.00 $m\,s^{-1}$ south. Calculate the final velocity of the 1500 kg ball if the 1200 kg ball rebounds at 3.50 $m\,s^{-1}$ south.

MOMENTUM WHEN MASSES COMBINE

It is important to note that in the situations described in Worked example 7.5.1, the two objects remain separate from each other. However, it is possible for two objects to combine (stick together) when they collide. If two objects combine when they collide, momentum is still conserved: $\Sigma p_{before} = \Sigma p_{after}$.

$\Sigma p_{before} = \Sigma p_{after}$

$m_1u_1 + m_2u_2 = m_3v_3$

where

- m_1 is the mass of object 1 (kg)
- m_2 is the mass of object 2 (kg)
- m_3 is the combined mass of objects 1 and 2 (kg)
- u_1 is the initial velocity of object 1 ($m\,s^{-1}$)
- u_2 is the initial velocity of object 2 ($m\,s^{-1}$)
- v_3 is the final velocity of the combined objects 1 and 2 ($m\,s^{-1}$)

Worked example 7.5.2

CONSERVATION OF MOMENTUM WHEN MASSES COMBINE

A 5.00 kg lump of clay is moving at 2.00 $m\,s^{-1}$ west towards a 7.50 kg mass of clay moving at 3.00 $m\,s^{-1}$ east. They collide to form a single, combined mass of clay. Calculate the final velocity of the combined mass of clay.

Thinking	Working
Identify the variables using subscripts and ensure that the variables are in their standard units. Add m_1 and m_2 to get m_3.	$m_1 = 5.00\,kg$ $u_1 = 2.00\,m\,s^{-1}$ west $m_2 = 7.50\,kg$ $u_2 = 3.00\,m\,s^{-1}$ east $m_3 = 12.50\,kg$ $v_3 = ?$
Apply the sign convention to the variables, using east as positive.	$m_1 = 5.00\,kg$ $u_1 = -2.00\,m\,s^{-1}$ $m_2 = 7.50\,kg$ $u_2 = +3.00\,m\,s^{-1}$ $m_3 = 12.50\,kg$ $v_3 = ?$
Apply the equation for conservation of momentum.	$\Sigma p_{before} = \Sigma p_{after}$ $m_1u_1 + m_2u_2 = m_3v_3$ $(5.00 \times -2.00) + (7.50 \times 3.00) = 12.50v_3$ $v_3 = \frac{-10.0 + 22.50}{12.50}$ $= 1.00\,m\,s^{-1}$
Apply the sign convention to describe the direction of the final velocity.	$v_3 = 1.00\,m\,s^{-1}$ east

➤ Try yourself 7.5.2

CONSERVATION OF MOMENTUM WHEN MASSES COMBINE

An 80.0 kg rugby player is moving at 1.50 $m\,s^{-1}$ north when he tackles an opponent with a mass of 50.0 kg who is moving at 5.00 $m\,s^{-1}$ south. Calculate the final velocity of the two players during the tackle.

MOMENTUM IN EXPLOSIONS

It is also possible for one object to break apart into two objects in what is known as an explosion. If an object breaks apart in an explosion, momentum is still conserved:

$$\Sigma p_{before} = \Sigma p_{after}$$

$\Sigma p_{before} = \Sigma p_{after}$

$m_1u_1 = m_2v_2 + m_3v_3$

where

m_1 is the mass of object 1 (kg)
m_2 is the mass of object 2 (kg)
m_3 is the mass of object 3 (kg)
u_1 is the initial velocity of object 1 ($m\,s^{-1}$)
v_2 is the final velocity of object 2 ($m\,s^{-1}$)
v_3 is the final velocity of object 3 ($m\,s^{-1}$)

Worked example 7.5.3

CONSERVATION OF MOMENTUM FOR EXPLOSIVE COLLISIONS

A 90.0 kg athlete holds a 1000.0 g javelin. She approaches the line at 7.75 $m\,s^{-1}$ west and releases the javelin down the field. After throwing it, she continues with a velocity of 7.25 $m\,s^{-1}$ west. Calculate the velocity of the javelin just after she releases it.

Thinking	Working
Identify the variables using subscripts and ensure that the variables are in their standard units. Note that m_1 is the sum of the bodies: 90.0 kg athlete and 1.00 kg javelin.	$m_1 = 91.0\,kg$ $u_1 = 7.75\,m\,s^{-1}$ west $m_2 = 90.0\,kg$ $v_2 = 7.25\,m\,s^{-1}$ west $m_3 = 1.00\,kg$ $v_3 = ?$
Apply the sign convention to the variables, using east as positive.	$m_1 = 91.0\,kg$ $u_1 = -7.75\,m\,s^{-1}$ $m_2 = 90.0\,kg$ $v_2 = -7.25\,m\,s^{-1}$ $m_3 = 1.00\,kg$ $v_3 = ?$
Apply the equation for conservation of momentum for explosive collisions.	$\Sigma p_{before} = \Sigma p_{after}$ $m_1u_1 = m_2v_2 + m_3v_3$ $91.0 \times -7.75 = (90.0 \times -7.25) + 1.00v_3$ $v_3 = \frac{-705.25 - (-652.5)}{1.00}$ $v_3 = \frac{-52.75}{1.00}$ $= -52.8\,m\,s^{-1}$
Apply the sign convention to describe the direction of the final velocity.	$v_3 = 52.8\,m\,s^{-1}$ west

➤ Try yourself 7.5.3

CONSERVATION OF MOMENTUM FOR EXPLOSIVE COLLISIONS

A 2000.0 kg cannon fires a 10.0 kg cannonball. The cannon and the cannonball are initially stationary. After firing, the cannon recoils with a velocity of 8.15 $m\,s^{-1}$ north. Calculate the velocity of the cannonball just after it is fired.

Road safety and technology

Worldwide, car accidents are responsible for over 2 million deaths each decade. Many more people are injured. One way of reducing the road toll is to design safer vehicles. Modern cars employ a variety of safety features that help to improve the occupants' survival chances in an accident. Some of these safety features are the antilock braking system (ABS), electronic stability control (ESC), inertia-reel seatbelts, variable-ratio-response steering systems, collapsible steering columns, head rests, shatterproof windscreen glass, padded dashboards, front and side air bags, front and rear crumple zones and a rigid passenger compartment. Many of these features are designed to increase the time over which a force acts, to reduce the force on the passengers.

Consider the example of the driver of a car that crashes into a tree at 60 km h^{-1} (16.7 m s^{-1}). If the driver has a mass of 90 kg, then the change in momentum of the driver as they come to rest is:

$$\Delta p = mu - mv$$
$$= (90 \times 16.7) - (90 \times 0)$$
$$= 1500 \text{ kg m s}^{-1}$$

As a result of this collision, the driver will lose all of this momentum as the car comes suddenly to a stop. The impulse experienced by the driver is the same, whether the stop is sudden or gradual. In either a sudden or gradual stop, the impulse is equal to the change in momentum: −1500 N s. So the idea of safety features such as inertia-reel seatbelts, collapsible steering columns, padded dashboards, air bags and crumple zones is not to reduce the size of the impulse, but to reduce the size of the forces that act to bring the driver to a stop. Automotive engineers strive to achieve this by extending the time over which the driver loses momentum.

Crumple zones

A popular misconception among motorists is that cars would be much safer if they were sturdier and more rigid. Drivers often complain that cars seem to collapse too easily during collisions, and that it would be better if cars were structurally stronger and more like an army tank. In fact, cars are specifically designed to crumple to some extent, as shown in Figure 7.5.1. This makes them safer and actually reduces the seriousness of injuries suffered in car accidents.

Army tanks are designed to be extremely sturdy and rigid vehicles. They are able to withstand the effect of collisions without suffering serious structural damage. If a tank travelling at 50 km h^{-1} crashed into a solid obstacle, the tank would be relatively undamaged. However, its occupants would very likely be killed. This is because the tank has no 'give' in its structure and so the tank and its occupants would stop in an extremely short time interval. The occupants would lose all of their momentum in an instant, which means that the forces acting on them would be extremely large. These large forces would cause the occupants of the tank to sustain serious injuries, even if they were wearing seatbelts.

FIGURE 7.5.1 Cars are designed with weak points in their chassis at the front and rear that enable them to crumple in the event of a collision. This extends the time over which the cars come to rest and so reduces the size of the forces acting on the occupants.

Cars today have strong, rigid passenger compartments, but they are also designed with non-rigid sections such as bonnets and boots that crumple if the cars are struck from the front or rear (Figure 7.5.2). The chassis contains parts that have grooves or beads cast into them. In a collision, these beads act as weak points, causing them to crumple in a concertina shape.

This 'concertina' effect allows the front or rear of the car to crumple, extending the time interval over which the car and its occupants come to a stop. This stopping time is typically longer than 0.1 s in a 50 km h^{-1} crash. Because the occupants' momentum is lost more gradually, the peak forces that act on them are smaller and so the chances of injury are reduced.

FIGURE 7.5.2 The Australian New Car Assessment Program (ANCAP) assesses the crashworthiness of new cars. This car has just crashed at 50 km h^{-1} into a 5 tonne concrete block. The crumpling effect can clearly be seen.

Airbags

The airbag in a car is designed to inflate within a few milliseconds of the occurrence of a collision, to reduce secondary injuries during the collision. The airbag is designed to inflate only when the vehicle experiences an impact with a solid object at 18–20 km h^{-1} or more. The required deceleration must be high, or accidental nudges with another car would cause the airbag to inflate. The car's computer control makes a decision within a few milliseconds to detonate the gas cylinders that inflate the airbag. The propellant detonates and inflates the airbag while, according to Newton's first law, the driver continues to move towards the dashboard. As the driver continues forwards into the airbag, the bag deflates, allowing the body to slow down over a longer time than would otherwise be possible as it moves towards the dashboard (Figure 7.5.3). The force is minimised, so injury is reduced.

FIGURE 7.5.3 Airbags can prevent injuries by extending the period of time you take to stop.

Calculating exactly when the airbag should inflate, and for how long, is a difficult task. Many cars have been crash tested and the results painstakingly analysed. High-speed film demonstrates precisely why the airbag is so effective. During a collision, only joints and muscles restrain the arms, legs and head of an occupant. Enormous forces are involved because of the large deceleration. The shoulders and hips can, in most cases, sustain the large forces for the short duration. However, the neck is the weak link. Victims of road accidents regularly receive neck and spinal injuries. An airbag reduces the enormous forces the neck must withstand by extending the duration of the collision. This involves the direct application of the concept of impulse. A comparison of the forces applied to the occupant of a car with and without airbags is shown in Figure 7.5.4.

Airbags prevent the high forces caused by contact of the head with the steering wheel. The airbag ensures that the main thrust of the expansion is directed outwards instead of towards the driver. The airbag's deflation rate, governed by the size of the holes in the rear of the air bag, provides the optimum deceleration of the head for a large range of impact speeds.

The airbag is not the answer to all safety concerns associated with a collision, but it is one of many safety features that form a chain of defence in a collision.

Review

1. An airbag can halve the force acting on the occupants of a car in a collision. Explain how an airbag reduces the force on the car's occupants.
2. Army tanks are designed to be extremely sturdy and rigid. They are able to withstand the effect of collisions without suffering serious structural damage. However, their occupants would very likely be killed. The army would not want all their soldiers killed. Suppose you could add a safety feature to the tank to protect the soldiers, describe what you would do.
3. Keira noticed that the article she was reading did not mention the importance of headrests in the seats of a car. Her friend John said he didn't think somewhere to rest your head was an important safety feature. Keira said that headrests were important when a car is hit from behind. Use the knowledge you have gained in this chapter to justify Keira's statement.

a

b

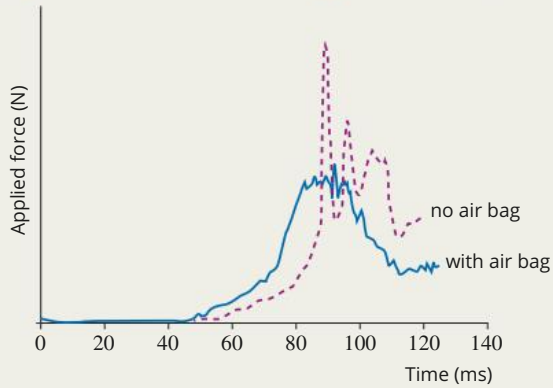


FIGURE 7.5.4 (a) The airbag extends the stopping time and distributes the force required to decelerate the mass of the driver or passenger over a larger area than a seatbelt. (b) The force withstood by the occupant of the car without an airbag is about double that felt with an airbag.

7.5 Review

SUMMARY

- Momentum is conserved in all collisions.
- The law of conservation of momentum can be applied to situations in which:
  - two objects collide and remain separate:
    $\Sigma p_{before} = \Sigma p_{after}$
    $m_1u_1 + m_2u_2 = m_1v_1 + m_2v_2$
  - two objects collide and combine together:
    $\Sigma p_{before} = \Sigma p_{after}$
    $m_1u_1 + m_2u_2 = m_3v_3$
  - one object breaks apart into two objects in an explosion:
    $\Sigma p_{before} = \Sigma p_{after}$
    $m_1u_1 = m_2v_2 + m_3v_3$

KEY QUESTIONS

Retrieval

1 Give an equation for the conservation of momentum (in terms of mass and velocity) when:
- **a** two objects collide and remain separate
- **b** two object collide and stick together
- **c** one object breaks apart into two objects.

Comprehension

2 Describe the following in terms of conservation of momentum:
- **a** A fast-moving train hardly slows down when it collides with a car left abandoned on the railway tracks.
- **b** A clay pigeon target moving horizontally across the sky is destroyed by a shotgun pellet.

Analysis

3 A rower of mass 70.0 kg steps out of a stationary boat with a velocity of 2.50 m s^{-1} forwards onto the nearby riverbank. The boat has a mass of 400 kg and was initially at rest. Determine the velocity of the boat as it begins to move as the rower steps out.

4 A golf ball of mass 70.0 g is stationary on the ground when it is hit by a 545 g golf club travelling at 80.0 m s^{-1}. If the ball leaves the club at a speed of 75.0 m s^{-1}, determine the speed at which the club moves just after it hits the ball.

5 A railway wagon of mass 2.50 tonnes moving along a horizontal track at 2.00 m s^{-1} runs into a stationary engine and is coupled to it. After the collision, the engine and wagon move off at a slow 0.300 m s^{-1}. Calculate the mass of the engine alone.

6 When playing roller derby, Ali is moving at 3.0 m s^{-1} and barges into another player who is moving at 0.50 m s^{-1}. If the two players move off locked together, and the mass of each player is 65.0 kg, calculate their final velocity.

7 A space shuttle of mass 10 000.0 kg, initially at rest, burns 5.0 kg of fuel and oxygen in its rockets to produce exhaust gases ejected at a velocity of 6000.0 m s^{-1}. Calculate the velocity that this exchange will give to the space shuttle.

8 A small research rocket of mass 250 kg is launched vertically as part of a weather study. It sends out 50.0 kg of burnt fuel and exhaust gases with a velocity of 180 m s^{-1} in a 2.0 s initial acceleration period.
- **a** Calculate the velocity of the rocket after this initial acceleration.
- **b** Determine the upwards force this applies to the rocket.
- **c** Calculate the net upwards acceleration acting on the rocket. (Use $g = 9.80$ m s^{-2} if required.)

Chapter review

07

KEY TERMS

collision
conserved
contact forces
equilibrium
explosion
force
impulse
inertia
momentum
net force
Newton's first law
Newton's second law
Newton's third law
non-contact forces
resultant force

KEY QUESTIONS

Retrieval

1 Match the statements **a**–**g** with the Newton's law they correspond to.

A Newton's first law
B Newton's second law
C Newton's third law

a The acceleration of a body experiencing an unbalanced force is directly proportional to the net force and inversely proportional to the mass of the body.
b Every object continues to be at rest, or continues with constant velocity, unless it experiences an unbalanced force.
c When one body exerts a force on another body (an action force), the second body exerts an equal force in the opposite direction on the first (the reaction force).
d $F_{AB} = -F_{BA}$
e $F_{net} = ma$
f the law of inertia
g $a = \frac{F_{net}}{m}$

2 The conservation of momentum in an interaction is given by the equation $m_1u_1 = m_2v_2 + m_3v_3$. Identify the statement that best describes the interaction between the two objects.

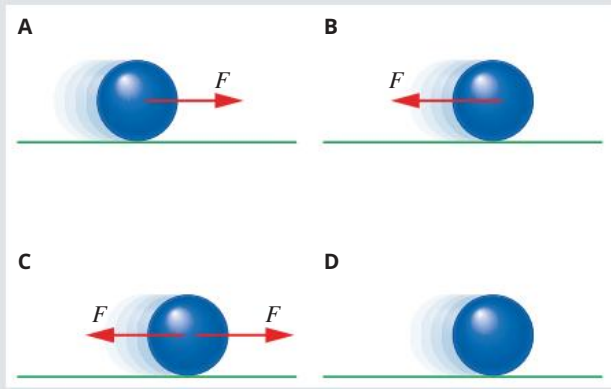
A The objects collide and move apart after the collision.
B The objects stick together upon collision.
C It is an explosion in which an object breaks apart.

3 If you wanted to reduce the force felt by the occupants of a car in the event of a car crash, state whether you would try to reduce or increase the time they took to stop in the crash.

4 A book is sitting at rest on a table. Identify the forces acting on the book.

Comprehension

5 A bowling ball rolls along a smooth wooden floor at constant velocity, as shown in the diagram. Ignoring the effects of friction and air resistance, identify the diagram (A, B, C, or D) that correctly indicates the forces acting on the ball.



6 A child wearing a backpack jumps from a tree and lands on his feet on the ground. Select one or more correct statements about factors that will influence the force on his knees and ankles when he lands.

A Wearing good runners will reduce the force, while being barefoot will increase the force.
B Bending his knees as he lands will increase the force.
C Landing on concrete will increase the force compared to landing on grass.
D Jumping from a lower branch will decrease the force.
E Leaving the backpack in the tree will make no difference to the force.

7 Aisha is playing rugby with her big brother Shaun. If Aisha is half Shaun's mass, determine how fast she needs to run to have the same momentum as him.

8 A student is travelling to school on a train. When the train starts moving, she notices that passengers tend to lurch towards the back of the train before grabbing a handrail to stop themselves from falling. Explain whether a force has acted on the passengers to push them backwards. Justify your answer.

Analysis

The following information relates to questions 9 and 10.
A tennis ball is thrown at a stationary bowling ball of mass 5.0 kg. The tennis ball rebounds and the bowling ball rolls forwards very slowly.

9 Identify the statement that best describes the forces that the two balls exert on each other during the collision.
- **A** The forces are equal.
- **B** The tennis ball exerts the greater force.
- **C** The bowling ball exerts the greater force.
- **D** The forces are equal in magnitude and opposite in direction.

10 Select the statement that best describes how the change in momentum of the tennis ball compares to the change in momentum of the bowling ball.
- **A** They are equal.
- **B** The tennis ball experiences a greater change of momentum.
- **C** The bowling ball experiences a greater change of momentum.
- **D** They are equal in magnitude and opposite in direction.

11 A ball has a force of 20.0 N upwards and 50.0 N downwards acting on it. Calculate the resultant force acting the ball.

12 A box has forces of 15 N west, 45 N east and 20.0 N west acting on it. Calculate the net force acting on the box, and state what will happen as a result.

13 A rally car gets stuck in the mud, so three spectators try to help push it out. The mud exerts a frictional force of 700.0 N on the car. The spectators provide forces of 9800 N forwards, 14 000 N backwards and 7200 N forwards. Determine whether they push the car out of the mud.

14 Calculate the mass of an object if it accelerates at $9.20\,m\,s^{-2}$ east when a force of 352 N east acts on it.

15 Calculate the acceleration of a 657 kg motorbike when a net force of 3550 N north acts on it.

The following information relates to questions 16–19.
Lachy is riding his bike and producing a forwards force of 150 N. The combined mass of Lachy and the bike is 100.0 kg.

16 If there is no friction or air resistance, calculate the magnitude of the acceleration of Lachy and the bike.

17 If friction opposes the bike's motion with a force of 45.0 N, determine the magnitude of the acceleration of the bike.

18 Calculate the magnitude of the force of friction if Lachy's acceleration is $0.600\,m\,s^{-2}$.

19 Lachy now carries his school bag, which is an additional mass of 25.0 kg. Determine the new forwards force he produces in order to accelerate at $0.800\,m\,s^{-2}$, if friction opposes the motion with a force of 30.0 N.

20 Calculate the momentum of a 100.0 g frisbee travelling at $5.0\,m\,s^{-1}$ north.

21 Calculate the momentum of a 10.0 tonne truck travelling south at $72\,km\,h^{-1}$.

22 Calculate the final velocity of a 14.0 kg remote-controlled car moving at $3.75\,m\,s^{-1}$ east, when a net force of 62.0 N west acts on it for 2.00 seconds.

23 A 65.0 kg student is standing on a 3.50 kg skateboard at rest when he steps off the board and exerts a horizontal force of 75.0 N south on the board. Determine the force the board exerts on the student.

24 Calculate the change in momentum of a 155 kg rock if its velocity changed from $6.50\,m\,s^{-1}$ east to $3.25\,m\,s^{-1}$ east in 8.50 s.

25 Calculate the impulse of a 25.5 kg robot if its velocity changes from $6.40\,m\,s^{-1}$ forwards to $2.25\,m\,s^{-1}$ backwards.

26 Calculate the impulse of a 50.0 g tennis ball that hits a wall and changes velocity from $10.0\,m\,s^{-1}$ forwards to $10.0\,m\,s^{-1}$ backwards.

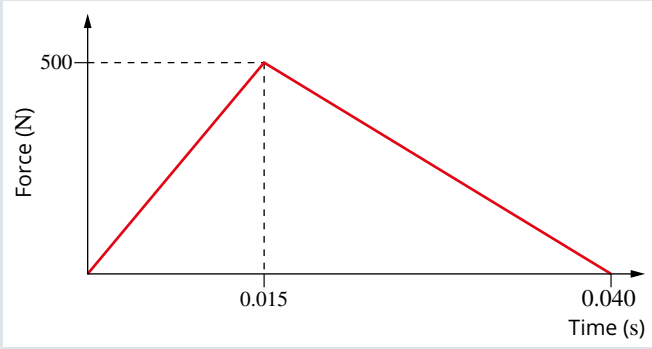
27 Calculate the impulse of an egg if it hits the floor with a force of 0.50 N, and the time it takes to change its velocity to zero is 3.0 ms.

28 An astronaut in a protective suit has a total mass of 154 kg and throws a 40.0 kg toolbox away from the space station. The astronaut and toolbox are initially stationary. After it has been thrown, the toolbox moves at $2.15\,m\,s^{-1}$. Calculate the velocity of the astronaut just after throwing the toolbox.

29 Nina throws a 50.0 g snowball at Katy, but it breaks into two equal pieces in mid-air. If the pieces move off with a velocity of $5.0\,m\,s^{-1}$, calculate the initial velocity of the snowball.

30 An athlete catches a 300.0 g volleyball by relaxing her elbows and wrists and 'giving' with the ball. Just before the athlete catches the ball, its velocity is $5.60\,m\,s^{-1}$ west. With soft hands, the velocity of the ball drops to zero in 1.00 second. Calculate the force exerted by the athlete on the volleyball.

The following information relates to questions 31–33. Jordy is playing softball and hits a ball with her bat. The force versus time graph for this interaction is shown. The ball has a mass of 170 g.



31 Determine the magnitude of the change in momentum of the ball.

32 Determine the magnitude of the change in momentum of the bat.

33 Determine the magnitude of the change in velocity of the ball.

34 A tennis ball of mass 57.5 g is tested for compliance with tennis regulations by being dropped from a height of 251 cm onto concrete. A bounce height of 146 cm is deemed acceptable. Calculate the magnitude of the force on the ball if it is in contact with the floor for 0.0550 s.

Knowledge utilisation

35 When Jordy, from questions 31–33, next came to bat she decided to just tap the ball into play so the ball is moving slowly. This is called a bunt play. Propose what Jordy would have to do to adapt her swing to make this play.

36 In a tug of war, two teams of eight people hold a rope between them and try to pull the other team towards them. If you were in charge of one of two teams of identical mass in a tug of war contest, propose how you would maximise the chance of your team winning.

37 An astronaut in a small spacecraft decides he could move the spacecraft by pushing hard on one of its inside walls. Predict what would result from his action.

38 Aristotle was an ancient Greek philosopher and scientist born in 384 BCE. One of the basic ideas of Aristotelian philosophy is that there is no effect without a cause. Considering moving objects, this means that there is no motion without a force. English physicist Isaac Newton, born in 1643, showed that this was not correct. Determine what evidence you would use to justify that Aristotle was wrong.

39 A student conducts an experiment with a basketball and a tennis ball. He drops each ball onto the ground and notes the height of their bounces. He then decides to drop the balls together with the tennis ball resting on top of the basketball as they fall. Predict what would happen. Justify your answer.

40 Newton's cradle is a popular toy in which a series of metal balls hang on strings next to each other. The end ball is pulled away from the rest and allowed to swing back towards the others. The collision causes one ball at the other end to swing away from the others. If two balls are pulled away and released, they will swing back and collide with others and cause two balls to swing away from the other end. Doing the same with three balls will cause three balls to swing away. Describe this action in terms of momentum.

CHAPTER

08 Energy

Energy is involved in every aspect of our lives. Energy from the Sun is converted into chemical energy in plants through photosynthesis, and then your body converts chemical energy into kinetic energy when you move.

This chapter explores how energy changes form and how work is done. When a force acts through a distance, work is done. The rate of doing work over time is called *power*.

As you learnt in Chapter 7, when objects collide momentum is conserved. Kinetic energy is sometimes conserved in collisions, and these are called elastic collisions. In other collisions, kinetic energy is converted into sound energy or used to deform the colliding objects, so kinetic energy is not conserved. These are called inelastic collisions.

Syllabus subject matter

Topic 1 • Linear motion and force

ENERGY

- define the terms *mechanical work*, *kinetic energy* and *gravitational potential energy*
- solve problems involving work done by a force
- solve problems involving kinetic energy and gravitational potential energy
- determine and interpret the area under a force–displacement graph
- interpret meaning from an energy–time graph
- define the terms *elastic collision* and *inelastic collision*
- compare and contrast elastic and inelastic collisions
- solve problems involving elastic collisions and inelastic collisions.

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8.1 Work

BY THE END OF THIS MODULE, YOU SHOULD BE ABLE TO:

- state that work is done when energy changes form
- use the correct SI unit for work and energy, the joule (J)
- calculate the work, W (J), done when a force, F (N), acts through a distance, s (m)
- calculate the work done when a force acts at an angle to the direction of motion
- interpret force–displacement graphs and calculate the work done.

The words 'energy' and 'work' are commonly used to describe a variety of everyday situations. However, these words take on quite specific definitions when used in a scientific context. They are two of the most important concepts in physics, allowing physicists to explain phenomena on a range of scales from collisions of subatomic particles to the interactions of galaxies.

DEFINING WORK

Although in everyday life the word 'work' can take on a variety of meanings, in a scientific context work has a very specific meaning. In physics, when a force acts on an object and causes energy to be transferred or transformed, then **work** is being done on the object. Although force is a vector, energy and work are scalar quantities.

The SI unit for work and energy, the joule (J), is named after the English scientist James Prescott Joule. He was the first person to show that kinetic energy could be converted into heat energy. The energy represented by 1 J is approximately the equivalent to the energy needed to lift a 1 kg mass (e.g. 1 L of water) through a height of 0.1 m. More commonly, scientists work in units of kilojoules (1 kJ = 1000 J) or even megajoules (1 MJ = 1 000 000 J).

CALCULATING WORK DONE

Work causes a change in energy. This can be represented using the equation $W = \Delta E$.

More specifically, **mechanical work** is defined as the product of the force causing the energy change and the displacement of the object in the direction of the force during the energy change.

Work corresponds to a change in energy, so the SI unit of work is also the joule. The definition of work, $W = Fs$, allows us to find a value for a joule in terms of other SI units.

$$1\,\text{J} = 1\,\text{N} \times 1\,\text{m} = 1\,\text{N m}$$

A joule is equal to a newton-metre, so a force of 1 N acting over a distance of 1 m does 1 J of work.

Using the definition of a newton:

$$1\,\text{J} = 1\,\text{N} \times 1\,\text{m} = 1\,\text{kg m s}^{-2} \times 1\,\text{m} = 1\,\text{kg m}^2\,\text{s}^{-2}$$

This defines a joule in terms of fundamental units.

Although both force and displacement are vectors, work is a scalar unit. So, like energy, work has no direction.

$W = \Delta E$
where
W is work
Δ is change
E is energy.

$W = Fs$
where
W is work (J)
F is force (N)
s is the displacement in the direction of the force (m).

Force at an angle

When a force is applied, the object does not always move in the same direction as the force. For example, when a person pushes a pram, the direction of the force is at an angle downwards, although the pram moves horizontally forwards, as shown in Figure 8.1.1.

FIGURE 8.1.1 When a person pushes a pram, the force is applied at an angle to the displacement of the pram.

In this case, only the horizontal component of the push contributes to the work being done on the pram. The vertical component of this force pushes the pram downwards and is balanced by the normal reaction force from the ground. This is shown in Figure 8.1.2.

In situations like this, a force is exerted at an angle to the direction of the motion. The work done can be calculated for the angle, θ, between the direction of the applied force and the direction of the displacement of the force using the equation:

$$W = Fs\cos\theta$$

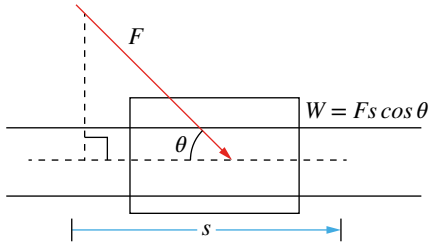


FIGURE 8.1.2 The work done can be calculated using the angle, θ, between the direction of the applied force and the direction of the displacement of the force.

$W = Fs\cos\theta$

where

W is work (J)

F is force (N)

θ is the angle between the direction of the applied force and the direction of the displacement of the force

s is the displacement in the direction of the force (m).

Worked example 8.1.1

CALCULATING WORK

The force exerted by the engine of a motorcycle acts in the same direction as the motion ($\theta = 0°$). Calculate the work done if the engine exerts a force of 3400 N for a distance of 80.0 m.	
Thinking	**Working**
Recall the expression for work in terms of force and distance.	$W = Fs\cos\theta$
Substitute in the data values, noting that $\cos 0° = 1$.	$= 3400 \times 80.0 \times \cos 0°$
Complete the calculation and include correct units.	$= 270\,000$ J

➤ Try yourself 8.1.1

CALCULATING WORK

A rope exerts a force of 53 N in the direction of motion of a barge on a river. The rope tows the barge 140 m. Calculate the work done on the barge.

Worked example 8.1.2

CALCULATING WORK WHEN THE FORCE IS AT AN ANGLE

A man exerts a force of 28 N at an angle of 60.0° to the direction of motion as he pushes a pram for 200.0 m on a flat path. Calculate the work done.	
Thinking	**Working**
Recall the expression for work in terms of force and distance.	$W = Fs\cos\theta$
Substitute in the data values.	$= 28 \times 200.0 \times \cos 60.0°$
Complete the calculation and include correct units.	$= 2800$ J

➤ Try yourself 8.1.2

CALCULATING WORK WHEN THE FORCE IS AT AN ANGLE

A broken-down train is pushed by a large group of people at an angle of 40.0° to the direction of the rails (and therefore the direction the train moves). If the people exert a force of 58 N and push the train 10.0 m, calculate the total work done on the train.

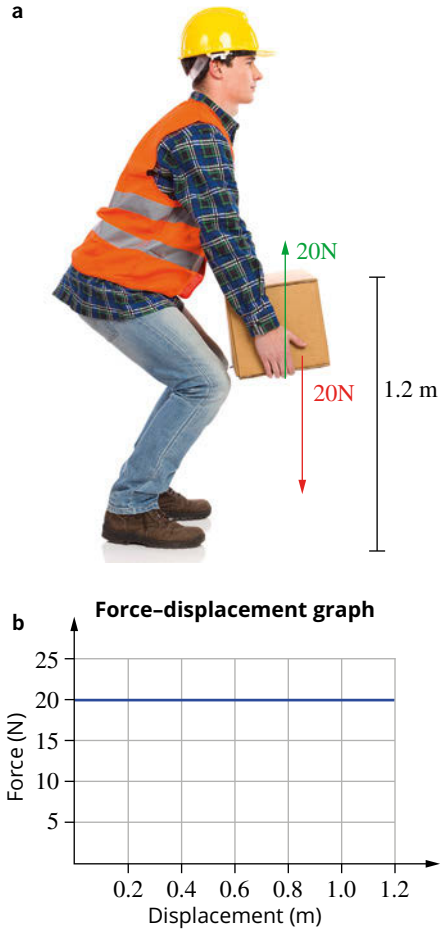


FIGURE 8.1.3 The force–displacement graph for a person picking up a box is a straight, horizontal line, indicating that the force applied to the box by the man is constant throughout the lifting process.

FORCE AND DISPLACEMENT

As its name suggests, a force–displacement graph illustrates the way a force changes with displacement. For a situation where the force is constant, this graph is simple. For example, in Figure 8.1.3, the force–displacement graph for a person picking up a box is a flat horizontal line showing that the force applied to the box is constant throughout the lift. Holding a heavy box in the same position uses energy for a human being because of the way our muscles operate, but no work is being done on the box, because the energy of the box is not changing. This illustrates the difference between the way you use the word 'work' in everyday life and the way you use it in science.

While the box is being lifted, work is done on the box and is converted into **gravitational potential energy** of the box. The gravitational potential energy could then be converted into kinetic energy if the box were dropped. The kinetic energy, in turn, could do mechanical work squashing an object or breaking the floor. Each time energy changes form, it has the capacity to do work.

An elastic object such as a spring can be stretched. Elastic objects obey a relationship known as Hooke's law. The law describes how, the more you stretch a spring, the greater the force required to keep stretching it. Hooke's law can be written as $F = -kx$, where x is the distance the spring has been stretched, in metres.

The spring constant, k, is a measure of the 'springiness' of the spring. The greater the spring constant, the greater the force required to compress or stretch the spring over a distance. The minus sign in the formula indicates that the force will be in the opposite direction from the displacement: if you push a spring it pushes back, and if you pull a spring it pulls back. The force exerted by the spring in the opposite direction to the force you apply is sometimes called the 'restoring' force, because it acts to restore the spring to its original position.

The force–displacement graph for a spring is a straight line that passes through the origin and increases at a constant rate. The line shows the direct relationship described by Hooke's law, as shown in Figure 8.1.4. (Note: sometimes, you will see force–displacement graphs for elastic objects labelled as force–extension graphs. In this context, the term 'extension' is the same as 'displacement'.)

Many everyday materials are only partially elastic. Their force–displacement graphs are relatively complex. For example, the force–displacement graph in Figure 8.1.5 for a sports shoe shows that the shoe is close to elastic for low displacements, but at high displacements the restoring force is relatively constant.

When a force changes with displacement, the amount of work done by the force can be calculated from the area under its force–displacement graph.

For a constant force, this is very simple. Consider the earlier example of a person lifting a box (Figure 8.1.3). The area can be found by counting the number of 'force times distance' squares under the line.

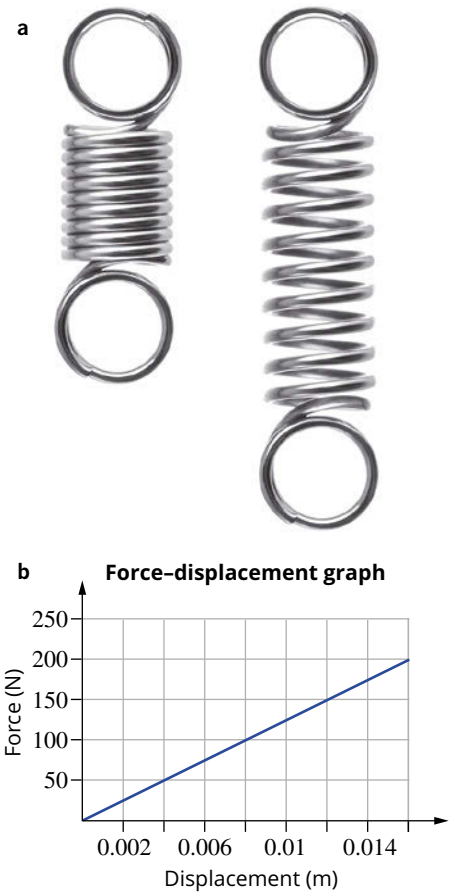


FIGURE 8.1.4 As a spring stretches, more force is required to keep stretching it. The force is proportional to the extension.

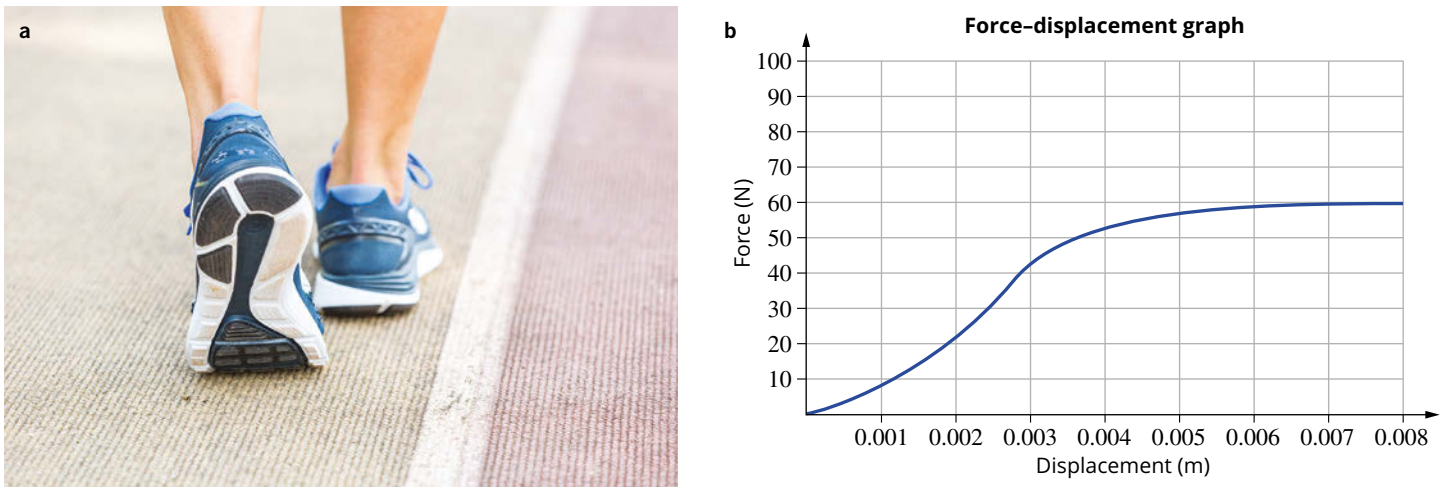


FIGURE 8.1.5 The force–displacement graph for a sports shoe is not a straight line; the change in force varies with how much the shoe has been stretched.

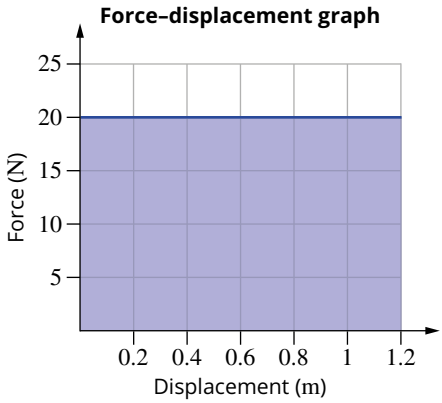


FIGURE 8.1.6 The area under a force–displacement graph gives the work done by the force.

Figure 8.1.6 has $6 \times 4 = 24$ squares.

Area of square: $5\,\text{N} \times 0.2\,\text{m} = 1\,\text{J}$

Each square has an area of 1 J so the total work done is 24 J.

Alternatively, this could be found by calculating the total area under the force–displacement graph.

For Figure 8.1.6:

$$\begin{aligned} A &= l \times w \\ &= 20\,\text{N} \times 1.2\,\text{m} \\ &= 24\,\text{J} \end{aligned}$$

Note that this second method is exactly the same as using the formula for work:

$$\begin{aligned} W &= Fs \\ &= 20 \times 1.2 \\ &= 24\,\text{J} \end{aligned}$$

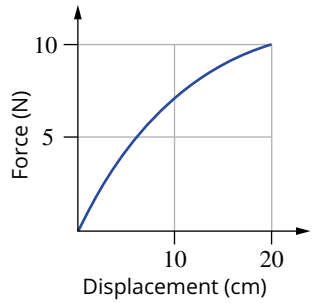
This relationship works in this case because the force is constant.

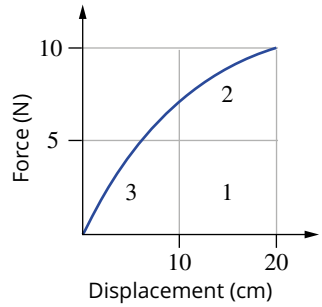
Similar strategies, either counting grid squares or calculating the area of the shape under the graph, can also be used when the force varies with the displacement.

Worked example 8.1.3

WORK FROM THE AREA UNDER A FORCE–DISPLACEMENT GRAPH

Use the force–displacement graph for an elastic band to estimate how much work is done in stretching the elastic band 20.0 cm. Give your answer to the nearest 0.50 J.

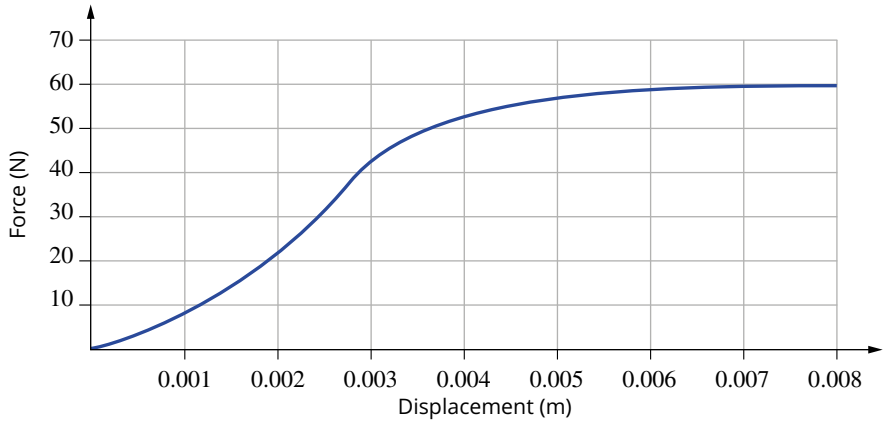


Thinking	Working
Calculate the work value of each grid square.	The dimensions of a grid square are: Force: 5 N, Displacement: 10 cm = 0.1 m Area of 1 square = $5 \times 0.1 = 0.5$ J
Count the number of grid squares under the curve.	Only count grid squares that are more than half under the curve. If the curve cuts a square in half, count every second one. Three of the squares shown below have more than half their area under the curve.  Number of squares = 3
Multiply the number of grid squares under the curve by the work value of each grid square.	$W = 3 \times 0.5\,\text{J} = 1.5\,\text{J}$

➤ Try yourself 8.1.3

WORK FROM THE AREA UNDER A FORCE–DISPLACEMENT GRAPH

The shoes of a jogger stretch by an average of 3 mm with each step. Use the force–displacement graph for a sports shoe to estimate how much work is done on the shoe with each step. Give your answer to the nearest 0.01 J.



WS 2.1.8

8.1 Review

SUMMARY

- Work is done when a force acts through a distance. When the force, F, acts in the same direction as the displacement, s, the work done $W = Fs$.
- When the force acts at an angle to the displacement, the work done is given by $W = Fs\cos\theta$.
- Work is done when energy changes form: $W = \Delta E$.
- The SI unit for work is the joule (J).
- Work can be done by stretching or compressing a spring.
- Work can be done by lifting something to a higher position within a gravitational field. The object then has gravitational potential energy, allowing it to do work.
- The area under a force–displacement graph allows the work done to be calculated.

KEY QUESTIONS

Retrieval

1 State the formula that expresses work as a relationship between force and distance.

2 Name is the SI unit for both work and energy.

Comprehension

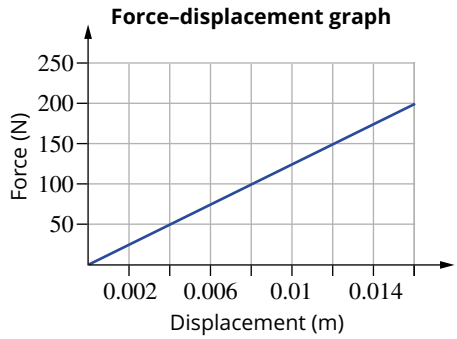
3 Explain why no work is being done in the case of a person leaning on a solid brick wall.

4 Explain why the equation $W = Fs$ cannot be used to calculate the work done in compressing a spring.

Analysis

5 When accelerating at the beginning of a ride, a cyclist applies a force of 500.0 N for a distance of 20.0 m. Calculate the work done by the cyclist on the bike.

6 A spring with this force–displacement graph is stretched as shown. Calculate the work done to stretch the spring by 0.016 m, using the formula for the area of a triangle.

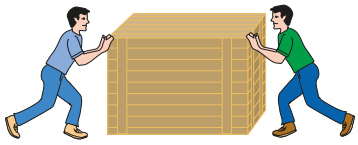


7 A cyclist does 2700 J of work when she rides her bike at a constant speed for 150 m. Calculate the average force the cyclist applies over this distance.

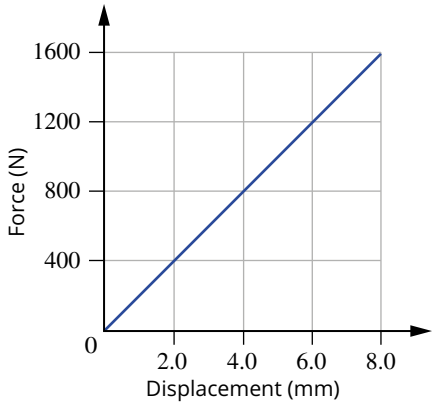
8.1 Review *continued*

8 A rope at 40.0° to the horizontal is used to drag a heavy box along the ground for a distance of 5.0 m. Calculate the work done if the tension in the rope is 80.0 N. Give your answer correct to the nearest 10.0 J.

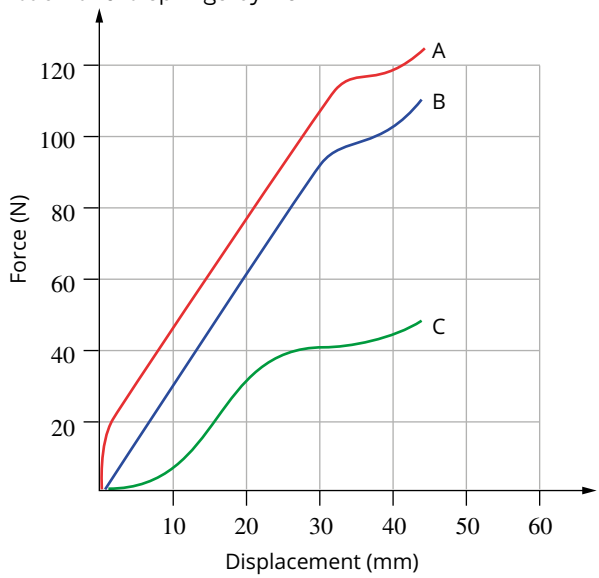
9 Two people push in opposite directions on a heavy box. One person applies 50.0 N of force, the other applies 40.0 N of force. There is 10.0 N of friction between the box and the floor, which means that the box does not move. Calculate the work done by the person applying 50.0 N of force.



10 The strings of a graphite-head tennis racquet have the force–displacement graph shown. Calculate the work done when the strings displace by 6 mm.



11 Three different springs have the force–displacement graphs shown. Estimate the work done by stretching each of the springs by 40 mm.



8.2 Potential energy

BY THE END OF THIS MODULE, YOU SHOULD BE ABLE TO:

- calculate the gravitational potential energy change of an object
- calculate the work done on an object as a measure of its gravitational potential energy change
- name forms of potential energy, including chemical, elastic, gravitational, magnetic, nuclear and spring.

The potential energy of an object is associated with its position relative to another object or within a field. For example, an object suspended by a crane has gravitational potential energy because of its position in the Earth's gravitational field. In Chapter 4, you saw that electrical potential energy is stored by the separation of charges in a cell.

Some examples of potential energy are listed in Table 8.2.1.

TABLE 8.2.1 Types of potential energy and their causes

Type of potential energy	Cause
chemical	relative positions of atoms
elastic	attractive forces between atoms
gravitational	gravitational fields
magnetic	magnetic fields
nuclear	forces within the nucleus of an atom
spring	a stretched, compressed or wound spring

GRAVITATIONAL POTENTIAL ENERGY

One of the easiest forms of potential energy to study is gravitational potential energy. Any object that is lifted above Earth's surface has the capacity to cause change due to its position in the Earth's gravitational field. An understanding of gravitational potential energy is essential to understanding common energy transformations.

Gravitational potential is a measure of the amount of energy available to an object due to its position in a gravitational field. The gravitational potential energy of an object can be calculated from the amount of work that must be done against gravity to get the object into its position.

Consider the weightlifter lifting a barbell in Figure 8.2.1. Assuming that the barbell is lifted at a constant speed, then the weightlifter must apply a lifting force equal to the force due to gravity on the barbell, F_g. The lifting force, F_l, is applied over a displacement, Δh, corresponding to the change in height of the barbell.

The work done against gravity by the weightlifter is:

$$W = F_{net}s = F_g\Delta h$$

The force due to gravity is given by the equation $F_g = mg$, so the work done can be written as:

$$W = mg\Delta h$$

The work carried out in this example has resulted in the transformation of chemical energy within the weightlifter into gravitational potential energy. Therefore the change in gravitational potential energy of the barbell is:

$$E_p = mg\Delta h$$

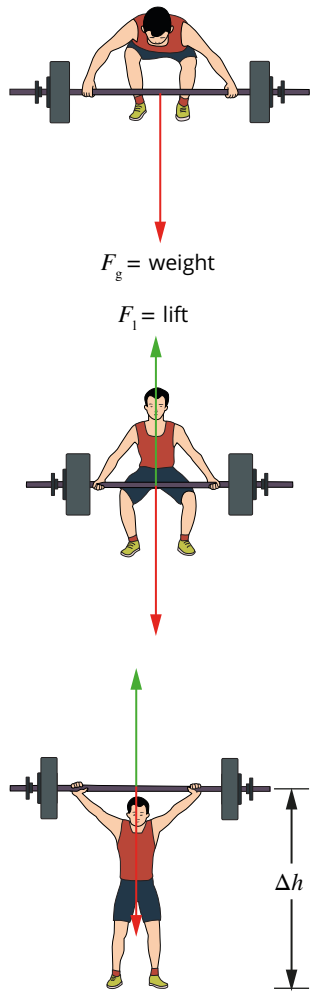


FIGURE 8.2.1 A weightlifter applies a constant force over a fixed distance to give the barbell gravitational potential energy.

The change in gravitational potential energy of an object, due to the work done against a gravitational field, is given by:

$\Delta E_p = mg\Delta h$

where

ΔE_p is the change in gravitational potential energy (J)

m is the mass of the object (kg)

g is the magnitude of the gravitational field strength (9.80 N kg^{-1} downwards on Earth)

Δh is the change in height of the object (m).

Units of *g*

Acceleration due to gravity can be expressed in units of N kg^{-1} or m s^{-2}. A newton is defined as a kg m s^{-2}, so:

$$\text{N kg}^{-1} = \frac{\text{N}}{\text{kg}} = \frac{\cancel{\text{kg}}\ \text{m s}^{-2}}{\cancel{\text{kg}}} = \text{m s}^{-2}$$

Use m s^{-2} when calculating acceleration due to gravity.

Use N kg^{-1} when measuring the force on a mass due to gravity.

Worked example 8.2.1

CALCULATING GRAVITATIONAL POTENTIAL ENERGY

A weightlifter lifts a barbell that has a total mass of 80.0 kg from the floor to a height of 1.8 m above the ground. Calculate the gravitational potential energy of the barbell at this height.	
Thinking	**Working**
Recall the formula for gravitational potential energy.	$\Delta E_p = mg\Delta h$
Substitute the values for this situation into the equation.	$= 80.0 \times 9.80 \times 1.8$
State the answer with appropriate units and significant figures.	$= 1411.2$ J $= 1.4$ kJ

➤ Try yourself 8.2.1

CALCULATING GRAVITATIONAL POTENTIAL ENERGY

A person doing their grocery shopping lifts a 5.0 kg grocery bag to a height of 30.0 cm. Calculate the gravitational potential energy of the grocery bag at this height.

CALCULATING GRAVITATIONAL POTENTIAL ENERGY AND THE 'REFERENCE LEVEL'

When calculating gravitational potential energy, it is important to define the level that corresponds to $E_p = 0$. Often this can be taken to be the ground or sea level, but the zero potential energy reference level is not always obvious.

It does not really matter which point is taken as the zero potential energy reference level, as long as the chosen point is used consistently throughout a particular problem (Figure 8.2.2). If objects move below the reference level, then their energies will become negative and should be interpreted accordingly.

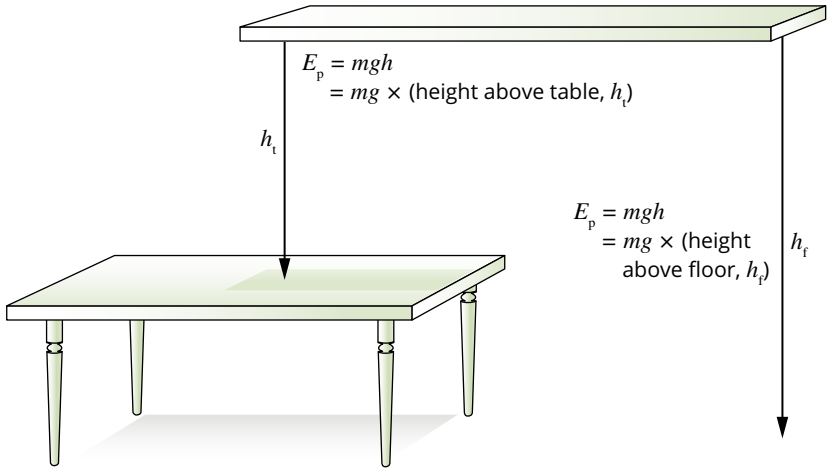


FIGURE 8.2.2 In this situation, the zero potential energy reference point could be taken as either the level of the table or the floor.

Worked example 8.2.2

CALCULATING GRAVITATIONAL POTENTIAL ENERGY RELATIVE TO A REFERENCE LEVEL

A weightlifter (m = 60.0 kg) lifts a 50.0 kg bar through a distance of 45 cm. Calculate the increase in gravitational potential energy of the bar with each lift. Use $g = 9.80\,\text{N kg}^{-1}$.

Thinking	Working
Recall the formula for gravitational potential energy.	$E_p = mg\Delta h$
Identify the relevant values for this situation. Only the mass of the bar is being lifted (the weightlifter's mass is a distractor). Take the weightlifter's body as the zero potential energy level.	$m = 50.0\,\text{kg}$ $g = 9.80\,\text{N kg}^{-1}$ $\Delta h = 45\,\text{cm} = 0.45\,\text{m}$
Substitute the values for this situation into the equation.	$E_p = 50.0 \times 9.80 \times 0.45$
State the answer with appropriate units and significant figures.	$= 220\,\text{J}$

➤ Try yourself 8.2.2

CALCULATING GRAVITATIONAL POTENTIAL ENERGY RELATIVE TO A REFERENCE LEVEL

A father picks up his baby from its bed. The baby has a mass of 6.0 kg and the mattress of the bed is 70.0 cm above the ground. When the father holds the baby in his arms, it is 125 cm off the ground. Calculate the increase in gravitational potential energy of the baby, using g as $9.80\,\text{N kg}^{-1}$.

8.2 Review

SUMMARY

- Forms of potential energy include chemical, elastic, spring, magnetic, nuclear and gravitational.
- The change in gravitational potential energy of an object, due to the work done against a gravitational field, is given by $\Delta E_p = mg\Delta h$.

KEY QUESTIONS

Retrieval

1 State the equation used to calculate the difference in gravitational potential energy of a mass at two points, when one point is h m higher than the other.

Comprehension

2 Explain why you are free to choose any height you like as the 'zero' level of gravitational potential energy.

3 If air resistance and other forms of frictional force are ignored, moving something horizontally in a gravitational field does not require doing any work. Explain why this is the case.

Analysis

4 Calculate the gravitational potential energy of a 115 kg climber standing at the top of Mount Kosciuszko when he is at an altitude of 2228 m above sea level.

5 A 57 g tennis ball is thrown 8.2 m into the air. Use $g = 9.80\,m\,s^{-2}$.

a Calculate the gravitational potential energy of the ball at the top of its flight.

b Calculate the change in the gravitational potential energy of the ball from the top of its flight to halfway back down to Earth.

6 When climbing Mount Everest ($h = 8848$ m), a mountain climber stops to rest at North Base Camp ($h = 5150$ m). If the mountain climber has a mass of 65.0 kg, calculate the gravitational potential energy she will gain in the final section of the climb (from base camp to the summit). For simplicity, assume that g remains at $9.80\,N\,kg^{-1}$.

7 An 80.0 kg skydiver falls from 20 000.0 m to 10 000.0 m.

a Calculate the work done on the skydiver by gravity (ignore air resistance and assume that g remains at $9.80\,N\,kg^{-1}$).

b Calculate the change in gravitational potential energy of the skydiver.

c Compare your answers for parts **a** and **b**.

8.3 Kinetic energy

BY THE END OF THIS MODULE, YOU SHOULD BE ABLE TO:

- list types of kinetic energy
- calculate the kinetic energy of an object
- calculate changes in the kinetic energy of an object.

Kinetic energy is energy associated with motion. Any moving object has kinetic energy.

In some forms of kinetic energy, the moving objects are not easily visible. An example of this is thermal energy, which is a type of kinetic energy related to the movement of particles. Table 8.3.1 lists some different types of kinetic energy.

TABLE 8.3.1 Types of kinetic energy and their associated moving objects

Type of kinetic energy	Type of motion
rotational kinetic	rotating objects
sound	air molecules vibrating
thermal	movement of atoms, ions or molecules due to temperature
translational kinetic	objects moving in a straight line

CALCULATING KINETIC ENERGY

Consider the dynamics cart in Figure 8.3.1 of mass, m, starting at rest ($u = 0$). It is pushed with force, F, which acts while the cart undergoes a displacement, s, and gains a final velocity, v.

Work is done by the force that changes the kinetic energy of the trolley. To find an equation for the work done, recall the velocity formula from Module 6.6:

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

$$s = \frac{v^2 - u^2}{2a}$$

Substitute this and $F = ma$ into $W = Fs$:

$$W = Fs$$

$$= ma\left(\frac{v^2 - u^2}{2a}\right)$$

$$= \frac{1}{2}mv^2 - \frac{1}{2}mu^2$$

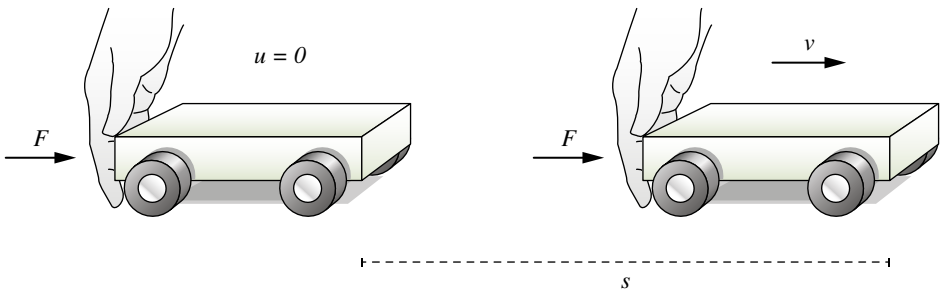


FIGURE 8.3.1 The kinetic energy of a dynamics cart can be calculated by considering the force (F) acting on it over a given displacement (s).

The relationship between the work done and the change in kinetic energy is:

$W = \Delta E_k$

$= \frac{1}{2}mv^2 - \frac{1}{2}mu^2$

where

W is work (J)

ΔE_k is the change in kinetic energy (J)

m is mass (kg)

u is initial velocity ($m\,s^{-1}$)

v is final velocity ($m\,s^{-1}$).

This equation is known as the 'work–energy theorem' because it shows the theoretical relationship between work and energy.

In this situation, the cart was originally at rest ($u = 0$) so:

$$W = \frac{1}{2}mv^2$$

Assuming that no energy was lost as heat or noise and that all of the work is converted into kinetic energy, this equation gives us a mathematical definition for the kinetic energy, E_k, of the cart in terms of its mass and velocity.

$$E_k = \frac{1}{2}mv^2$$

Worked example 8.3.1

CALCULATING KINETIC ENERGY

A car with a mass of 1200 kg is travelling at 90.0 $km\,h^{-1}$. Calculate its kinetic energy at this speed.

Thinking	Working
Convert the car's speed to $m\,s^{-1}$.	$90.0\,km\,h^{-1} = \frac{90.0}{1}$ $= \frac{90000}{3600}$ $= 25\,m\,s^{-1}$
Recall the equation for kinetic energy.	$E_k = \frac{1}{2}mv^2$
Substitute the values for this situation into the equation.	$= \frac{1}{2} \times 1200 \times 25^2$
State the answer with appropriate units.	$= 375000\,J$ $= 380\,kJ$

➤ Try yourself 8.3.1

CALCULATING KINETIC ENERGY

PA 2.1.4

A person crossing the street is walking at 5.0 $km\,h^{-1}$. If the person has a mass of 80.0 kg, calculate their kinetic energy.

Kinetic energy and momentum

In Module 7.3, momentum is given as $p = mv$. Substituting this into the kinetic energy formula shows the relationship between kinetic energy and momentum.

$$E_k = \frac{mv^2}{2}$$

Multiplying by $\frac{m}{m}$ and expanding v^2 gives:

$$E_k = \frac{m}{m} \times \frac{mvv}{2}$$

Rearranging gives:

$$E_k = \frac{mv \times mv}{2m}$$
$$= \frac{p^2}{2m}$$

Kinetic energy at high speeds

The expression $E_k = \frac{1}{2}mv^2$ is accurate for the speeds you usually encounter in everyday life. At speeds much closer to the speed of light, Einstein's theory of special relativity shows that length and time change, and the expression for the kinetic energy of an object becomes more complex.

Kinetic energy can be calculated from the velocity and mass of an object:

$$E_k = \frac{1}{2}mv^2$$

where

E_k is kinetic energy (J)

m is mass (kg)

v is final velocity ($m\,s^{-1}$).

8.3 Review

SUMMARY

- Kinetic energy is energy associated with motion.
- The kinetic energy, E_k, of an object of mass m (kg) and a velocity of v ($m\,s^{-1}$) is given by $E_k = \frac{1}{2}mv^2$.
- The change in the kinetic energy of an object is given by $\Delta E_k = \frac{1}{2}mv^2 - \frac{1}{2}mu^2$, which is equal to the work done on the object.
- Types of kinetic energy include translational, rotational, thermal and sound.

KEY QUESTIONS

Retrieval

1 State the name given to the kind of energy that a mass has because it is in motion.

2 State the formula used to calculate the energy of an object in motion.

Comprehension

3 Identify the amount by which kinetic energy is increased when the mass of an object is doubled.

4 Identify the amount by which kinetic energy is increased when the velocity of an object is doubled.

Analysis

5 The mass of a motorbike together with its rider is 230 kg. If the motorbike is travelling at 80.0 $km\,h^{-1}$, calculate its kinetic energy.

6 A 1500 kg car is travelling at 17 $m\,s^{-1}$. Determine how much work its engine would need to do to accelerate the car to 28 $m\,s^{-1}$.

7 A cyclist has a mass of 72 kg and is riding a bicycle that has a mass of 9.0 kg. When riding at top speed, cyclist and bicycle combined have a kinetic energy of 5.0 kJ. Calculate the top speed of the cyclist.

8 A school zone with a 40.0 $km\,h^{-1}$ speed limit is within an area with a 60.0 $km\,h^{-1}$ speed limit. Calculate the kinetic energy of a 2000.0 kg SUV at 40.0 $km\,h^{-1}$ and 60.0 $km\,h^{-1}$ and compare the two answers.

8.4 Conservation of energy

BY THE END OF THIS MODULE, YOU SHOULD BE ABLE TO:

- state that energy is conserved—it is not created or destroyed
- complete calculations about situations in which energy is transformed from one form to another (e.g. gravitational potential energy being transformed into kinetic energy)
- calculate the mechanical energy of an object from its kinetic and potential energy
- calculate the efficiency of energy transformations from the energy input and output
- state that elastic collisions occur when kinetic energy is conserved and inelastic collisions occur when it is not
- conduct calculations for elastic and inelastic collisions.

Recall that energy comes in many forms such as heat, light, sound, chemical energy and electrical energy. It is a scalar quantity and is measured in joules (J). Energy is also associated with the motion and position of an object, and this energy is called the **mechanical energy** of the object. In the motion problems of this chapter, moving objects have been described as having kinetic energy. An object can also have stored or gravitational potential energy because of its position. Engineers need to consider stored energy to avoid a disaster. For example, a building crane that has lifted a steel beam several storeys has given the beam gravitational potential energy that could be converted to kinetic energy if the lifting chain were to break and the beam were to accelerate to the ground under gravity.

The changing of gravitational potential energy to kinetic energy is an illustration of the **law of conservation of energy**, a fundamental principle of nature. The law of conservation of energy states that energy is not created or destroyed, but can only change from one form to another, or in other words, **transform**. As the gravitational potential energy of the beam decreases, its kinetic energy increases. The total amount of mechanical energy remains constant.

Energy is never destroyed, but it can be dissipated in forms that are not easily recoverable. For example, the kinetic energy of a vehicle is reduced if it encounters friction, causing the tyres to heat up, or the bodywork to be crushed if it collides with another object. The mechanical energy before and after a collision is only the same under ideal conditions, but in many cases it is a useful approximation.

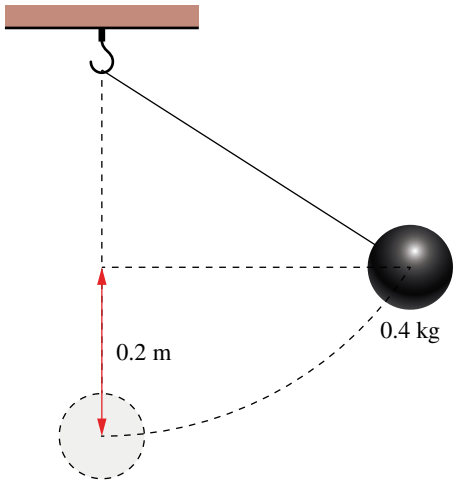


FIGURE 8.4.1 A falling pendulum provides an example of conservation of mechanical energy.

ENERGY IS CONSERVED

The concept of mechanical energy allows physicists to determine outcomes in non-linear situations, where the equations of linear motion cannot be used. For example, consider a pendulum with a bob of mass 400 g displaced from its average position such that its height is increased by 20 cm, as shown in Figure 8.4.1.

The conservation of mechanical energy applies to this situation because the gravitational potential energy of a free-falling pendulum is converted into kinetic energy. Therefore, the velocity formula can be used to find the velocity of the pendulum bob at its lowest point.

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

For an object falling a height h, $u = 0$ and $a = g = 9.80\,\text{m s}^{-1}$:

$$\begin{aligned} v^2 &= u^2 + 2as \\ &= 2gh \\ v &= \sqrt{2gh} \\ &= \sqrt{2 \times 9.80 \times 0.2} \\ &= 2\,\text{m s}^{-1} \end{aligned}$$

The speed of the pendulum bob will be $2\,\text{m s}^{-1}$ at its lowest point. However, unlike the falling tennis ball discussed below, the direction of the bob's motion will be horizontal instead of vertical at its lowest point. The equations of motion relate to linear motion and cannot be applied to this situation, as the bob swings in a curved path.

Conservation of energy can also be used to analyse projectile motion, such as when an object is thrown or fired into the air with some initial velocity. Energy is not a vector, so no vector analysis is required, even if the initial velocity is at an angle to the ground.

Energy conversions

Mechanical energy is defined as the energy that a body possesses due to its position or motion. Kinetic energy and gravitational potential energy are both forms of mechanical energy.

In many situations, energy is transformed between kinetic and gravitational potential energy. For example, when a tennis ball bounces, as shown in Figure 8.4.2, much of its kinetic energy is converted into gravitational potential energy and then back into kinetic energy again.

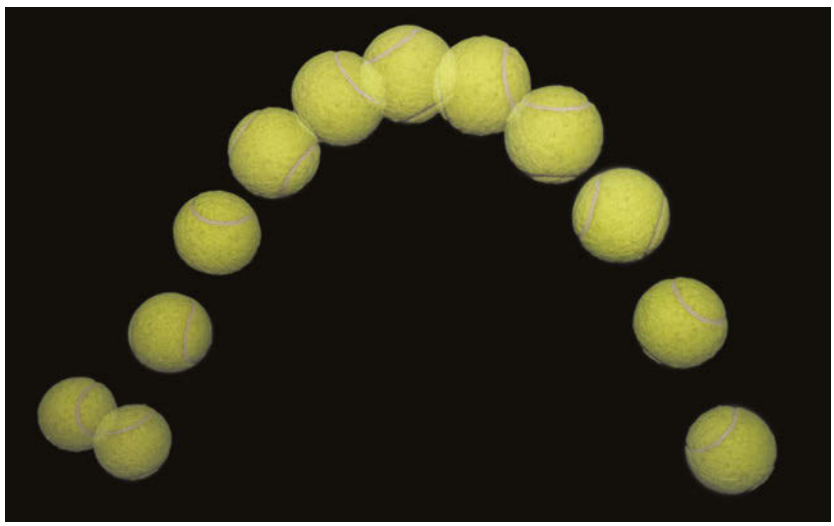


FIGURE 8.4.2 Bouncing tennis ball

In analysing this type of situation, the concept of mechanical energy is useful. Mechanical energy is the sum of the potential energies available to an object and the kinetic energy of an object.

In situations where mechanical energy is conserved, it is possible to use this to predict the outcome of the situation. Where mechanical energy is not conserved, this can be used to help identify other important energy transformations.

Physicists describe the rate at which work is done using the concept of **power**. Like work and energy, this is a word that takes on a specific meaning in a scientific context.

Mechanical energy

For falling objects, the mechanical energy is calculated from the sum of their kinetic and gravitational potential energies. Recall from previous modules that $E_k = \frac{1}{2}mv^2$ and $\Delta E_p = mg\Delta h$.

$$\begin{aligned} E_m &= E_k + \Delta E_p \\ &= \tfrac{1}{2}mv^2 + mg\Delta h \end{aligned}$$

This is a useful concept in situations where gravitational potential energy is converted into kinetic energy or vice versa. For example, consider the tennis ball in Figure 8.4.3. It has a mass of 60.0 g and is dropped from a height of 1.00 m. Initially, its total mechanical energy would comprise the sum of the kinetic energy, which would be 0 J, and the gravitational potential energy that is stored at this height ($g = 9.80\,\text{m s}^{-2}$):

$$\begin{aligned} \Delta E_p &= mg\Delta h \\ &= 0.0600 \times 9.80 \times 1.00 \\ &= 0.588\,\text{J} \end{aligned}$$

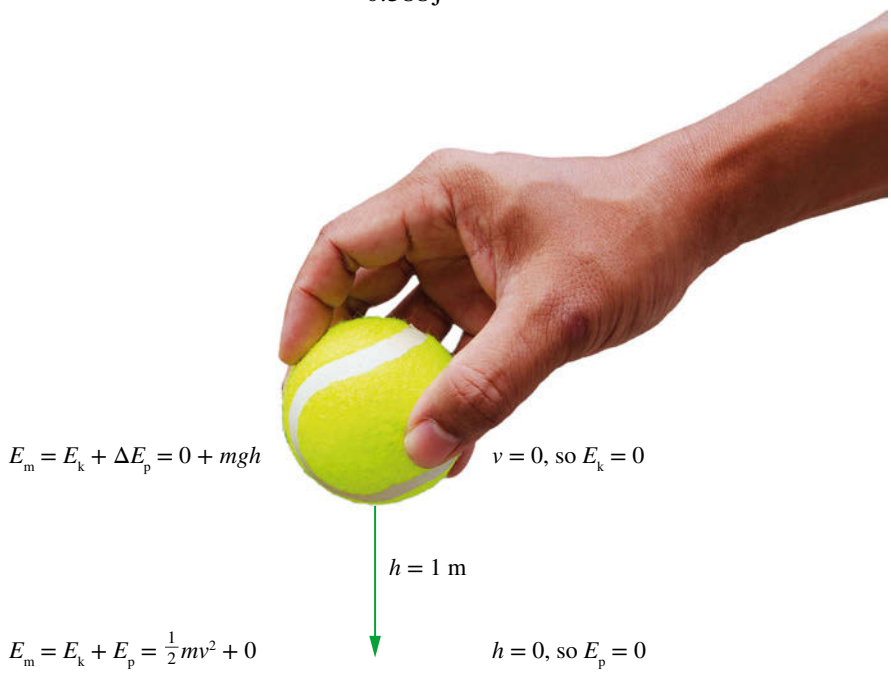


FIGURE 8.4.3 A falling tennis ball provides an example of conservation of mechanical energy.

At the instant the ball hits the ground, the total mechanical energy would comprise the gravitational potential energy available to it and the kinetic energy just prior to hitting the ground. The gravitational potential energy is 0 J because the ball is at ground level. To calculate kinetic energy, the ball's velocity just before it hits the ground can be calculated using one of the equations of motion: $v^2 = u^2 + 2as$.

When the ball is just about to hit the ground:

$s = -1.00$ m, $a = -9.80\,\text{m s}^{-2}$ and $u = 0\,\text{m s}^{-1}$:

$$\begin{aligned} v^2 &= u^2 + 2as \\ v^2 &= 0^2 + 2(-9.80 \times -1.00) \\ v &= \sqrt{19.6} \\ &= 4.43\,\text{m s}^{-1} \text{ downwards} \end{aligned}$$

Therefore the kinetic energy of the tennis ball just before it hits the ground is:

$$\begin{aligned} E_k &= \tfrac{1}{2}mv^2 \\ &= \tfrac{1}{2} \times 0.06 \times 4.43^2 \\ &= 0.588\,\text{J} \end{aligned}$$

Notice that at both the top and the bottom of the 1.00 m fall, the mechanical energy is the same.

At the top:

$$\begin{aligned} E_m &= E_k + \Delta E_p \\ &= 0 + 0.588 \\ &= 0.588\,\text{J} \end{aligned}$$

At the bottom:

$$\begin{aligned} E_m &= E_k + \Delta E_p \\ &= 0.588 + 0 \\ &= 0.588\,\text{J} \end{aligned}$$

In fact, mechanical energy is constant throughout the drop. Consider the tennis ball when it has fallen halfway to the ground. At this point, $h = 0.500\,\text{m}$ and $v = 3.13\,\text{m s}^{-1}$:

$$\begin{aligned} E_m &= E_k + \Delta E_p \\ &= \left(\tfrac{1}{2} \times 0.0600 \times 3.13^2\right) + (0.0600 \times 9.80 \times 0.500) \\ &= 0.294 + 0.294 \\ &= 0.588\,\text{J} \end{aligned}$$

Notice that, at this halfway point, the mechanical energy is evenly split between kinetic energy (0.294 J) and gravitational potential energy (0.294 J). Throughout the drop, the mechanical energy has been conserved.

Worked example 8.4.1

CALCULATING MECHANICAL ENERGY

Calculate the mechanical energy of a 0.025 kg projectile that is at a height of 22 m and falling at $18\,\text{m s}^{-1}$.

Thinking	Working
Recall the equation for mechanical energy.	$E_m = E_k + \Delta E_p$ $= E_k = \frac{1}{2}mv^2 + mg\Delta h$
Substitute in the data values for each variable.	$= \left(\frac{1}{2} \times 0.025 \times 18^2\right) + (0.025 \times 9.80 \times 22)$
State the answer with appropriate units.	$= 4.05 + 5.39$ $= 9.4\,\text{J}$

➤ Try yourself 8.4.1

CALCULATING MECHANICAL ENERGY

A 3.2 kg object is moving upwards at $15.7\,\text{m s}^{-1}$, and is 22.2 m above the ground. Calculate its mechanical energy.

Efficiency of energy conversions

In the real world, energy transformations are never perfect and some energy is always 'lost'. Because of this, for a system to continue operating (doing work), it must be constantly provided with energy. The percentage of energy that is effectively transformed by a device is called the **efficiency** of that device. A device operating at 45% efficiency is converting 45% of its supplied energy into the useful new form. The other 55% is 'lost' or transferred to the surroundings, usually as heat and/or sound. It is not truly lost because energy cannot be created or destroyed; rather, the form it becomes (heat and sound) is not useful.

The efficiency of a transfer from one energy form to another is expressed as:

$$\text{Efficiency } (\eta) = \frac{\text{energy output}}{\text{energy input}} \times 100\%$$

Table 8.4.1 includes the approximate efficiencies of some common devices.

TABLE 8.4.1 Efficiencies of some common devices

Device	Energy transfer	Efficiency (%)
electric motor	electric to kinetic	90
gas heater	chemical to thermal	75
steam turbine	thermal to kinetic	45
high-efficiency solar cell	radiation to electrical	35
coal-fired generator	chemical to electrical	30
car engine	chemical to kinetic	25
human body	chemical to kinetic	25
LED household light	electric to light	15
open fireplace	chemical to thermal	15
compact fluorescent light	electric to light	10
incandescent light globe	electric to light	2

ELASTIC AND INELASTIC COLLISIONS

FIGURE 8.4.4 Collisions often occur in sport.

In a collision, two or more objects hit each other and exchange momentum and energy. These are important interactions. In everyday life, energy and momentum can help you to understand collisions. For example, collisions occur between sports players (Figure 8.4.4) or between a bat and a ball, or more serious collisions occur in car crashes. For physicists, studying collisions between subatomic particles may be the key to unlocking the secrets of the universe.

In this module you have seen that in all interactions both energy and momentum are conserved. However, there are no restrictions on the conversion of energy during collisions. During a collision or an interaction, kinetic energy can be entirely conserved, or it can be converted into other types of energy such as heat energy, sound energy, and deformation of the objects. Collisions for which the initial kinetic energy of all of the objects involved is the same as the final kinetic energy are termed **elastic collisions**. Collisions for which the final kinetic energy is lower are termed inelastic.

Recall that kinetic energy (E_k) is the energy of motion of a body. For low speeds, it is calculated using:

$$E_k = \frac{1}{2}mv^2$$

In perfectly elastic collisions, kinetic energy is transferred between objects, and no energy is transformed into heat or sound or deformation. In cases such as these, the relationship is stated as:

$$E_k \text{ (before)} = E_k \text{ (after)}$$

Therefore

$$\Sigma \frac{1}{2}mv^2\text{(before)} = \Sigma \frac{1}{2}mv^2 \text{ (after)}$$

$$\Sigma \frac{1}{2}mv^2_{\text{before}} = \Sigma \frac{1}{2}mv^2_{\text{after}}$$

In Chapter 7 you saw that momentum is always conserved in a collision. The total energy is also always conserved in a closed system but, in general, kinetic energy is not conserved, and such collisions are called **inelastic collisions**.

Perfectly elastic collisions do not exist in everyday situations, but they do exist in the interactions between atoms and subatomic particles. A collision between two billiard balls or the spheres in a Newton's cradle is almost perfectly elastic because very little of their kinetic energy is transformed into heat and sound energy.

Collisions such as a bouncing basketball, a gymnast on a trampoline and a tennis ball being hit are moderately elastic, with about half the kinetic energy of the system being retained.

Perfectly inelastic collisions are those in which the colliding bodies stick together after impact with no kinetic energy. Some car crashes, a collision between a meteorite and the Moon, and a collision involving two balls of plasticine, could all be perfectly inelastic. In these collisions, most or all of the initial kinetic energy of the system is transformed into other forms of energy.

Worked example 8.4.2

CALCULATING ELASTIC COLLISIONS

A 35 kg child is sliding at 4.0 m s^{-1} on ice skates on a frozen pond and collides elastically with her large stationary uncle. The child is stationary after the collision. Calculate the mass of the uncle, if his velocity is 2.30 m s^{-1} after the collision.

Thinking	Working
Recall the equation for kinetic energy.	$E_k = \frac{1}{2}mv^2$
The collision is elastic, so the uncle's kinetic energy after the collision will be the same as that of the child before the collision.	$E_k(\text{before}) = E_k(\text{after})$ $\frac{1}{2}m_1v_1^2 = \frac{1}{2}m_2v_2^2$
Substitute in the data values.	$\frac{1}{2} \times 35 \times 4^2 = \frac{1}{2} \times m_2 \times 2.30^2$ $280 = \frac{1}{2} \times m_2 \times 2.30^2$
Rearrange the kinetic energy to make the uncle's mass the subject.	$m_2 = \frac{2 \times 280}{(2.30)^2}$
State the answer with appropriate units.	$m = 106$ kg

➤ Try yourself 8.4.2

CALCULATING ELASTIC COLLISIONS

A 20.0 kg object moving at 20.0 m s^{-1} collides with a stationary 20.0 kg object and stops; the collision is elastic. Calculate the velocity of the second object after the collision.

Worked example 8.4.3

CALCULATING INELASTIC COLLISIONS

A 60.0 kg gymnast is bouncing on a trampoline. If the efficiency of the trampoline is 50.0% and the initial velocity of the gymnast is 5.0 m s^{-1} as he hits the trampoline, calculate his speed straight after the bounce.

Thinking	Working
Recall the equation for kinetic energy.	$E_k = \frac{1}{2}mv^2$
The collision is inelastic, so the gymnast's kinetic energy after the bounce will less than his initial kinetic energy. Calculate his kinetic energy before the bounce.	$E_{k\ \text{before}} = \frac{1}{2} \times 60.0 \times 5.0^2$ $= 750$ J
Calculate his kinetic energy after the bounce, given that the trampoline is 50.0% efficient.	$E_{k\ \text{after}} = 750 \times 0.50$ $= 375$ J
Calculate his speed after the bounce. Note that speed is requested, so no direction is necessary.	$v = \sqrt{\frac{2E_k}{m}}$ $= \sqrt{\frac{2 \times 375}{60.0}}$ $= 3.5$ m s^{-1}

➤ Try yourself 8.4.3

CALCULATING INELASTIC COLLISIONS

A keen physics student performs an experiment to test the efficiency of a bouncy rubber ball when it is bounced on the ground. The student finds the bounce to be 60.0% efficient. If the mass of the ball is 100.0 g, and the speed of the ball after the bounce is 3.0 m s^{-1}, calculate the speed of the ball immediately before the bounce.

8.4 Review

SUMMARY

- Energy is not created or destroyed: it is conserved.
- Energy may be lost as heat, a form of energy that no longer has the ability to do work.
- The mechanical energy of an object is the sum of its kinetic and potential energy:

$$E_m = E_k + \Delta E_p$$

- Collisions in which kinetic energy is conserved are described as elastic collisions.
- In an elastic collision:

$$\sum \tfrac{1}{2} m v^2_{before} = \sum \tfrac{1}{2} m v^2_{after}$$

- Collisions in which some kinetic energy is lost as heat, sound or deformation of the objects are called inelastic collisions.
- Transformations of energy from one form to another are seldom 100% efficient: some energy is usually lost as heat.
- The efficiency of a transformation is given by:

$$\text{Efficiency } (\eta) = \frac{\text{energy output}}{\text{energy input}} \times 100\%$$

KEY QUESTIONS

Retrieval

1 Recall the equation used to calculate the efficiency of an energy transformation.

Comprehension

2 Describe the energy transformations a tennis ball undergoes if the ball is dropped from the player's hand.

Analysis

3 A piano with a mass of 180 kg is pushed off the roof of a five-storey apartment block. The piano falls 3.0 m for each storey (i.e. a total of 15 m).

a Calculate the piano's kinetic energy as it hits the ground.

b Calculate the piano's kinetic energy as it passes the windows on the second floor, having fallen 10.0 m.

4 A branch falls from a tree and hits the ground with a speed of 5.4 m s^{-1}. Calculate the height from which the branch fell.

5 A javelin with a mass of 800.0 g is thrown at an angle of inclination of 40.0°. It is released at a height of 1.45 m with a speed of 28.5 m s^{-1}.

a Calculate the javelin's initial mechanical energy.

b Calculate the speed of the javelin as it hits the ground.

6 When moving around on the Moon, astronauts find it easier to use a series of small jumps rather than to walk. If an astronaut (with a mass of 120 kg including equipment) jumps to a height of 10.0 cm on the Moon, where the gravitational field strength is 1.6 m s^{-2}, calculate roughly how much her potential energy increases.

7 A white billiard ball moving with a speed of 5.00 m s^{-1} strikes a stationary red billiard ball. After the collision, the white ball continues in the same direction at a speed of 1.00 m s^{-1}. The red ball rolls ahead of it (in the direction of the white ball's initial motion) with a speed of 4.00 m s^{-1}. Each ball has a mass of 160 g. Determine the energy of the objects both before and after the collision, and state whether it was elastic or inelastic.

8.5 Power

BY THE END OF THIS MODULE, YOU SHOULD BE ABLE TO:

- state that power is the rate at which work is done
- calculate the power being expended when a given amount of work is done in a given time
- correctly use the SI unit for power, the watt (W)
- calculate work done by a force acting at a particular velocity
- use energy–time graphs to calculate power being expended.

In many situations, energy is transformed between kinetic and gravitational potential energy. For example, when a tennis ball bounces, much of its kinetic energy is converted into gravitational potential energy and then back into kinetic energy again.

In analysing this type of situation, the concept of mechanical energy is useful. Mechanical energy is the sum of the potential energies available to an object and the kinetic energy of an object.

When mechanical energy is conserved, the energy change can be used to predict the outcome of the situation. When mechanical energy is not conserved, the energy change can be used to help identify other important energy transformations.

DEFINING POWER

Power is a measure of the rate at which work is done. So power is the work is done in a period of time.

$$P = \frac{W}{\Delta t}$$

Imagine running up a set of stairs. You would do exactly the same amount of work as if you walked up the stairs. Recall from Module 8.2 that $W = mg\Delta h$. This means that the work you do depends on your mass and the height you climb, and not on how quickly you climb the stairs. However, the power you apply does depend on the time it takes to climb the stairs. When you run up the stairs, the energy change is faster, so you apply more power than when walking, as shown in Figure 8.5.1.

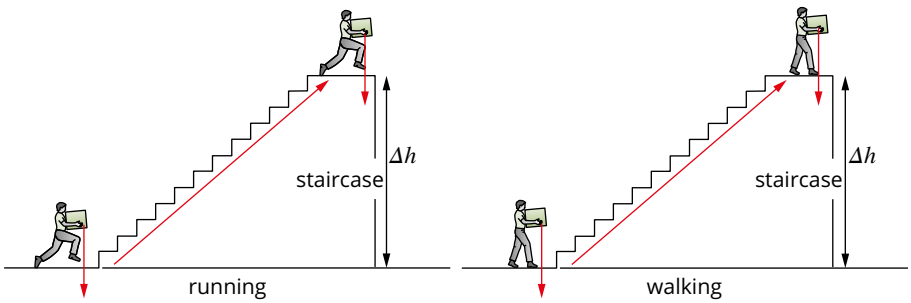


FIGURE 8.5.1 The runner and the walker both do the same amount of work, but the power output of the runner is higher than that of the walker.

Unit of power

The unit of power is named after the Scottish engineer James Watt, who is most famous for inventing the steam engine. A watt (W) is defined as a rate of work of one joule per second; in other words:

$$1\text{W} = \frac{1\text{J}}{1\text{s}} = 1\,\text{J}\,\text{s}^{-1}$$

CALCULATING POWER

In many everyday situations, a force is applied to an object to keep it moving at a constant speed, such as when pushing a wardrobe across a carpeted floor or driving a car at a constant speed. In these situations, the power being applied can be calculated directly from the force applied and the speed of the object.

$$P = \frac{W}{\Delta t} \text{ and } W = Fs$$

$$P = \frac{Fs}{\Delta t} = F \times \frac{s}{\Delta t}$$

Recall that $\frac{s}{\Delta t}$ is the definition of average speed, so the power equation can be written as:

$$P = Fv_{\text{av}}$$

$P = Fv_{\text{av}}$

where

P is power (W)

F is force (N)

v_{av} is average speed ($\text{m}\,\text{s}^{-1}$).

Worked example 8.5.1

CALCULATING POWER USING FORCE AND VELOCITY

A motorcycle racing at a speed of $216\,\text{km}\,\text{h}^{-1}$ requires a force of 2800 N to maintain its velocity. Determine how much power its engine is expending.

Thinking	Working
Convert the motorcycle's speed to $\text{m}\,\text{s}^{-1}$.	$216\,\text{km}\,\text{h}^{-1} = \frac{216\,\text{km}}{1\,\text{h}} = \frac{216\,000\,\text{m}}{3600\,\text{s}} = 60\,\text{m}\,\text{s}^{-1}$
Recall the equation for power in terms of force and velocity.	$P = Fv_{av}$
Substitute the values for this situation into the equation.	$= 2800 \times 60$
State the answer with appropriate units.	$= 168\,000\,\text{W}$ $= 168\,\text{kW}$ $= 170\,\text{kW}$ (to 2 significant figures)

➤ Try yourself 8.5.1

CALCULATING POWER USING FORCE AND VELOCITY

Calculate the power expended when a cyclist exerts a force of 17 N to travel at an average speed of $22\,\text{m}\,\text{s}^{-1}$.

ENERGY AND TIME

Recall that when work is done, energy is transferred or transformed. So the equation for power can be written as a rate of change of energy, ΔE, over time.

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

The average change in power is the change in energy divided by the change in time. The instantaneous power is the gradient of an energy–time graph at that instant, as shown in Figure 8.5.2.

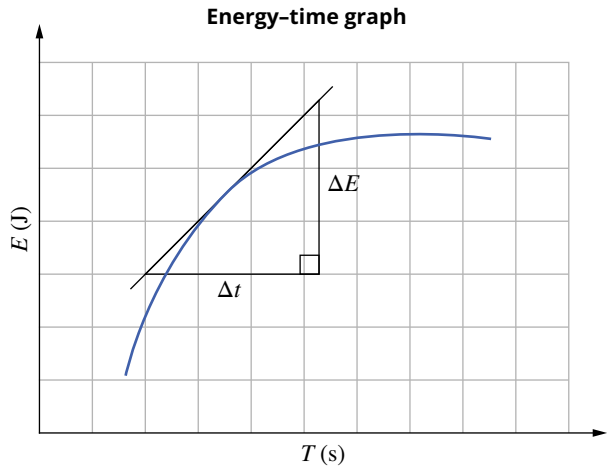


FIGURE 8.5.2 The gradient (slope) of an energy–time graph gives the power being expended at a moment in time.

Worked example 8.5.2

CALCULATING POWER AS THE RATE OF CHANGE OF ENERGY

An accelerating speedboat changes its kinetic energy from 280 kJ to 970 kJ over 30.0 s. Calculate the power used for this acceleration.	
Thinking	**Working**
Recall the equation for power.	$P = \frac{\Delta E}{\Delta t}$
Calculate the change in the kinetic energy of the boat.	$\Delta E = E_{final} - E_{initial}$ $= 970 - 280$ $= 690\,\text{kJ} = 690\,000\,\text{J}$
Substitute the values into the equation for power.	$P = \frac{\Delta E}{\Delta t}$ $= \frac{690\,000}{30.0}$
State the answer with appropriate units.	$P = 23\,000\,\text{W}$ $= 23\,\text{kW}$

➤ Try yourself 8.5.2

CALCULATING POWER AS THE RATE OF CHANGE OF ENERGY

A drone flying upwards increases its gravitational potential energy by 76 J over 3.8 s. Calculate the power expended.

8.5 Review

SUMMARY

- Power is the rate at which work is done or energy is converted.
- The gradient of an energy–time graph is a measure of the power expended.
- Power can be calculated as the product of force and velocity.
- The SI unit of power is the watt (W).

KEY QUESTIONS

Retrieval

1 Define power, and state the SI unit used to measure it.

Comprehension

2 Explain how the power being expended at a particular moment can be determined from an energy–time graph.

Analysis

3 A coal-fired generator has an efficiency of about 30.0%. If 2000.0 J of energy is supplied to the generator, calculate how much is converted into electrical energy.

4 A rubber ball is dropped from a height of 1.5 m and loses 20.0% of its mechanical energy as it hits the ground. Determine the height of the rebound.

5 A 1610 kg car accelerates from zero to 100.0 km h^{-1} in 5.50 s. Calculate its average power output over this time.

6 A locomotive engine applies a force of 4.0 kN to keep a train moving at 20.0 m s^{-1}. Calculate the power output of the engine.

7 A 1700 kg car's engine uses 40.0 kW of power to maintain a constant speed of 80.0 km h^{-1}. Calculate the force being applied by its engine.

8 The motor of a crane has a maximum power output of 25 kW. Determine the average speed at which it can lift a concrete slab with a mass of 500.0 kg.

9 A crane can lift a load of 5.0 tonnes vertically through a distance of 20.0 m in 5.0 s. Determine the approximate power of the crane.

10 A sports car with a mass of 650 kg can accelerate from 0.0 to 100.0 km h^{-1} in 7.2 s. Calculate the average power output of the car over this time.

11 If the engine of a 1400 kg car uses 25 kW to maintain an average speed of 17 m s^{-1}, calculate how much friction is acting on the car.

Chapter review

WS 2.1.10 WS 2.1.11 TR 2.1

08

KEY TERMS

efficiency
elastic collision
gravitational potential energy
inelastic collision
kinetic energy
law of conservation of energy
mechanical energy
mechanical work
power
transform
work

KEY QUESTIONS

Retrieval

1 State the formula used to calculate the gravitational potential of an object with mass m that is h metres above the chosen zero point.

2 State the term used to describe a collision in which both momentum and kinetic energy are conserved.

3 State the name given to the combined kinetic and gravitational potential energy of an object.

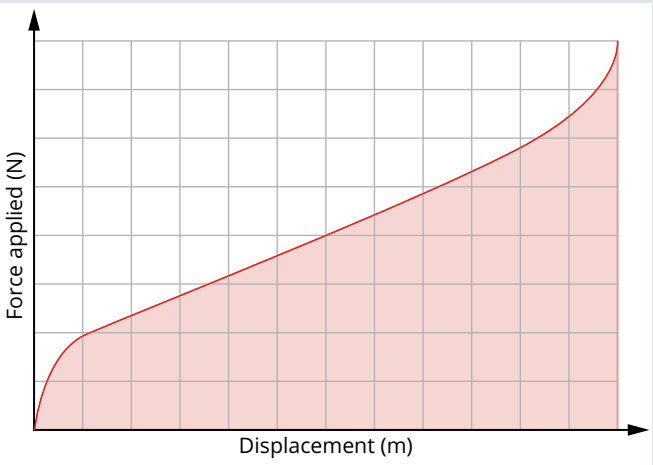
Comprehension

4 The speed of an object is doubled. State the magnitude of the increase in its kinetic energy.

Analysis

5 A car drives at a constant speed for 80.0 m. In order to overcome friction, its engine applies a force of 2000.0 N. Calculate the work done by the engine.

6 Use the force–displacement graph below to estimate how much work is done, given that each grid square corresponds to 1 J.



7 A crane lifts a 200.0 kg load from the ground to a height of 30.0 m. Calculate the work done by the crane.

8 A person walks up a flight of 12 stairs. Each step is 240 mm long and 165 mm high. If the person has a mass of 60.0 kg and $g = 9.80\,m\,s^{-2}$, calculate the total amount of work done against gravity.

9 If 4000.0 J is used to lift a 50.0 kg object with a constant velocity, calculate the theoretical maximum height to which the object can be raised.

10 A pram is pushed by the handle, which is at an angle of 35° to the horizontal (the direction of motion). If 1200 J of work is done pushing the pram 20.0 m, calculate the force with which the pram was pushed.

11 A cricket ball with a mass of 160 g is bowled with a speed of $150\,km\,h^{-1}$. Calculate the kinetic energy of the cricket ball.

12 If a 1200 kg car has kinetic energy of 70.0 kJ, calculate its speed.

13 A plumber (mass 88.0 kg) digs a ditch 40.0 cm deep. Calculate the change in the plumber's gravitational potential energy when he steps from the ground down into the ditch.

14 If the engine of a 1400 kg car uses a force of 15 kN to maintain an average speed of $17\,m\,s^{-1}$, calculate the frictional force acting on the car.

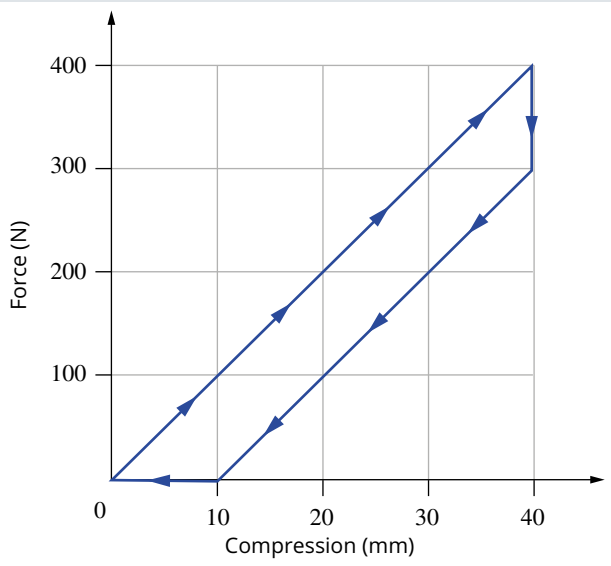
15 At the start of a 100.0 m race, a runner with a mass of 60.0 kg accelerates from a standing start to $8.0\,m\,s^{-1}$ in a distance of 20.0 m.

a Calculate the average force that the runner's legs apply over this distance.

b Calculate the work done by the runner's legs.

16 The efficiency of an appliance is known to be 80.0%. Calculate the energy supplied if the output was 1250 J.

17 The diagram below is a simplified representation of the forces acting on a basketball when it bounces. The upwards arrows show the force as the basketball compresses and the downwards arrows show the force as it rebounds.



a Calculate the work done on the basketball when it compresses by 40 mm.

b Calculate the work done by the ball as it decompresses from a compression of 40 mm.

c Explain why your answers to parts **a** and **b** are different.

Knowledge utilisation

18 A football with a mass of 0.43 kg is kicked off the ground with a speed of 16 m s^{-1}. Calculate the speed of the ball when it hits the crossbar, which is 2.44 m above the ground.

19 A thrown stone of mass 110 g strikes a piece of plasticine of mass 3.5 kg hanging from a string with speed v and becomes embedded in the plasticine. When the plasticine swings back, its height increases by 0.25 m.

For the tasks that follow, assume that the initial gravitational potential energy of the plasticine was zero (i.e. we choose its starting height as the zero point for gravitational potential energy).

a Calculate the gravitational potential energy of the plasticine at the top of its swing.

b Calculate the kinetic energy of the plasticine when the stone first embedded in it.

c Calculate the speed of the plasticine when it started to swing.

CHAPTER

09 Properties of waves

Have you ever watched ocean waves heading towards the shore? For many people, their first thought when encountering a topic called 'waves' is to picture a water wave moving across the surface of an ocean. The wave may be created by some kind of disturbance such as the action of wind on water or a boat as it moves through the water.

WS 2.2.1

Waves are, in fact, everywhere. Sound, visible light, radio waves, waves in the string of an instrument, the wave of a hand, the 'Mexican wave' at a stadium and the recently discovered gravitational waves all are waves or wave-like phenomena. Understanding the physics of waves provides a broad base on which to build your understanding of the physical world. A knowledge of waves gives an introduction to the concepts that describe the nature of light.

Syllabus subject matter

Topic 2 • Waves

WAVE PROPERTIES

- recall that waves transfer energy
- define the term *mechanical wave*
- compare the terms *transverse wave* and *longitudinal wave*
- describe examples of transverse and longitudinal waves, such as sound, seismic waves and vibrations of stringed instruments
- recall the terms *compression*, *rarefaction*, *crest*, *trough*, *displacement*, *amplitude*, *period*, *frequency*, *wavelength* and *velocity*, identifying them on graphical and visual representations of a wave
- interpret and calculate the amplitude, period, frequency and wavelength from graphs of transverse and longitudinal waves
- solve problems involving the wavelength, frequency, period and velocity of a wave
- define the terms *reflection*, *refraction*, *diffraction* and *superposition*
- using the wave model of light, explain phenomena related to reflection and refraction
- describe the reflection and refraction of a wave at a boundary between two media
- apply the principle of superposition to determine the resultant amplitude of two simple waves
- explain constructive interference and destructive interference of two simple waves
- explain the formation of standing waves in terms of superposition with reference to constructive and destructive interference, and nodes and antinodes.

SCIENCE AS A HUMAN ENDEAVOUR

- Monitoring earthquakes and tsunamis

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9.1 Describing a wave

BY THE END OF THIS MODULE, YOU SHOULD BE ABLE TO:

- recall that waves transfer energy
- recall examples of waves
- define the term 'mechanical wave'
- determine the amplitude and wavelength from a displacement–distance graph
- determine the amplitude and period from a displacement–time graph
- relate the period to the frequency using the inverse relationship $f = \frac{1}{T}$
- solve problems involving wavelength, frequency, period and velocity using $v = f\lambda$.

FIGURE 9.1.1 The ripples in a pond indicate a transfer of energy.

Throw a stone into a pool or lake, and you will see circular waves form and move outwards from the source as ripples, as shown in Figure 9.1.1. Stretch a cord out on a table and wriggle one end back and forth across the table surface and another type of wave can be observed. Sound waves, water waves and waves in strings are all examples of **mechanical waves**. Mechanical waves, as opposed to electromagnetic waves, cannot transmit energy through a vacuum. Mechanical waves are the focus of this chapter.

MECHANICAL WAVES

Watch a piece of driftwood, a leaf, or even a surfer, resting in the water as a smooth wave goes past, and you'll notice that the object moves up and down but doesn't move forwards with the wave. The movement of the object on the water reveals how the **particles** in the water move. As the wave passes, the particles in the water move up and down from an average position.

Any wave that needs a **medium** (such as water or air particles) through which to travel is called a mechanical wave. Mechanical waves can move over very large distances, but the particles of the medium only have very limited movement.

Mechanical waves transfer energy from one place to another through a medium. The particles of the matter vibrate back and forth or up and down about an average position, which transfers the energy from one place to another. For example, energy is given to an ocean wave by the action of the wind far out at sea. The *energy* is transported by waves to the shore but (except in the case of a tsunami event) most of the ocean water itself does not travel onto the shore.

A wave involves the transfer of energy without the net transfer of matter.

PULSES VERSUS TRAVELLING WAVES

A single wave **pulse** can be formed by giving a slinky spring or rope a single up-and-down motion, as shown in Figure 9.1.2a. As the hand pulls upwards, the adjacent parts of the slinky will also feel an upwards force and begin to move upwards. The source of the wave energy is the movement of the hand.

If the up-and-down motion is repeated, each successive section of the slinky will move up and down, moving the wave forwards along the slinky as a travelling wave, as shown in Figure 9.1.2b. Connections between each loop of the slinky cause the wave to travel away from the source, carrying with it the energy from the source.

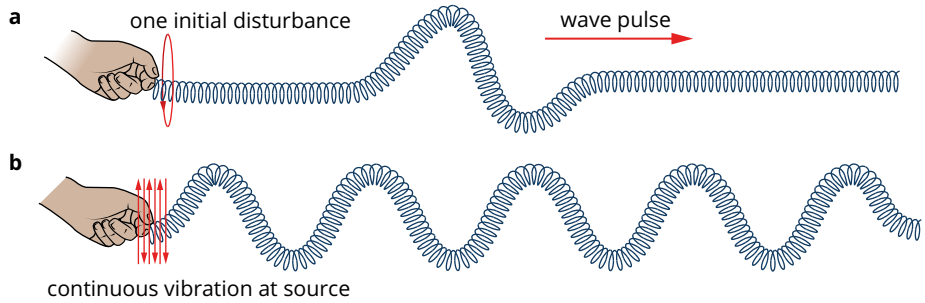


FIGURE 9.1.2 (a) A single wave pulse can be sent along a slinky by a single up-and-down motion. (b) A continuous or travelling wave is created by a regular, repeated movement of the hand.

In a continuous wave or **travelling wave**, continuous vibration of the source will cause the particles within the medium to oscillate about their average position in a regular, repetitive or periodic pattern. This is shown in Figure 9.1.2b. The source of any mechanical wave is this repeated motion or vibration. The energy from the vibration moves through the medium and constitutes a mechanical wave.

MEASURING MECHANICAL WAVES

The features of a mechanical wave can be represented using a graph. In this section you will explore how the displacement of particles within the wave can be represented using graphs. From these graphs, several key features of a wave can be identified:

- amplitude
- wavelength
- frequency
- period
- speed.

Waves of different amplitudes and wavelengths can be seen in Figure 9.1.3.

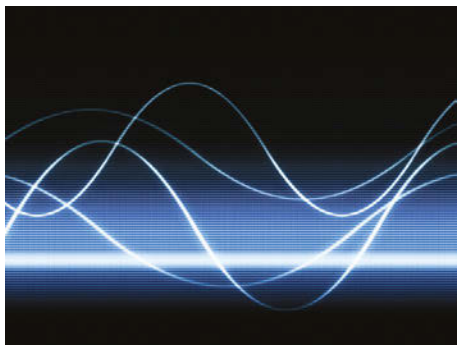


FIGURE 9.1.3 Waves have different wavelengths, amplitudes, frequencies, periods and velocities, which can all be represented on a graph.

Displacement–distance graphs

Figure 9.1.2b shows a continuous wave in a slinky. This 'snapshot' in time shows the particles moving up and down about a central rest position. This is called a **sinusoidal oscillation**. As a wave passes a given point, the particle at that point will go through a complete cycle before returning to its starting point. The wave spread along the length of the slinky has the shape of a sine or cosine function, which you will recognise from mathematics. A displacement–distance graph shows the position (displacement) of the particles at any moment in time along the slinky about a central position.

The displacement–distance graph in Figure 9.1.4 shows the displacement of all particles along the length of a transverse wave at a particular point in time.

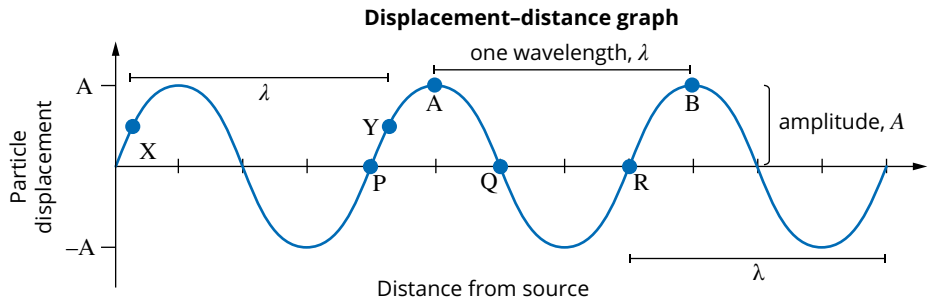


FIGURE 9.1.4 The graph shows the particle displacements along a wave.

From a displacement–distance graph, the amplitude and wavelength of a wave are easily recognisable.

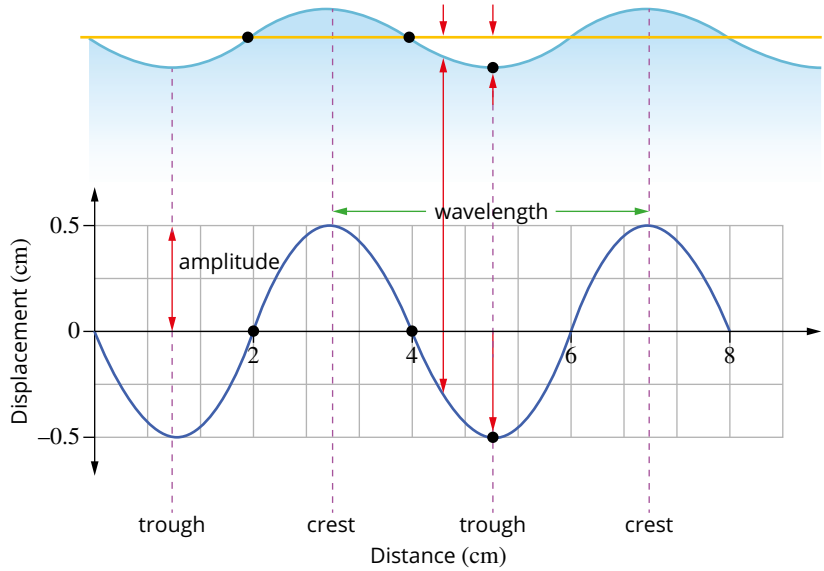
- The **amplitude** (shown as A on the vertical axis in Figure 9.1.4) of a wave is the maximum displacement of a particle from the average or rest position. That is, the amplitude is distance from the middle of a wave to the top of a **crest** or to the bottom of a **trough**. The total distance through which a particle will move in one cycle is twice the amplitude.
- The **wavelength**, λ, of a wave is the distance between any two successive points in phase (e.g. points A and B or X and Y in Figure 9.1.4). It is denoted by the Greek letter λ (lambda), and is measured in metres. Two particles on the wave are said to be in **phase** if they have the same displacements from the average position and are moving in the same direction. Points P and R in Figure 9.1.4 are two such particles that are in phase, as are points A and B and X and Y, but not P and Q.
- The **frequency**, f, is the number of complete cycles that pass a given point per second and is measured in hertz (Hz).
- The **period**, T, of the wave is the amount of time that it takes one complete cycle of the wave to pass a particular point.

By drawing a series of displacement–distance graphs at various times, you can see the motion of the wave. By comparing the changes in these graphs, you can find the travelling speed and direction of the wave, as well as the direction of motion of the vibrating particles.

Worked example 9.1.1

DISPLACEMENT–DISTANCE GRAPH

The displacement–distance graph below shows a snapshot of a mechanical water wave as it travels to the right. Use the graph to determine the amplitude and the wavelength of this wave.



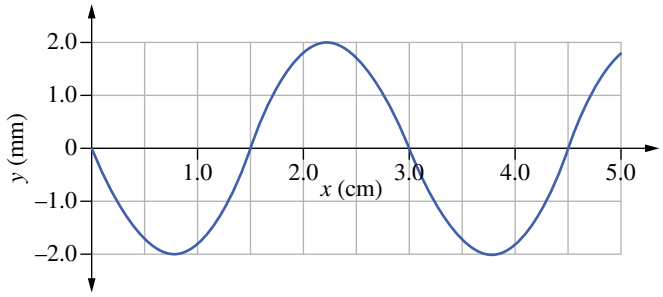
Thinking	Working
Amplitude on a displacement–distance graph is the distance from the average or rest position to a crest or a trough. Read the displacement of a crest or a trough from the vertical axis. Convert to SI units where necessary.	Amplitude = 0.5 cm = 5×10^{-3} m

Wavelength is the distance for one complete cycle. Any two consecutive points in phase and at the same position on the wave could be used. Convert to SI units where necessary.	The first cycle runs from the origin (0, 0) through a trough (1.0, –0.5), crosses the *x*-axis at (2.0, 0), up to the crest (3.0, 0.5) and then crosses the *x*-axis at (4.0, 0). The horizontal distance of one complete cycle is the wavelength. Wavelength $\lambda = 4.0\,\text{cm} = 4.0 \times 10^{-2}\,\text{m}$

➤ Try yourself 9.1.1

DISPLACEMENT–DISTANCE GRAPH

The graph below shows a snapshot of a mechanical wave as it travels along a string towards the right. The displacement, *y*, varies with the distance, *x*, as shown. Use the graph to determine the amplitude and the wavelength of this wave.



Displacement–time graphs

Figure 9.1.5 shows a displacement–time graph that tracks the position of one point over time as the wave moves through the point.

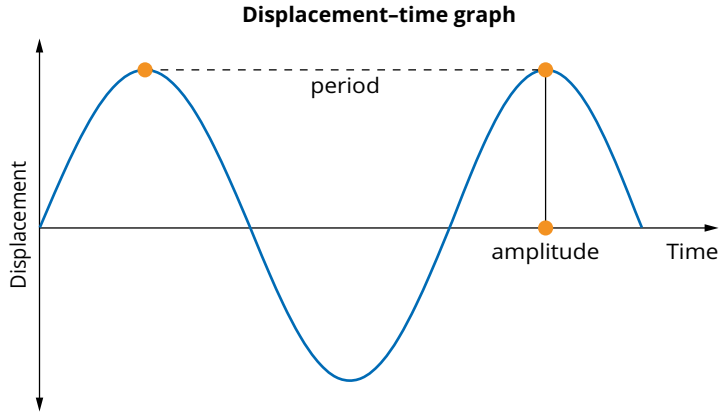


FIGURE 9.1.5 The graph of displacement versus time from the source of a transverse wave shows the movement of a single point on a wave over time as the wave passes through that point.

The displacement–time graph looks very similar to a displacement–distance graph of a transverse wave, so be careful to check the horizontal axis label.

Crests and troughs are shown the same way in both graphs. The amplitude is still the maximum displacement from the average or rest position of either a crest or a trough. But the distance between two successive points in phase in a displacement–time graph represents the period of the wave, *T*, measured in seconds.

The period, *T*, is the time it takes for any point on the wave to go through one complete cycle (e.g. from crest to successive crest). The period of a wave is inversely related to its frequency, *f*.

The amplitude and period of a wave, and the direction of motion of a particular particle, can be determined from a displacement–time graph.

$T = \frac{1}{f}$

where

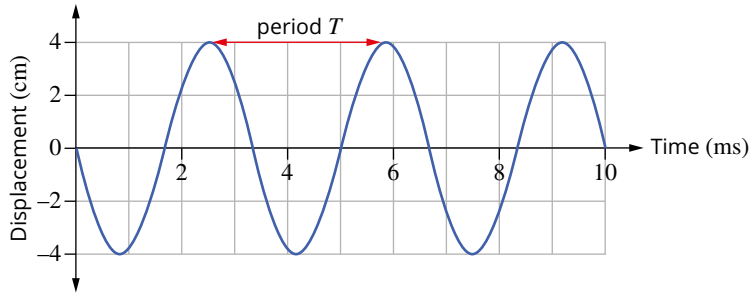
T is the period of the wave (s)

f is the frequency of the wave (Hz).

Worked example 9.1.2

DISPLACEMENT–TIME GRAPHS

The displacement–time graph below shows the motion of a single point of a rope as a wave travels to the right. Use the graph to find the amplitude, period and frequency of the wave.

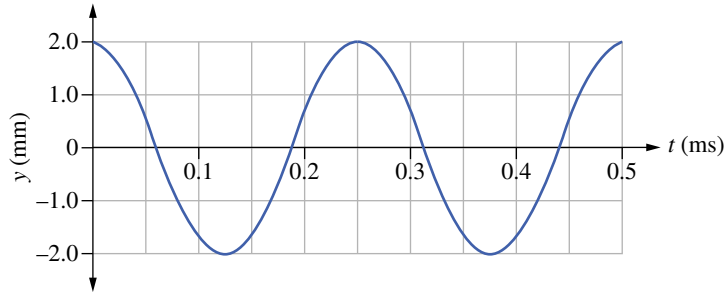


Thinking	Working
The amplitude on a displacement–time graph is the displacement from the average position to a crest or trough. Note the displacement of successive crests and/or troughs on the wave and carefully note units on the vertical axis. Where necessary, convert to SI units.	Maximum displacement is 4.0 cm. Therefore amplitude = 4.0×10^{-2} m.
Period is the time it takes to complete one cycle and can be identified on a displacement–time graph as the time between two successive points that are in phase. Identify two points on the graph at the same position in the wave cycle, or the total number of oscillations on the graph. Divide the total time t by the total number of oscillations. Note, there are three troughs and three crests, or three complete oscillations in 10 ms. Where necessary, convert to SI units.	Period: $T = \frac{10}{3}$ ms $= 3.3$ ms $= 3.3 \times 10^{-3}$ s
Frequency can be calculated using $f = \frac{1}{T}$, measured in hertz (Hz).	$f = \frac{1}{T}$ $= \frac{1}{3.3 \times 10^{-3}}$ $= 300$ Hz

➤ Try yourself 9.1.2

DISPLACEMENT–TIME GRAPHS

The displacement–time graph below shows the displacement of a particle on a mechanical wave moving to the right. The displacement, y, varies with the time, t. Use the graph to find the amplitude, period and frequency of the wave.



THE WAVE EQUATION

Although the speed of a wave can vary, there is a relationship between the speed of a wave and other significant wave characteristics. In the study of motion, speed is given by:

$$v = \frac{\text{distance travelled}}{\text{time taken}} = \frac{d}{\Delta t}$$

This can be rewritten in terms of the distance of one wavelength (λ) in one period (T): $v = \frac{\lambda}{T}$

Using the relationship between the period and frequency $T = \frac{1}{f}$:

$$v = \frac{\lambda}{T} = \frac{\lambda}{\frac{1}{f}} = \lambda f$$

This is known as the wave equation and applies to all types of waves.

The wave equation

$v = f\lambda$

where

v is the speed ($m\,s^{-1}$)

f is the frequency (Hz)

λ is the wavelength (m).

Worked example 9.1.3

WAVE EQUATION FREQUENCY

A mechanical wave has a wavelength of 1.5 m and a speed of 6.0 $m\,s^{-1}$. Determine the frequency, f, of the wave.

Thinking	Working
The wave equation states that $v = f\lambda$. Knowing both v and λ, the frequency, f, can be found. Rewrite the wave equation in terms of f.	$f = \frac{v}{\lambda}$
Substitute the known values and solve.	$= \frac{6.0}{1.5}$ $= 4.0$ Hz

➤ Try yourself 9.1.3

WAVE EQUATION FREQUENCY

A mechanical wave has a wavelength of 0.5 m and a speed of 4.0 $m\,s^{-1}$. Determine the frequency, f, of the wave.

Worked example 9.1.4

WAVE EQUATION PERIOD

A mechanical wave has a wavelength of 3.0 m and a speed of 150 $m\,s^{-1}$. Calculate the period, T, of the wave.

Thinking	Working
Rewrite the wave equation in terms of T.	$v = f\lambda$ and $f = \frac{1}{T}$ $v = \frac{1}{T} \times \lambda$ $= \frac{\lambda}{T}$
Substitute the known values and solve.	$T = \frac{\lambda}{v}$ $= \frac{3.0}{150}$ $= 2.0 \times 10^{-2}$ s

➤ Try yourself 9.1.4

WAVE EQUATION PERIOD

A mechanical wave has a wavelength of 1.7×10^{-4} m and a speed of 340 $m\,s^{-1}$. Calculate the period, T, of the wave.

INTENSITY

As well as being described by their speed, frequency and amplitude, waves can be described by their **intensity**, which is a measure of their power per unit area. Intensity is measured in units of watts per square metre ($W\,m^{-2}$).

Light waves emitted from the surface of a luminous object such as a lamp or neon sign, emits light waves of a certain intensity. Bright lights that are shone into the eyes of people (e.g. when caving or in dark locations) can be unpleasant to view. The iris and pupil of the eye take time to adjust to the sudden change in intensity entering the light-sensitive retina at the back of the eye.

Intensity applies to sound waves as well as light. The threshold of human hearing is 0 decibels, which is usually associated with sounds that can just be heard. The decibel scale is a ratio of the intensity of a noise or sound to the threshold of hearing intensity. One of the loudest sounds or sounds of highest intensity was the Krakatoa volcanic eruption, which left people with ruptured eardrums. The noise of the launch of the *Saturn V* rocket measures an amazing 220 decibels at close range, and the energy from the sound waves it produces can melt concrete. Other sound intensities are busy city traffic, which has been measured at 85 decibels, and typical speech at around 55 decibels.

The intensity of light waves is discussed further in Chapter 11.

9.1 Review

SUMMARY

- Vibrating objects transfer energy through waves, which travel outwards from the source. Examples include waves on water, waves on a string and sound waves in air.
- A wave may be a single pulse or it may be continuous or periodic (successive crests and troughs).
- A wave only transfers energy from one point to another. There is no net transfer of matter or material.
- Waves can be represented by displacement–distance graphs and displacement–time graphs.
- From a displacement–distance graph, you can determine amplitude and wavelength.
- From a displacement–time graph, you can determine amplitude, frequency and period.
- The period of a wave has an inverse relationship to the frequency, according to the relationship:

$$T = \frac{1}{f}$$

- The speed of a wave can be calculated using the wave equation:

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

- The intensity of a wave is a measure of its power per unit area.

KEY QUESTIONS

Retrieval

1 Recall at least five waves or wave-like phenomena.

2 Recall what all waves transfer.

Comprehension

3 Describe a pulse and a travelling wave.

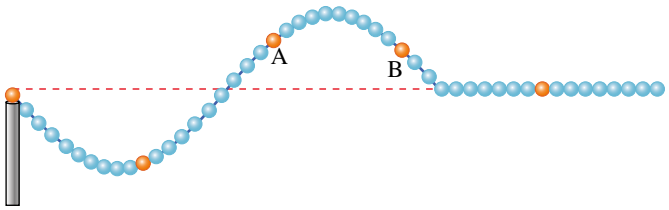
4 At a K-pop concert, sound waves are emitted from a speaker. Max sits in a seat 25 m away from the speaker. He turns to his friend and makes some statements about the sound he is hearing. Identify the correct statements below. Justify the correct statements with an explanation.

a The air particles carried the energy as they travelled from the speaker to me.

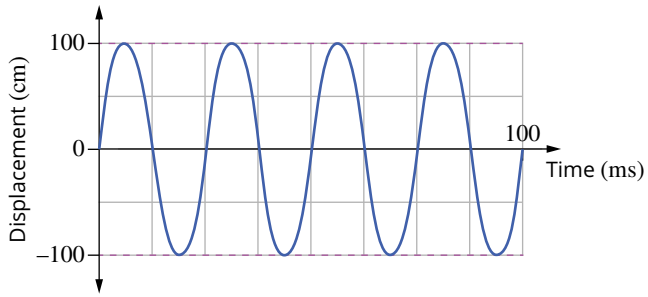
b Energy has been transferred from the speaker to me due to the oscillation of the air particles.

c The air particles transfer the energy as they oscillate about an average rest position; the particles do not have any net movement.

5 A mechanical arm moves to produce a pulse transferring energy to the right of the page, as shown below. The dots represent the particles on a string. Describe the movement of particles A and B for one complete oscillation, as the pulse moves to the right.



6 The displacement–time graph below is for a particle on a mechanical wave. Determine the amplitude, period and frequency of the wave.

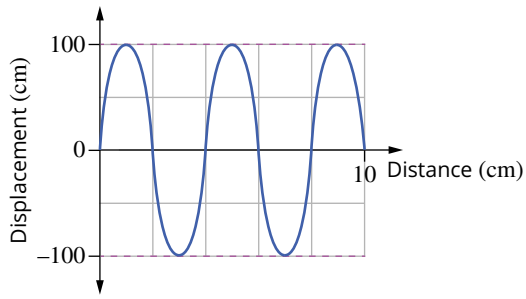


Analysis

7 Assess whether each of the following statements is true or false. For the false statements, rewrite them so they become true.

- **a** The energy from the vibration moves through the medium (example: air particles) and is called a mechanical wave.
- **b** Mechanical waves include sound, ripples on a pond, vibrations in a rope and light.
- **c** Mechanical waves transfer energy without a net transfer in matter.

8 The displacement–distance graph for a mechanical wave at an instant in time is shown below. Determine the wavelength and amplitude of this wave.



9 Five complete waves pass a point in 1.0 minute. The amplitude of these waves is 0.70 m and the distance between successive troughs on each wave is 1.2 m. Calculate the speed of the wave.

10 A wave has a period of 2.0×10^{-3} s (or 2.0 ms). Calculate the frequency of this wave.

9.2 Types of waves

BY THE END OF THIS MODULE, YOU SHOULD BE ABLE TO:

- describe transverse waves in terms of the direction of oscillation and the direction of wave energy movement
- describe longitudinal waves in terms of the direction of oscillation and the direction of wave energy movement
- provide examples of both transverse and longitudinal waves
- draw and label a transverse wave
- state a third type of wave, or torsional wave
- represent a travelling wave using wavefronts and a ray diagram
- represent (or draw) a longitudinal wave as a sinusoidal wave with labels for compressions and rarefactions
- determine amplitude, period, frequency and wavelength of longitudinal and transverse waves from their graphs
- classify everyday types of waves such as seismic waves, tsunami waves and stringed instruments as either longitudinal waves or transverse waves.

Mechanical waves are involved in many everyday experiences. Pluck a guitar string and watch the string vibrate or listen to the sound it makes. Watch the stereo speaker membrane vibrate back and forth when you play your favourite music or song. Have you ever heard the sound produced when the top of a wine glass is rubbed by a finger? Different types of mechanical waves can be observed in each of these examples.

TRANSVERSE AND LONGITUDINAL WAVES

Mechanical waves can be grouped into two main types: transverse and longitudinal waves.

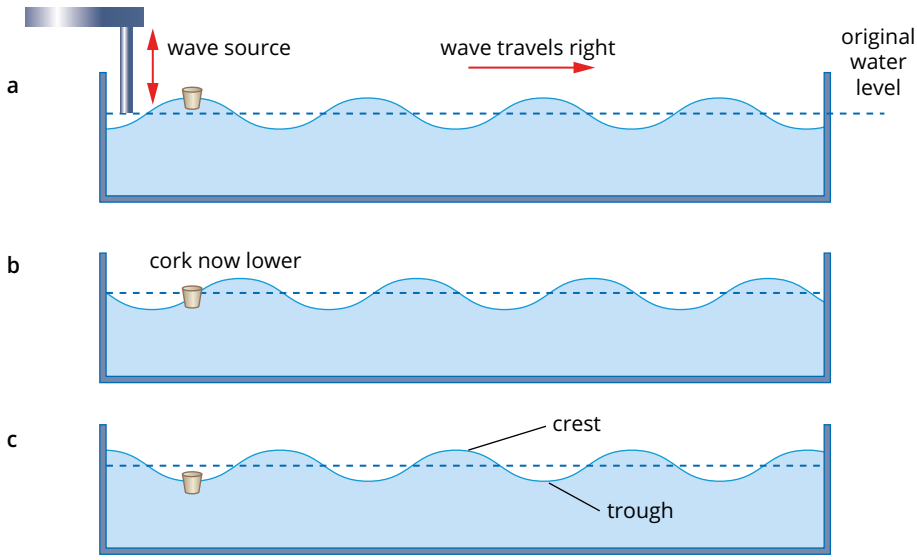


FIGURE 9.2.1 As a continuous water wave moves to the right, the up-and-down displacement of the particles, which is transverse to the wave motion, can be monitored using a cork. The cork simply moves up and down as the wave passes through it.

Transverse waves

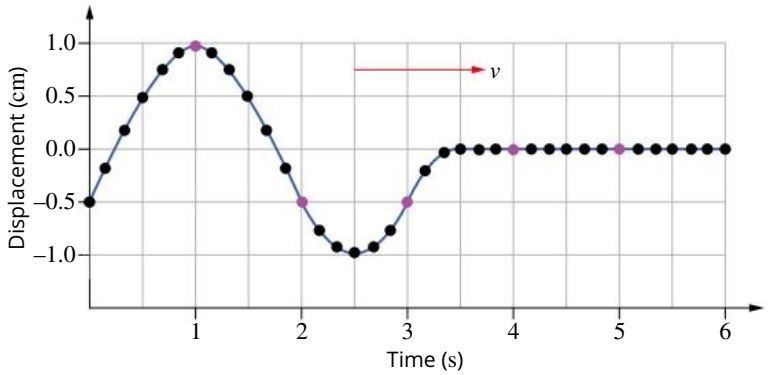
In a **transverse** mechanical wave, the wave travels in the direction of motion of the wave energy. When waves travel on water, or through a rope, spring or string, the particles within the medium vibrate up and down in a direction perpendicular, or transverse, to the direction of the wave energy. When the particles are displaced upwards from the average position, or resting position, they reach a maximum positive displacement called a crest. Particles below the average position fall to a maximum negative position called a trough, as shown in Figure 9.2.1.

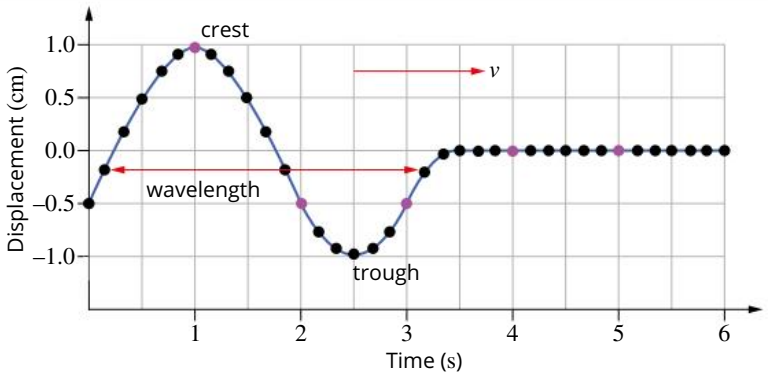
Worked example 9.2.1

TRANSVERSE WAVES

A transverse wave is shown below transferring energy to the right. The displacement (y-axis) is shown in cm, and the time (x-axis) is shown in seconds. Label the crest, the trough, and the wavelength, λ.

Determine the amplitude, frequency and period of the transverse wave.



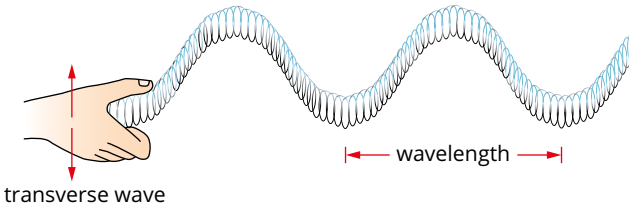
Thinking	Working
A crest is a point on a transverse wave where the particles are at a maximum positive displacement from the rest position. A trough is a point on a transverse wave where the particles are at the maximum negative displacement from the rest position. The wavelength of a transverse wave is measured from identical points, or phases, on successive waves.	
The amplitude is measured from the rest position ($y = 0.0$ cm) to the maximum displacement ($y = 1.0$ cm).	$A = 1.0$ cm
The period is the time a complete wave oscillation takes to pass a given point. The particle ($y = –0.5$ cm) moves up and down and is back at its original position ($y = –0.5$ cm) in a time of 3.0 seconds.	$T = 3$ s
Use the inverse relationship between frequency and period to solve for frequency f.	$f = \frac{1}{T}$ $= \frac{1}{3}$ $= 0.3$ Hz
Write the amplitude, frequency and period of the wave. Convert to SI units when necessary.	The amplitude is 1.0×10^{-2} m. The frequency is 0.3 Hz. The period is 3 s.

➤ Try yourself 9.2.1

TRANSVERSE WAVES

A slinky spring is being moved up and down perpendicular to the net movement of energy, as shown in the diagram. The hand moves a total distance of 40.0 cm from the lowest point to the highest, completing one oscillation in 0.60 seconds. The transverse wave travels a length of 3.0 m in 2.8 seconds.

Determine the amplitude A, wavelength λ, frequency f, period T and velocity v.



Longitudinal waves

In a **longitudinal** mechanical wave, the vibrations of the particles within the medium are in the same direction, or parallel to, the direction of energy flow of the wave. You can demonstrate this type of wave with a slinky by moving your hand backwards and forwards in a line parallel to the length of the slinky, as shown in Figure 9.2.2.

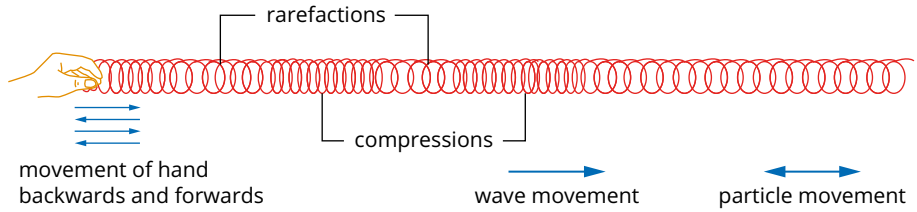


FIGURE 9.2.2 When the direction of the vibrations of the medium and the direction of travel of the wave energy are parallel, a longitudinal wave is created. This can be demonstrated with a slinky.

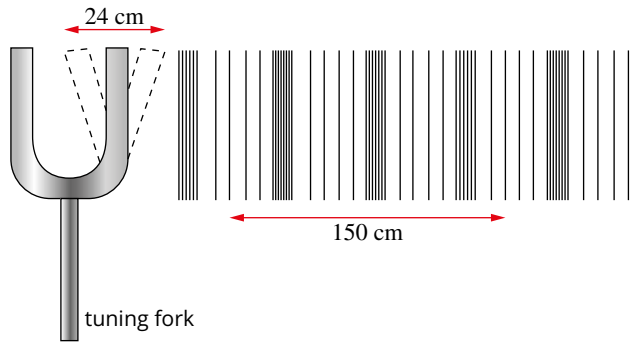
As you move your hand, a series of compressed and expanded areas form along the slinky. **Compressions** are those areas where the coils of the slinky come together. Expansions are regions where the coils are spread apart. Areas of expansion are termed **rarefactions**. The compressions and rarefactions in a longitudinal wave correspond to the crests and troughs of a transverse wave.

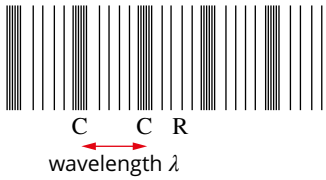
Worked example 9.2.2

LONGITUDINAL WAVES

The diagram below shows a tuning fork producing longitudinal waves. Label a compression, C, a rarefaction, R, and the wavelength, λ.

Determine the amplitude, wavelength, frequency and period of the longitudinal wave. The speed of sound in air is 340 m s^{-1}.



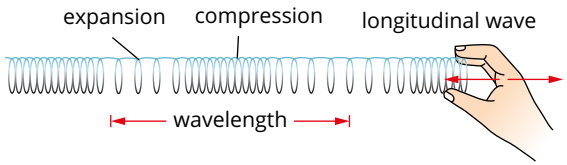
Thinking	Working
A compression (C) is a section where the air molecules are closer together due to greater air pressure. A rarefaction (R) is a region where the air molecules are further apart due to lower air pressure. The wavelength (λ) of a longitudinal wave is the distance between successive compressions. Wavefronts are drawn to represent the longitudinal wave instead of particles.	
The amplitude A is the displacement from the rest position of the tuning fork leg to the maximum displacement from the rest position.	$A = 12\,\text{cm}$
The 150 cm line measures the distance from the first rarefaction to the fourth rarefaction. This is three wavelengths in length.	$\lambda = \frac{150}{3}$ $= 50\,\text{cm}$
The frequency can be calculated using the wave equation. The speed of sound in air is $340\,\text{m s}^{-1}$ and the wavelength is 0.50 m.	$f = \frac{v}{\lambda}$ $= \frac{340}{0.50}$ $= 680\,\text{Hz}$
The period T is the inverse of the frequency f. Convert to SI units where necessary.	$T = \frac{1}{f}$ $= \frac{1}{680}$ $= 0.0015\,\text{s}$
Write the amplitude, wavelength, frequency and period of the wave. Convert to SI units when necessary.	The amplitude is 1.2×10^{-1} m. The wavelength is 5.0×10^{-1} m. The frequency is 680 Hz. The period is 1.5×10^{-3} s.

➤ Try yourself 9.2.2

LONGITUDINAL WAVES

A slinky spring is being moved backwards and forwards parallel to the net movement of energy, as shown in the diagram. The hand moves back and forth a total distance of 20.0 cm, backwards 10.0 cm and then forwards 10.0 cm, completing one oscillation in 0.80 seconds. The longitudinal wave travels a length of 2.0 m in 0.60 seconds.

Determine the amplitude, A, wavelength, λ, frequency, f, period, T, and velocity, v. The speed of sound in air is $340\,\text{m s}^{-1}$.



TORSIONAL WAVES

Another type of wave that will be briefly mentioned is a twisting or **torsional wave**. Engineers need to know the effects of wind on supertall skyscraper buildings, as this twisting or torsional effect may have a damaging impact on the structure of these very tall buildings. A wave that causes the medium to twist is called a torsional wave, as shown in Figure 9.2.3.

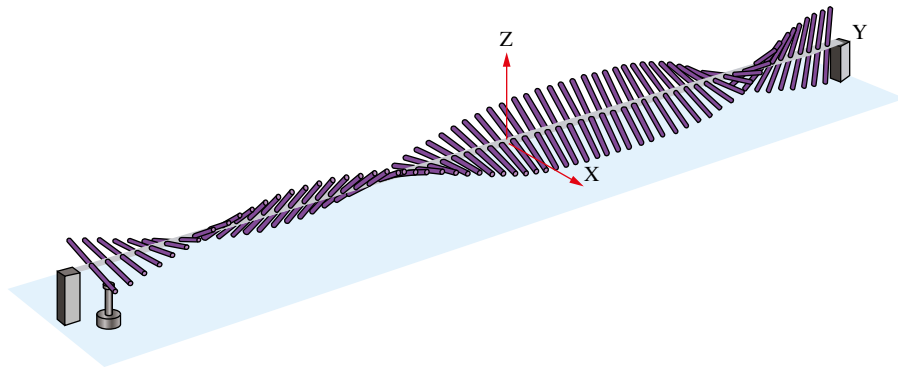


FIGURE 9.2.3 A torsional wave causes the medium to twist.

The first Tacoma Narrows Bridge (Figure 9.2.4) was a suspension bridge built in the USA state of Washington and opened to traffic on 1 July 1940. It collapsed in November the same year. The suspension bridge was destroyed by relatively light winds of 60 km h^{-1} causing the structure of the bridge to twist and bend. It was nicknamed 'Galloping Gertie' by construction workers who noticed the bridge moving vertically in windy conditions during its construction.

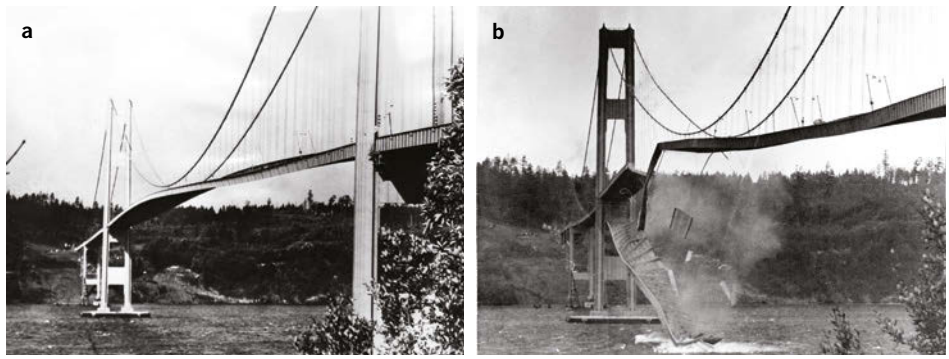


FIGURE 9.2.4 Tacoma Narrows Bridge (a) Showing the twisting effect of approximately 60 km h^{-1} winds and (b) the eventual destruction of the bridge span after experiencing the destructive effects of torsional waves.

REPRESENTING WAVES

Waves are often represented with **wavefronts** and **rays** instead of the sinusoidal waveform. These lines represent information such as wavelength and the direction of net energy movement of the travelling wave, without adding any complex information such as particle vibrations or sinusoidal graphs. Both wavefronts and rays are a simplified ways of drawing wave motion.

Wavefronts and rays

It is easier to sketch waves showing only the crests of a wave. As the wave passes through the medium, like ripples in a pond, you notice only the crests of the ripples. The crests on the ripples are points where the particles of the medium are in phase. You will also notice that after every crest there follows a trough, followed by another crest and so on. The distance between successive crests, or successive troughs, is called the wavelength. The wavefronts are drawn on these points (either crest to crest, or trough to trough) perpendicular to the direction of the net energy movement of the wave.

A ray is drawn in the direction of the net energy movement of the travelling wave. This is shown in Figure 9.2.5 for a plane wave (one-dimensional wave) and in Figure 9.2.6 for a three-dimensional wave.

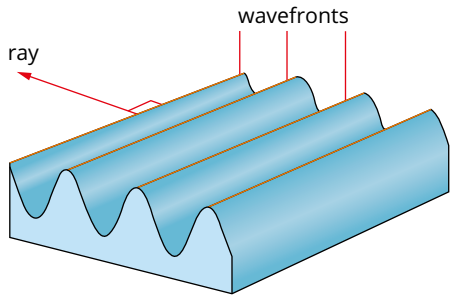


FIGURE 9.2.5 The wavefronts and the ray are shown on a plane wave with energy movement in the direction of the ray. The energy is moving in one dimension.

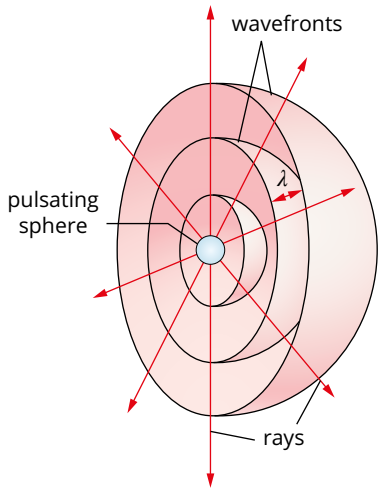


FIGURE 9.2.6 The wavefronts and rays representing three-dimensional wave energy transfer. Note the distance between the wavefronts and the symbol λ for wavelength.

EXAMPLES OF TRANSVERSE AND LONGITUDINAL WAVES

When at the beach in the surf, or when listening to a podcast, watching television, or streaming online music sites, you are dealing with waves. Examples of both transverse and longitudinal waves will be discussed further, with some examples exhibiting both transverse and longitudinal wave properties.

Sound waves

A sound wave is an important example of a longitudinal wave. As the cone of a loudspeaker vibrates, the layer of air next to it is alternately pushed away and drawn back, creating a series of compressions and rarefactions in the air (Figure 9.2.7). This vibration is transmitted through the air as a sound wave. As in transverse waves, the individual molecules vibrate over a very small distance, while the wave itself can carry energy over very long distances. If the vibration was from a single point, then the waves would tend to spread out spherically.

FIGURE 9.2.7 The motion of a flame in front of a loudspeaker is clear evidence of the continuous movement of air backwards and forwards as the loudspeaker creates a sound wave.

Seismic waves

Three main types of waves are produced by an earthquake. Primary P-waves, secondary S-waves and the **surface waves** that result from earthquakes will be covered in this module, but not the different types of earthquakes.

1 **P-waves** are compressional or longitudinal waves travelling at somewhere between 1.5–8.0 km s^{-1}. The ground shakes in the direction the P-waves are transferring energy, as shown in Figure 9.2.8. The P-waves are the first to be detected by seismic stations and travel through the Earth's core.

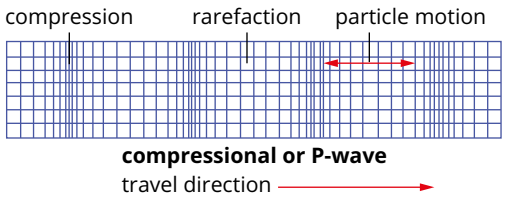


FIGURE 9.2.8 The diagram of a P-wave shows particle motion as the wave travels from left to right.

2 **S-waves** are transverse waves. They travel at almost half the speed of P-waves, and shake the ground in a direction perpendicular to the direction of energy movement, as shown in Figure 9.2.9. These waves do not travel through liquids such as molten material, or Earth's outer core. Seismic stations detect S-waves after P-waves.

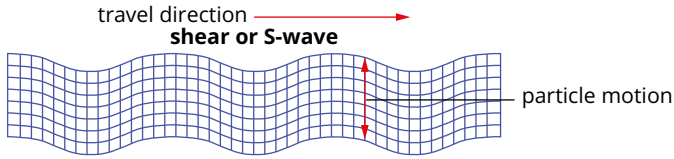


FIGURE 9.2.9 The diagram of an S-wave shows particle motion as the wave travels from left to right.

3 Surface waves travel just below or along the ground's surface and are slower than both the P-waves and S-waves. These waves have some rolling and side-to-side movement and are very damaging to built-up environs, as shown in Figure 9.2.10. Buildings experience structural damage due to these surface waves.

The three types of seismic waves are shown in Figure 9.2.10. The type of wave is shown on the left-hand side, and the effects on the Earth's crust are shown on the right-hand side. The waves are ordered top to bottom in terms of the relative speeds of each type of seismic wave. Unlike the shallow surface waves, both P-waves and S-waves penetrate deep inside the Earth and provide detail about the Earth's structure that is otherwise inaccessible.

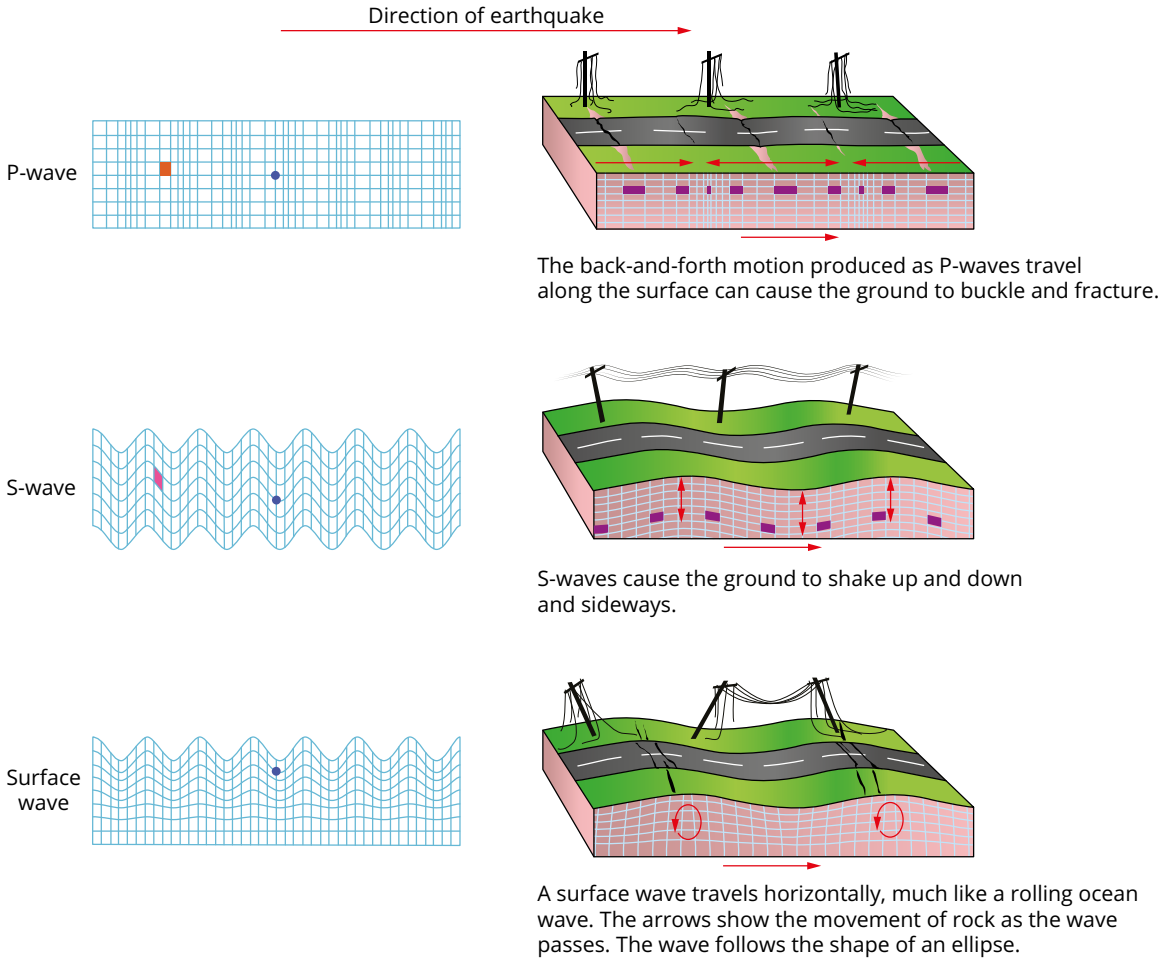


FIGURE 9.2.10 The three types of seismic waves, showing both wave type and effects on the Earth's crust

Worked example 9.2.3

SEISMIC WAVES

A longitudinal P-wave travelling at $3.0\,km\,s^{-1}$ is detected by a seismic station at 1.00.00 p.m. AEST. If the epicentre of the earthquake is 45 km away, determine the time at which the transverse S-wave is detected at the same seismic station. Assume the S-wave is travelling at half the speed of the P-wave.

Thinking	Working
The S-wave has half the speed of the P-wave. Rearrange the velocity equation $v = \frac{d}{t}$ to solve for time. $v = 1.5\,km\,s^{-1}$ $d = 45\,km$	S-wave: $t = \frac{d}{v}$ $= \frac{45}{1.5}$ $= 3.0 \times 10^{1}\,s$
S-waves arrive at a later time as they are transverse seismic waves. Convert to standard time.	The time the S-waves are detected is 1.00.30 p.m.

➤ Try yourself 9.2.3

SEISMIC WAVES

The University of Queensland Seismology Station reported that seismic waves have been recorded at their seismic station in Saint Lucia. The longitudinal P-waves were travelling at $3.0\,km\,s^{-1}$ and the transverse S-waves were travelling at $1.5\,km\,s^{-1}$. If the epicentre of the earthquake was 90.0 km away, and the earthquake happened at 7.35.00 a.m., calculate the times when the station detected the P-waves and the S-waves.

Stringed instruments

When a guitar string is plucked, the vibrating object produces a sound wave. Surrounding air molecules start to vibrate in unison with the guitar string, as shown in Figure 9.2.11. This air particle motion is in the same direction as the travelling sound wave. This is an example of a longitudinal wave. The wave on the guitar string is a transverse wave as the string vibrates, or oscillates, perpendicular to the direction of the travelling wave in the string, setting up a standing wave, which will be discussed later in Module 9.7.

The frequency of the vibrating air molecules is the same as the frequency of the vibrating guitar string. The speed of sound in air is $340\,m\,s^{-1}$ at room temperature.

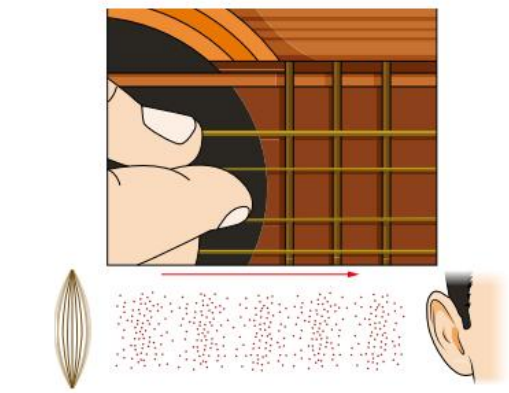


FIGURE 9.2.11 A vibrating guitar string and the resulting movement of air particles passing on the energy of the vibrations

Tsunami waves

An example of a transverse wave is a **tsunami** wave. The Earth's tectonic plates constantly move against each other, causing one plate to slip below another plate. This sudden giving way is felt as an earthquake as the tectonic plate boundary snaps back up. This displacement of the Earth's tectonic plate forces the water immediately above it to move up. This results in a massive displacement of water in the ocean. Deep-ocean tsunamis are barely noticed on the ocean surface but as the wave reaches land, the tsunami increases in height as the water becomes shallower, as shown in Figure 9.2.12. This wave phenomenon is also well known near sand banks, where navigation of boats needs to take this phenomenon into account, for example, when entering the ocean from a river inlet. Tsunami waves have been recorded as high as 30–40 metres in wave height near landfall.

All tsunami waves **dissipate** (or lose) energy as the wavefronts radiate outwards from the point of origin. As the waves travel outwards from the source, the energy is spread out over a greater volume of water. This has the effect of reducing the impact of the tsunami when it reaches land.

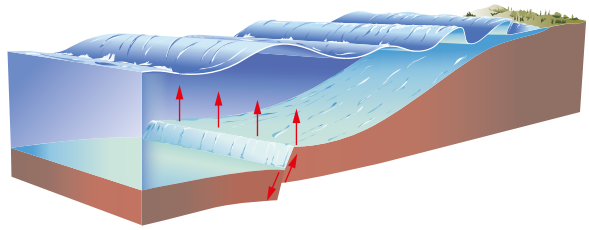


FIGURE 9.2.12 The tsunami wave shown above is a transverse wave in the deep-water section.

Some of the most devastating tsunamis ever recorded have happened in the 21st century.

- On 11 March 2011 a tsunami hit the nuclear power plant at Fukushima. It was triggered by a magnitude 8.9 earthquake off the east coast of northern Japan. The epicentre of the earthquake was approximately 130 km off the coast of Sendai.
- On 26 December 2004 (Boxing Day) a tsunami was triggered in the Indian Ocean when the Indo–Australian plate subducted (slipped) below the Eurasian plate. It was caused by an earthquake of magnitude greater than 9.0. The earthquake caused the seafloor to uplift, displacing the seawater above it. The impact zone of this tsunami is shown in Figure 9.2.13.

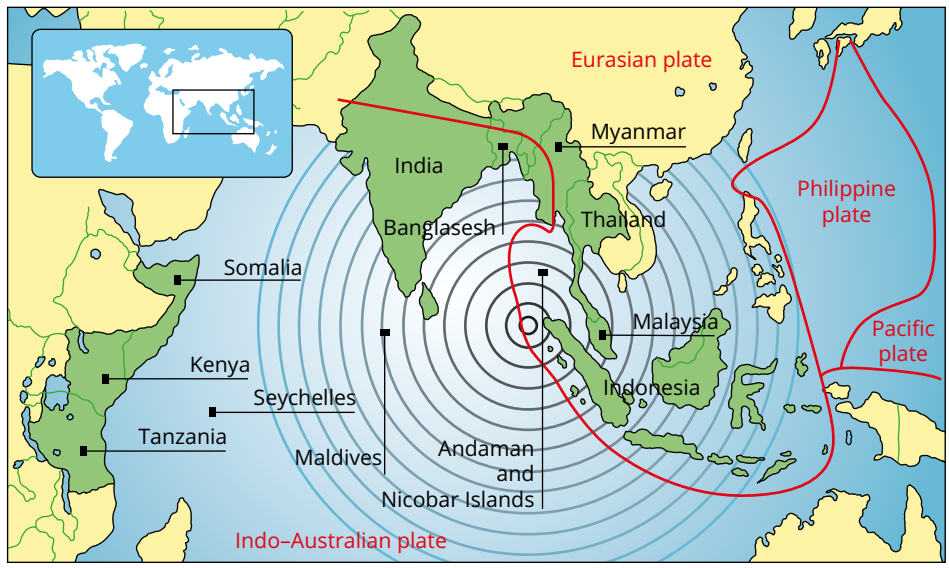


FIGURE 9.2.13 The map of the Indian Ocean tsunami shows the point of subduction between two massive plates at the centre of the concentric circles. Note the wavefronts (concentric circles) showing how the tsunami wave dissipated energy over distance.

PA 2.2.1

Monitoring earthquakes and tsunamis

Knowledge of different types of waves and their motion through the ocean and the continents, allows prediction of the possible extent of damage, or the timing of a tsunami.

Monitoring and locating an earthquake

Scientists use their knowledge of seismic waves to determine the epicentre of an earthquake. A seismogram is a sensitive machine that records the arrival time of both P-waves and the S-waves at a seismograph station. The seismogram also records the amplitude of the vibration (Figure 9.2.14). This allows scientists to determine the magnitude of the earthquake.

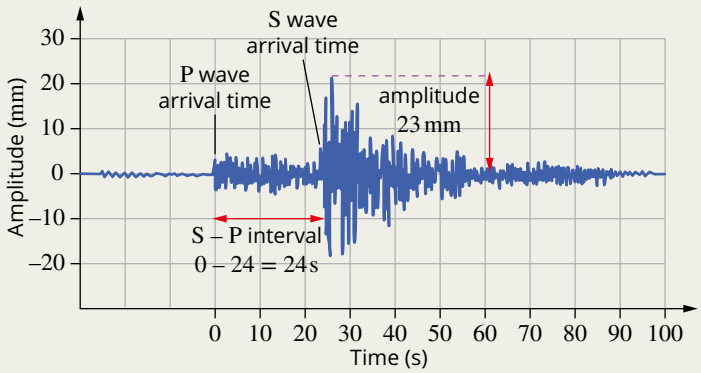


FIGURE 9.2.14 A seismograph showing the difference in time of arrival of P and S seismic waves. Note the amplitude of the strongest wave.

The difference between the arrival times of the S- and P-waves is converted to a distance from the seismograph station in kilometres. An S–P difference of 24 s corresponds with a distance of 215 km. A conversion chart also determines the magnitude of the earthquake from the amplitude of the strongest wave. An amplitude of 23 mm corresponds with a magnitude 5.0 earthquake. The Newcastle earthquake in 1989 recorded a magnitude of 5.6 (Figure 9.2.15). The magnitude determines the destructive energy released by the earthquake (it is called the strength of the earthquake).Two other seismograph stations are required to determine the exact epicentre of the earthquake.

Being able to locate the epicentre of an earthquake that occurs in deep oceans allows scientists to predict the possible extent of damage and possibly even warn residents of the possibility of a tsunami.

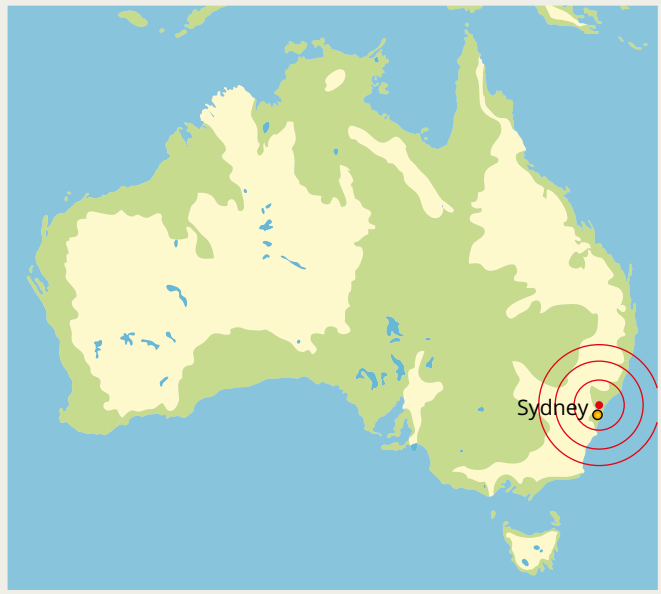


FIGURE 9.2.15 The epicentre of the 1989 Newcastle earthquake (red dot), a magnitude 5.6 earthquake that caused $4 billion of damage to buildings.

Deep-ocean tsunami detection buoys

Deep-ocean tsunami detection buoys (Figure 9.2.16) are one of two types of instrument used by the Bureau of Meteorology. These buoys observe and record changes in sea level out in the deep ocean. This enhances the capability for early detection and real-time reporting of tsunamis before they reach land.

A typical system comprises of a pressure sensor anchored on the sea floor and a surface buoy. The sensor on the sea floor measures the change in height of the water column above by measuring associated changes in the water pressure. This water column height is communicated to the surface buoy and then relayed via satellite to the tsunami–warning centre.

The tsunami buoy is triggered into ‘event’ mode when the pressure sensor first detects the faster-moving seismic wave moving through the sea floor. The system returns to standard mode after 4 hours if no further seismic events are detected.

Australia's first tsunami detection buoy was deployed on 15 April 2007 in the South-East Tasman Sea, some 1200 km from Tasmania. A few more tsunami buoys have since been deployed strategically to protect Australia from tsunami threat due to earthquake sources to the northwest, northeast and southeast of the Australian mainland.

Due to the complexity and uncertainty as to whether an undersea earthquake has the potential to generate a tsunami, the observation of sea levels is a critical factor in verifying whether a tsunami has actually been generated. The use of actual sea level observations, rather than reliance on seismic observations alone, helps to significantly reduce the risk of false tsunami warnings being issued. All Australian-owned buoys, as well as deep-ocean buoys operated by other countries in the Australian region, provide critical data to Australia's tsunami warning system.

The buoys are just one part of Australia's sea-level observing system, which also includes a number of new and long standing coastal sea level stations that now have the ability to report sea level variations in real-time to monitor for tsunamis. Combined, these technologies provide a constant stream of sea level data for the Joint Australian Tsunami Warning Centre (JATWC) operated by the Bureau of Meteorology and Geoscience Australia, enhancing tsunami warnings for the Australian public.

FIGURE 9.2.16 A deep-ocean tsunami detection buoy (DART) is deployed in the Tasman Sea.

Review

1 **a** Explain why it is important to be able to detect earthquake waves.
b Describe the sort of information that is obtained.

2 Explain why the Australian Government is deploying detection buoys in the deep ocean.

3 Summarise the benefits to society of the early detection of earthquakes and tsunamis.

9.2 Review

SUMMARY

- In a transverse wave, the oscillations are perpendicular to the direction in which the wave energy is travelling. Examples of transverse waves include waves in strings, seismic S-waves, and tsunami waves.
- In a longitudinal wave, the oscillations are parallel to the direction in which the wave is travelling. Examples of longitudinal waves include sound waves, and seismic P-waves.
- In a torsional wave, the waves cause a twisting motion in the medium, which can cause structural weaknesses.
- Both longitudinal and transverse waves can be represented by drawing wavefronts and rays. The distance between wavefronts is one wavelength, λ. The ray is drawn in the direction of net energy transfer.
- The wavelength of a longitudinal wave is the distance between successive compressions, or the distance between successive rarefactions.
- From graphs of longitudinal waves and transverse waves, you can determine the amplitude, period, frequency and wavelength.

KEY QUESTIONS

Retrieval

1 Identify whether statements a–d are true or false. Rewrite the false statements to make them true.

- **a** Longitudinal waves occur when the particles vibrate perpendicular to the direction of energy transfer of the wave.
- **b** Transverse waves occur when the particles vibrate parallel to the direction of energy transfer of the wave.
- **c** In sound waves, the area of expansion is called a rarefaction.
- **d** The vibrating string of a guitar is an example of a longitudinal wave.

2 Identify whether statements a–e are true or false. Rewrite the false statements to make them true.

- **a** The wavefronts on a travelling wave represent the crests of a transverse wave.
- **b** On a longitudinal slinky wave, the rarefactions are regions where the slinky hoops are compressed close together.
- **c** On a transverse wave, the maximum negative displacement of the wave is called a trough.
- **d** A ray is drawn in the direction of the oscillation of the wave particles.
- **e** Sound waves do not travel through a vacuum, only through a medium such as air.

Comprehension

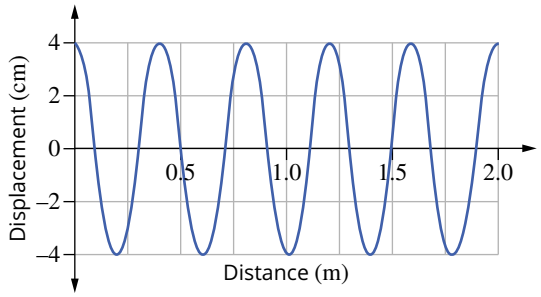
3 Classify the waves described below as either longitudinal or transverse waves:

- **a** tsunami waves
- **b** seismic P-waves
- **c** seismic S-waves
- **d** slinky moved backwards and forwards
- **e** air particles bunching up and stretching out due to changes in air pressure.

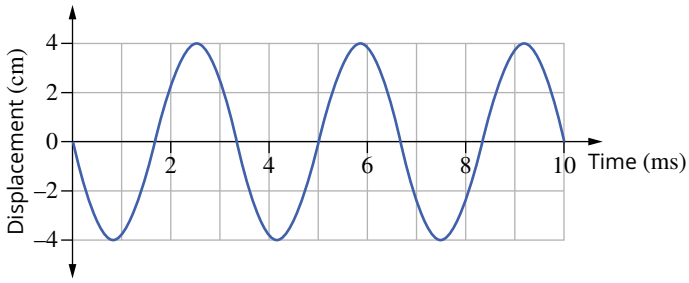
4 Draw a displacement–time graph and displacement–position graph for a transverse and a longitudinal wave. Explain the key attributes of each graph.

Analysis

5 A displacement–distance graph of a longitudinal sound wave is shown below. Calculate the amplitude, A, and wavelength, λ, of the wave.



6 A displacement–time graph for a transverse wave in a vibrating string is shown below. Calculate the amplitude, period and frequency of the wave.

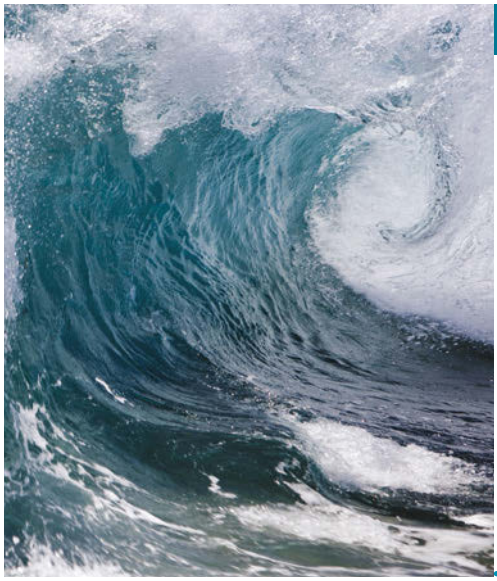


7 P-waves and S-waves are two types of seismic wave. Compare the key attributes of each wave in a table.

8 A tuning fork is oscillating with an amplitude of 10 mm and producing the musical note A with a frequency of 440 Hz. The sound waves travel through the air at 340 $m\,s^{-1}$.

- **a** Calculate the wavelength of the sound waves.
- **b** Draw a displacement–time graph for the sound wave including labels and values.
- **c** State whether the sound wave produced is a transverse or longitudinal wave. Explain the air particle oscillations with reference to the graph drawn in part **b**.

9.3 Reflection



BY THE END OF THIS MODULE, YOU SHOULD BE ABLE TO:

- recall the conservation of energy of a wave at a change in medium
- define 'reflection'
- describe the reflection of a wave or pulse at a boundary between two media
- use a ray diagram to represent the path of a wavefront
- recall the law of reflection
- interpret ray diagrams, particularly angle of incidence, angle of reflection, the normal line and the mirror surface
- use the wave model of light and the law of reflection to explain the position of an image in a mirror
- recall that an image observed in a plane mirror undergoes horizontal reversal
- recall there is no change in frequency when a wave is reflected off a surface such as a mirror.

Mechanical waves transfer energy through a medium, in contrast to electromagnetic waves, which do not need a medium at all (this will be discussed further in Chapter 11 on light). A medium is necessary for the mechanical wave to transfer energy, but there will be times when that medium physically ends, such as when a water wave meets the edge of a pool or air meets a wall. A change in the physical characteristics in the same medium, such as density and temperature, can act like a change in medium. When the medium ends, or changes, the wave doesn't just stop. Instead, the energy that the wave is carrying will undergo three processes:

- some energy will be reflected (Figure 9.3.1)
- some energy will be absorbed by the new medium
- some energy will be transmitted.

The energy the wave is carrying is conserved regardless of how much is reflected, absorbed and transmitted.

Rarely in the real world does one mechanical wave occur in isolation. From the ripples that form on a pond hit by raindrops to the complex interactions of multiple reflected sound waves, the world is full of mechanical waves. The sounds produced by acoustic musical instruments and the human voice come from the interaction between sound waves and their **reflections**. The interaction of mechanical waves results in superposition and creates, among many other things, the characteristic sounds of musical instruments and of the human voice. This will be covered in more detail in Module 9.6.

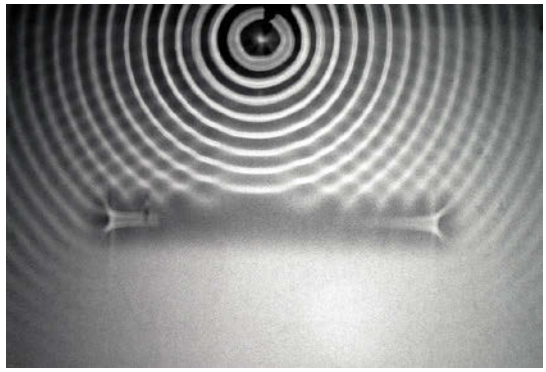


FIGURE 9.3.1 Waves in a ripple tank are reflected when they meet a solid surface. Here, a barrier positioned below the source of the circular waves reflects the waves.

When a transverse wave pulse reaches a hard surface, such as the fixed end of a rope, the wave is bounced back or reflected. When the end of the rope is fixed, the reflected pulse is inverted, as shown in Figure 9.3.2. A wave crest is reflected as a trough and a trough is reflected as a wave crest. The inversion of a reflected wave is a 180° **phase change**, or a shift in phase of $\frac{\lambda}{2}$. The phase of a wave is described in fractions of wave cycles. One complete wave cycle or full period of a wave is expressed as 360°, half a wave cycle or half a period is expressed as 180°.

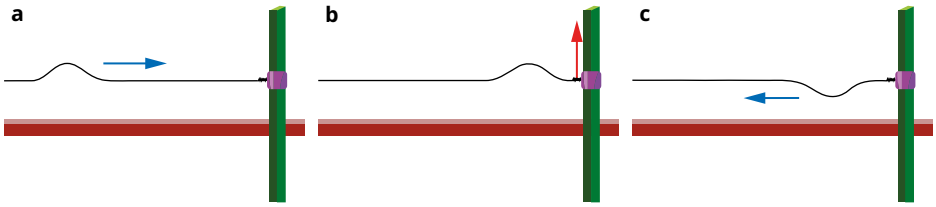


FIGURE 9.3.2 (a) A wave pulse moves along a string to the right and approaches a fixed end at the post. (b) When the wave reaches the post, the string exerts an upwards force on the fixed post. Due to Newton's third law, the fixed post exerts an equal and opposite force on the string, which inverts the wave pulse (c) and sends its reflection back to the left on the bottom side of the string. There is a phase reversal on reflection from the fixed end.

When a wave pulse hits the end of the rope that is free to move (known as a free boundary), the pulse returns with no phase change, as shown in Figure 9.3.3. The reflected pulse is the same as the incident pulse. A crest is reflected as a crest and a trough is reflected as a trough.

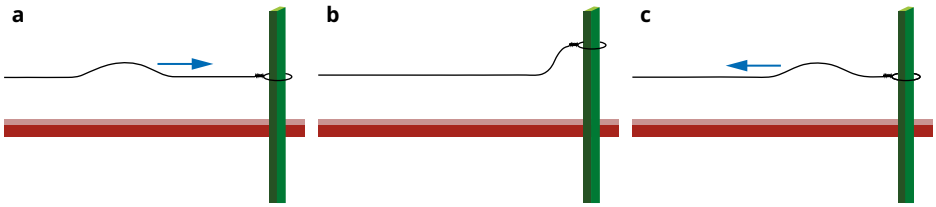


FIGURE 9.3.3 (a) A wave pulse moves along a string to the right and approaches a free end at the post. (b) When the wave reaches the post, the free end of the string is free to slide up the post. (c) No inversion happens and the wave pulse is reflected back to the left on the same side of the string; there is no phase reversal on reflection from a free end.

When the transverse wave pulse is reflected, the amplitude of the reflected wave isn't quite the same as the original. Some of the energy of the wave is **absorbed** by the post and transformed into heat energy, and some of the energy will continue to travel through the post. You can see this more clearly by connecting a heavier rope to a lighter rope. The change in density has the same effect as a change in medium (Figure 9.3.4).

When a transverse wave pulse is sent down the rope from the light rope to the heavier rope, part of the wave pulse will be reflected and part of it will be **transmitted** to the heavier rope. As the second rope is heavier, a smaller proportion of the wave is transmitted into it and a larger proportion of the wave is reflected back.

This is just the same as a wave pulse striking a wall. The more rigid and/or dense the wall, the more the wave energy will be reflected and the less it will be absorbed, but some energy will be absorbed by or transferred to the second medium. This explains why sound can travel through walls.

- When a transverse wave reaches a fixed end, the reflected pulse is inverted. A wave crest is reflected as a trough and a trough is reflected as a wave crest. The inversion of a reflected wave is a 180° phase change.
- When a transverse wave reaches a free boundary, the reflected pulse is not inverted and there is no phase change.
- When a transverse wave reaches a more rigid or heavier medium, some of the wave pulse is reflected and some is transmitted through the heavier medium. The reflected pulse will be inverted.

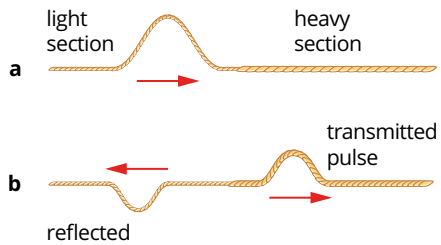


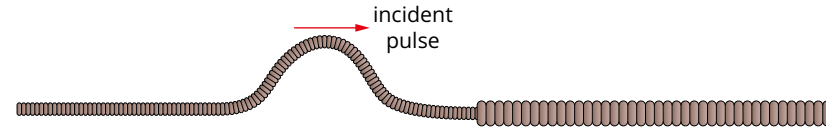
FIGURE 9.3.4 (a) A wave pulse travels along a light rope towards a heavier rope. (b) When the wave reaches a change in density, the wave pulse will be partly reflected and partly transmitted. This is analogous to a change in medium.

Worked example 9.3.1

REFLECTION

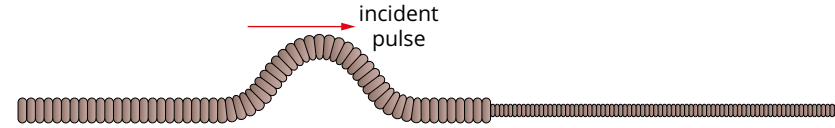
Predict what happens to the reflected pulse in each of the following situations using information about reflection.

a An incident transverse wave pulse travels to the right along a light string attached to a heavier string.



Thinking	Working
The incident pulse in the light string reflecting off the heavier string is similar to the pulse in a string being reflected from a fixed end. A pulse is also transmitted to the right into the heavier string.	The incident pulse will be reflected and the reflected pulse will be inverted.

b An incident transverse wave pulse travels to the right along a heavy string attached to a lighter string.



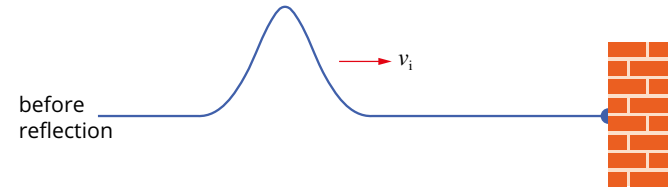
Thinking	Working
The incident pulse in the heavy string reflecting off the lighter string is similar to the pulse in a string reflected from a free end. A pulse is also transmitted to the right into the lighter string.	The incident pulse will be reflected and will not be inverted. There is no change in phase.

➤ Try yourself 9.3.1

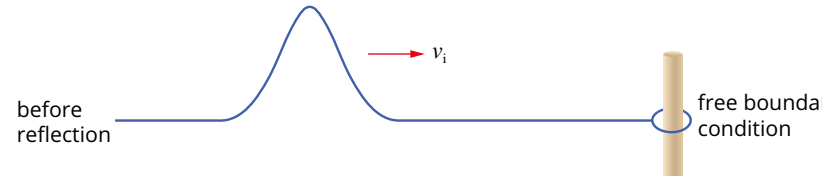
REFLECTION

Predict what happens to the reflected pulse in the string in each of the following situations, using the information about reflection.

a An incident pulse travels along a string fixed to a wall.



b An incident pulse travels along a string attached to a moveable hoop over a pole.



Reflected wavefronts

As introduced in Module 9.2, both two-and three-dimensional waves travel as wavefronts. When drawing wavefronts, it is common to show the crests of the waves, as shown in Figure 9.3.5. When close to the source, wavefronts can show considerable curvature and are spherical when generated in three dimensions. Where a wave has travelled a long distance from its source, the wavefront is nearly straight and is called a **plane wave** (Figure 9.3.5b). Plane waves can also be generated by a long, flat source, such as those often used in a ripple tank.

The direction of motion of any wavefront can be represented by a line drawn perpendicular to the wavefront and in the direction the wave is moving (Figure 9.3.5a). This is called a ray. Rays can be used to study or illustrate the properties of two- and three-dimensional waves without the need to draw individual wavefronts.

Ray diagrams can be used to illustrate the path of a wavefront reflecting from a surface. The incident and reflected waves are also shown. The **normal** in a ray diagram is an imaginary line at 90° to the reflecting surface; that is, perpendicular to the surface. For two- and three-dimensional waves, the angle between the normal and the incident waves is equal to the angle between the normal and the reflected waves.

The angles of the incident and reflected waves from the normal are labelled θ_i and θ_r respectively (Figure 9.3.6).

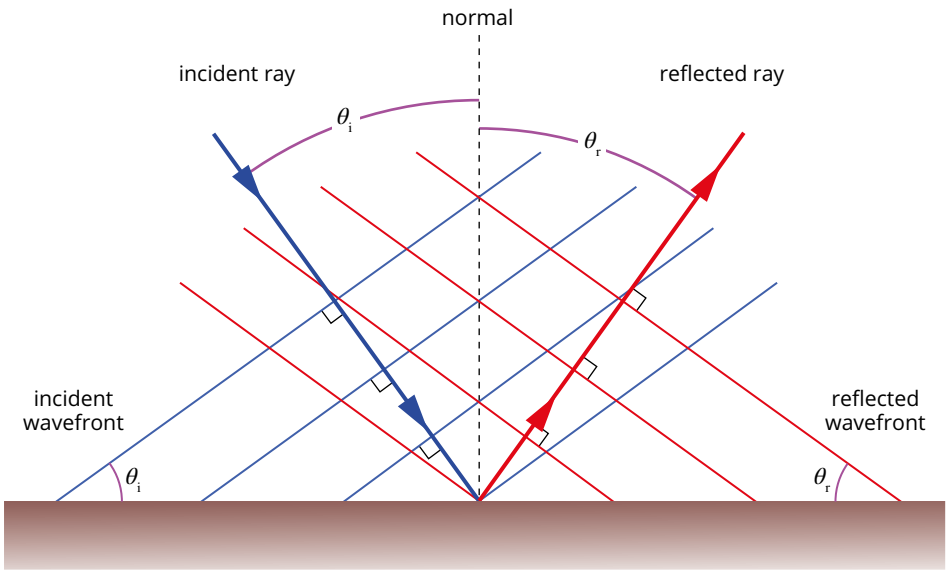


FIGURE 9.3.6 The law of reflection. The angle between the incident ray and the normal (θ_i) is the same as the angle between the normal and the reflected ray (θ_r).

This is referred to as the **law of reflection**. The law of reflection states that the **angle of reflection**, measured from the normal, equals the **angle of incidence** measured from the normal; that is $\theta_i = \theta_r$.

The law of reflection is true for any straight, curved or irregular surface. For all surfaces, the normal is drawn perpendicular to the surface at the point of contact of the incident wave.

When wavefronts meet an irregular, rough surface, the resulting reflection can be spread over a broad area. This is because each point on the surface may reflect the portion of the wavefront reaching it in a different direction, as seen in Figure 9.3.7. This is referred to as **diffuse reflection**.

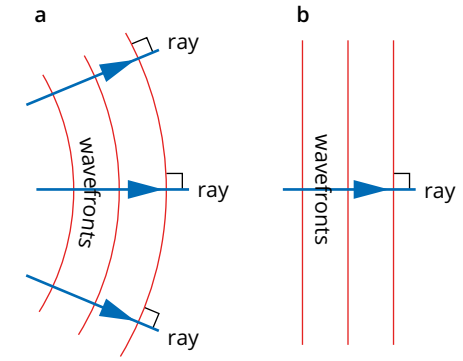


FIGURE 9.3.5 Rays can be used to illustrate the direction of motion of a wave. They are drawn perpendicular to the wavefront of a two- or three-dimensional wave and in the direction of travel of the wave; (a) illustrates rays for circular waves near a point source and (b) shows a ray for plane waves.

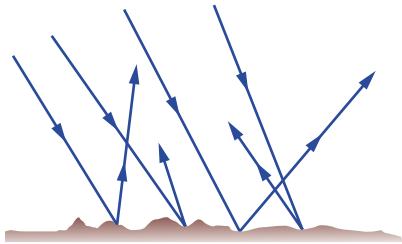


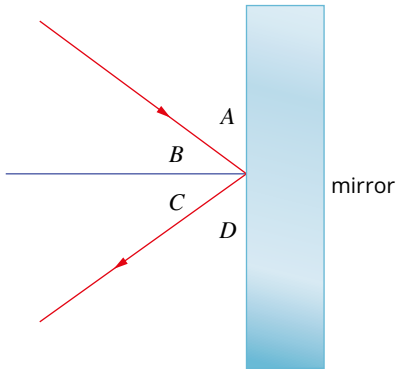
FIGURE 9.3.7 Reflection from an irregular surface. Each **incident ray** may be reflected in a different direction, depending upon how rough or irregular the reflecting surface is. The resulting wave will be diffuse (spread out).

Worked example 9.3.2

REFLECTED WAVEFRONTS

A light ray is incident on a flat surface mirror and reflects off the surface of the mirror as shown. Four labels *A*, *B*, *C*, and *D* have been drawn to represent the angles.

State the letters that represent the angle of the incident ray relative to the surface of the mirror, the angle of incidence, θ_i, and the angle of reflection, θ_r. Name the line that represents the imaginary normal line.



Thinking	Working
The angle between the incoming (incident) ray and the flat-surfaced mirror is the angle the ray strikes the mirror.	The angle the incident ray strikes the mirror at is the angle *A*.
The angle of incidence is the angle between the incident ray and the normal line, not the surface of the mirror. The angle of reflection is the angle between the reflected ray and the normal line. The normal line is a perpendicular line to the surface of the flat mirror. It is drawn at the point where the incident ray strikes the mirrors surface.	The angle of incidence, θ_i is represented by the letter *B*. The angle of reflection θ_r is represented by the letter *C*. The normal line is the flat horizontal line between *B* and *C*.

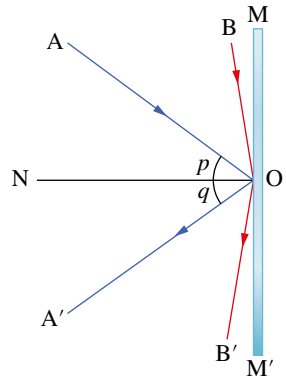
➤ Try yourself 9.3.2

REFLECTED WAVEFRONTS

Rays A and B are incident on a straight reflecting mirror surface, as shown below. The imaginary normal line has been drawn and labelled, N.

State the letters that represent the angle of incidence, θ_i, and the angle of reflection, θ_r, for ray A and ray A′. State the relationship between these angles. Name the line that represents the imaginary normal line.

For ray B, use the law of reflection to state the relationship between angles *BON* and *B′ON*.



Images in plane mirrors

The most obvious examples of reflection occur at the boundaries of plane mirrors. When you brush your teeth and look into a mirror, you observe the reflected **image** of yourself and your teeth, but the image is actually reversed. If you raise your right arm, you observe the left arm of the image being raised. If you hold up the toothpaste tube, the lettering will be reversed. This observation is referred to as horizontal reversal of an image.

When standing in front of a mirror, the reflected image appears to be the same distance behind the mirror as the object is in front of the mirror. The reflection is called an image because the light seems to converge on a point that is not real, because it is behind the mirror.

In Figure 9.3.8, two rays of light are travelling away from an **object**, *O*, and being reflected respectively at positions *A* and *C* at the mirror boundary. The reflected rays *AB* and *CD* travel towards the observer's eye. The rays appear to travel from position *I*, the image location. The distance the image appears from the surface boundary is the same as the distance from the object *O* to the surface boundary.

When you stand in front of a mirror, your image appears at the same depth, or distance behind the mirror, as you stand in front of the mirror. This is due to the law of reflection of the light rays off the surface of a plane boundary such as a flat mirror, shown in Figure 9.3.9.

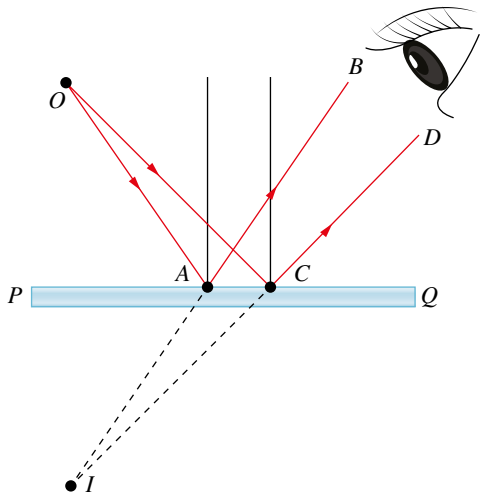


FIGURE 9.3.8 The rays *OA* and *OC* are incident on a flat mirror boundary and are reflected as respective rays *AB* and *CD* towards the observer. The dashed lines show the position of the observed image.

Try moving away from the mirror and notice the image moving away also.

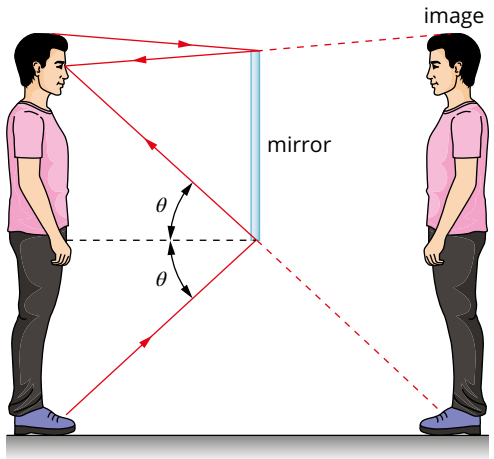


FIGURE 9.3.9 Two light rays reflecting off the surface of a plane mirror. The depth of the image from the mirror is identical to the depth of the person or object from the mirror.

Worked example 9.3.3

IMAGES IN PLANE MIRRORS

When you look in a mirror, where does the reflection appear? Select the most correct response and give a brief explanation.

A on the mirror
B in front of the mirror
C behind the mirror
D in the mirror

Thinking	Working
Incident light is reflecting off the surface of the mirror. The reflected light travels to the observer's eye. The reflected light ray appears to come from behind the mirror.	Correct answer is C.
The explanation needs to be clear and concise.	Light rays reflect off the surface of the mirror at the same angle as the incident rays strike the surface. These reflected rays appear to originate from the image at the same distance behind the mirror.

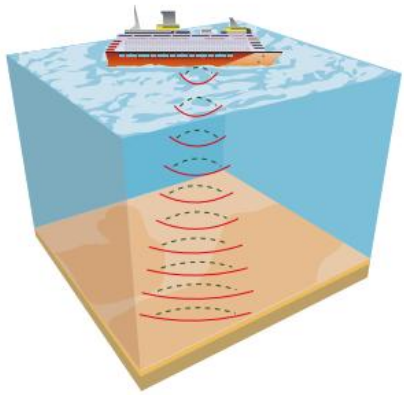


FIGURE 9.3.10 The ship sends a sound wave into the water below the ship. By measuring the time between the emitted sound (red waves) and its reflection (dashed lines), the ship's sonar can determine the depth of the water under the ship.

➤ Try yourself 9.3.3

IMAGES IN PLANE MIRRORS

A person stands in front of a mirror and then takes a step closer to the mirror. What would the reflection appear to do? Select the most correct response and give a brief explanation.

A move closer to the mirror
B not move at all
C move away from the mirror
D stay in the mirror

Sonar images

Echoes provide the most obvious evidence that sound waves are reflected. Like all waves, sound can be reflected when it strikes an obstacle, or there is a change in the medium.

The phenomenon of an echo can be used to measure extremely large distances. For example, an echo-sounding device is used to measure the depth of the sea (Figure 9.3.10). This equipment works by measuring the time taken for the echo of a sound wave to be reflected by the seabed back to a ship. Another use of echo-sounding devices is to produce images of shipwrecks on the seabed floor, as is shown with *RMS Titanic* (Figure 9.3.11).

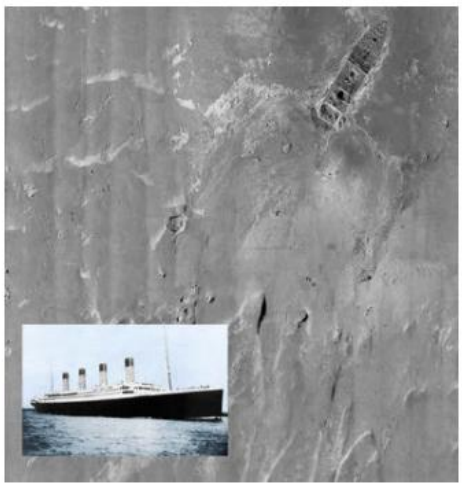


FIGURE 9.3.11 *RMS Titanic* on its maiden voyage (inset) and a sonar image showing the shipwreck of the *Titanic* on the ocean floor.

Worked example 9.3.4

SONAR IMAGES

The Mariana Trench is a very deep-sea trench located in the western Pacific Ocean near the Philippines. It is a scar in the Earth's crust and reaches a maximum known depth of 10 994 m below the surface of the ocean. This is deeper than the highest Himalayan peak.

Sound waves travel 4.3 times faster in water than air. The speed of sound in water is 1481 $m\,s^{-1}$ when the temperature of the water is 20°C. Calculate the time taken for the echo signal generated by a ship to travel to the bottom of the trench and return to the ship.

Thinking	Working
Assume the speed of sound in the water is 1481 $m\,s^{-1}$. The total distance travelled by the echo is twice the ocean depth. $d = 21\,988\,m$ Rearrange the equation for velocity to solve for time: $t = \frac{d}{v}$	Time t for echo signal to return to the ship: $t = \frac{d}{v}$ $= \frac{21988}{1481}$ $= 14.8\,s$

➤ Try yourself 9.3.4

SONAR IMAGES

Of the 9000 species of bats, more than half rely on echolocation. These bats use sonar and echolocation to avoid obstacles during flight, forage for food and to locate their roosts. The echolocation calls of bats range in frequency from 20 to 80 kilohertz (kHz). This frequency range is beyond the range of human hearing and commonly referred to as ultrasonic.

A leaf-nosed bat emits an ultrasound and receives the return echo from its prey some 0.25 s later. Calculate how far away the bat is from its prey if the speed of sound in air is 340 $m\,s^{-1}$.

9.3 Review

SUMMARY

- A wave reaching the boundary between two materials in which it can travel will always be partly reflected, partly transmitted and partly absorbed because of the law of conservation of energy.
- A wave has been reflected if it bounces back after reaching a boundary or surface.
- Waves reflect with a 180° phase change from fixed boundaries. That is, crests reflect as troughs and troughs reflect as crests.
- Waves reflect with no phase change from free boundaries. That is, crests reflect as crests and troughs as troughs.
- When a wave is reflected from a surface, the angleof reflection will equal the angle of incidence.
- The image of an object will appear behind the surface of the mirror. There is no change in frequency when a wave is reflected off a surface such as a mirror.
- An image observed in a vertical plane mirror appears to undergo horizontal reversal.

KEY QUESTIONS

Retrieval

1 A wave travels along a rope that is fixed to a wall. Recall what happens after the wave reaches this fixed end.

2 Recall what happens to the energy of a pulse when it reaches a boundary between two different media.

3 Identify whether the statements a–d about wave pulses are true or false. Rewrite the false statements to make them true.

- **a** An incident pulse is always inverted when reflected from both free and fixed boundary conditions.
- **b** The amplitude of the reflected pulse in a string is less than the amplitude of the incident pulse.
- **c** An incident pulse is travelling through a heavier string attached to a lighter string. A smaller portion of the pulse is transmitted through the lighter string and a larger portion of the pulse is reflected in the heavier string.
- **d** The more rigid or dense the wall or barrier, the more pulse energy will be reflected and less pulse energy will be transmitted. Regardless of the barrier rigidity some pulse energy will be transmitted into the barrier.

Comprehension

4 Identify which of the following properties of a wave can change when the wave is reflected: frequency or amplitude.

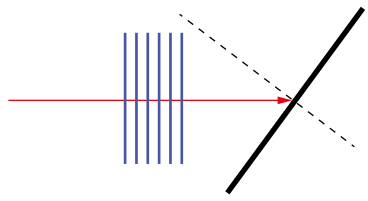
5 A light ray strikes a flat mirror surface at an angle of 38°. Determine the angle of reflection of the ray.

6 Explain how the inverted or upside down image of the mountain on a flat lake surface is formed when viewed from above the surface of the lake, as seen in the photo. Hint: you may need to use a ray diagram in the explanation.

Analysis

7 A sonar echo was received 3.8 seconds after the original signal was sent. Assume the signal was sent vertically down from the boat and bounces off the floor of a lake before returning to the echo receiver on the same boat. Analyse what can be determined from this information, given that the deepest known lake on Earth is approximately 1642 m deep.
Assume the speed of sound in water is 1481 $m\,s^{-1}$.

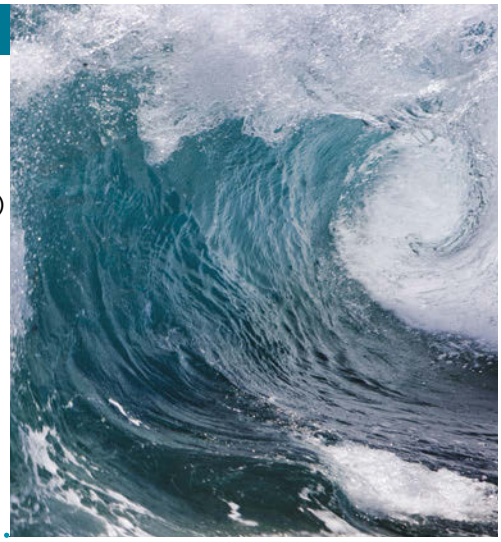
8 Plane waves are incident on a boundary between two media, as shown in the diagram. Construct the reflected ray and six reflected wavefronts for the incident ray shown. Label the angle of incidence and the angle of reflection.



9.4 Refraction

BY THE END OF THIS MODULE, YOU SHOULD BE ABLE TO:

- define 'refraction'
- describe the refraction of a wave at a boundary between two media
- recall the wave model of light is able to explain the property of refraction
- state the theoretical basis for explaining wave propagation (Huygens' principle)
- interpret ray diagrams for waves speeding up or slowing down when light waves travel from one medium to another
- recall how frequency, velocity and wavelength of light waves are affected by various types of media
- use the principle of refraction to explain the apparent position of objects that are under water, and the shape of the Sun at sunrise and sunset
- provide examples of when refraction occurs for types of waves other than light waves.



In Module 9.3, you learnt that waves are reflected when they meet a solid surface, and explored how an image is reflected in a mirror using the wave model of light. In this module, you will learn about another property of waves: refraction.

Refraction of light can be seen when a straw sits in a glass of water and appears to bend at the boundary of the air and water (Figure 9.4.1). Other examples of refraction include the oval shape of a setting or rising sun, and when spear fishermen are hunting for fish below the water's edge. Refraction describes the change in direction of waves as they travel from one medium to another; for example, as light travels from air into water. Refraction is most commonly observed for light; but it also occurs for other types waves, such as water waves, seismic waves and sound. In this module, you will study the refraction of light, and see that refraction also occurs in seismic waves and sound waves.

FIGURE 9.4.1 The straw in the glass appears to have a bend. This apparent bend is due to refraction of light.

HUYGENS' PRINCIPLE

In Module 9.3, you learnt how to draw wavefronts and rays to illustrate the direction of motion of a wave. The theoretical basis for wave **propagation** in two dimensions was first explained by the Dutch scientist Christiaan Huygens in 1678. **Huygens' principle** states that each point on a wavefront can be considered as a source of secondary wavelets (small waves).

Consider the plane wave shown in Figure 9.4.2. Each point on the initial wavefront can be treated as if it is a point source producing circular waves, some of which are shown in green. After one period, these circular waves will have advanced by a distance equal to one wavelength. Huygens proved mathematically that when the amplitudes of each of the individual circular waves are added, the result is another plane wave as shown by the new wavefront.

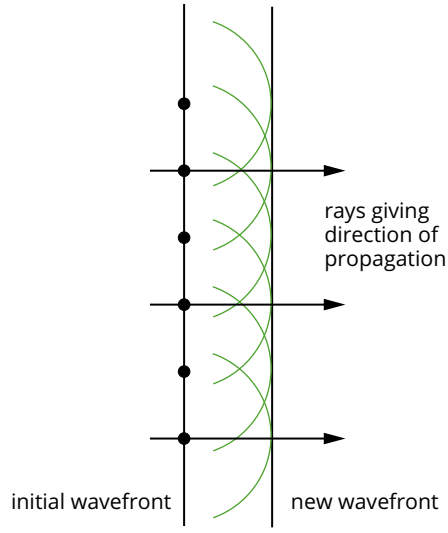


FIGURE 9.4.2 Each point on the wavefront of a plane wave can be considered as a source of secondary wavelets. These wavelets combine to produce a new plane wavefront.

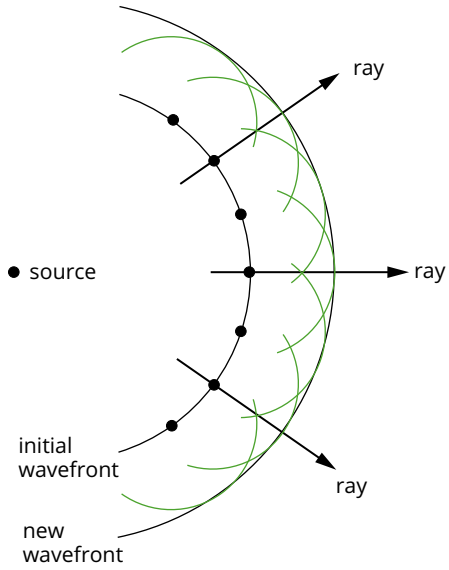


FIGURE 9.4.3 Each point on the wavefront of a circular wave can be considered as a source of secondary wavelets. These wavelets combine to produce a new circular wavefront.

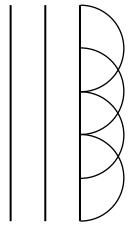
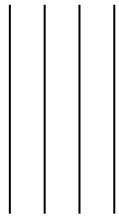
This process is repeated at the new wavefront, causing the wave to propagate in the direction shown. Circular waves are propagated in a similar way, as shown in Figure 9.4.3.

Huygens' principle is useful for understanding wave behaviour, including refraction.

Worked example 9.4.1

APPLYING HUYGENS' PRINCIPLE

On the plane wave shown moving from left to right below, sketch some of the secondary wavelets on the wavefront and draw the appearance of the new wavefront formed after one period.

Thinking	Working
Sketch a number of secondary wavelets on the advancing wavefront. Each secondary wavelet has the same radius as it propagates outward with equal speed. During one period the amplitudes of the secondary wavelets add up to produce a new wavefront that has progressed in the direction of the energy transfer of the wave.	
Sketch the new wavefront that is a combination of the secondary wavelets.	

➤ Try yourself 9.4.1

APPLYING HUYGENS' PRINCIPLE

On the circular waves shown below, sketch some of the secondary wavelets on the outer wavefront, and draw the appearance of the new wavefront formed after one period.

REFRACTION OF LIGHT

Refraction is a change in the direction of light caused by changes in its speed. Changes in the speed of light occur when light passes from one medium (substance) into another. For example, the speed of light in air, or a vacuum, is approximately $300\,000\,\text{km}\,\text{s}^{-1}$ but in normal glass the speed of light is approximately $200\,000\,\text{km}\,\text{s}^{-1}$.

In Figure 9.4.4, the light changes direction as it leaves the glass prism and re-enters the air.

FIGURE 9.4.4 Light refracts as it moves from one medium (the semicircular glass prism) into another (air) causing a change in direction.

In Figure 9.4.5, light waves move from an incident medium, where they have high speed, v_1, into a transmitting medium, where they have a lower speed, v_2. At the same time that the wave travels a distance $v_1\Delta t$ from B to D in the incident medium, it travels a shorter distance $v_2\Delta t$ from A to C in the transmitting medium. In order to do this, the wavefronts must change direction or 'refract' as shown.

Light waves behave in a similar way when they move from a medium such as air into water. The direction of the refraction depends on whether the waves speed up or slow down when they move into the new medium. The angle of incidence, i, is the angle between the direction of propagation and the normal and the angle of refraction, r, is the angle between the direction of reflection and the normal.

In Figure 9.4.6, light waves slow down as they move from air into glass, so the direction of propagation of the wave is refracted towards the normal. The angle of incidence, i, is greater than the angle of refraction, r.

In Figure 9.4.7, light waves speed up as they move from glass into air, so the direction of propagation of the wave is refracted away from the normal. The angle of incidence, i, is less than the angle of refraction, r.

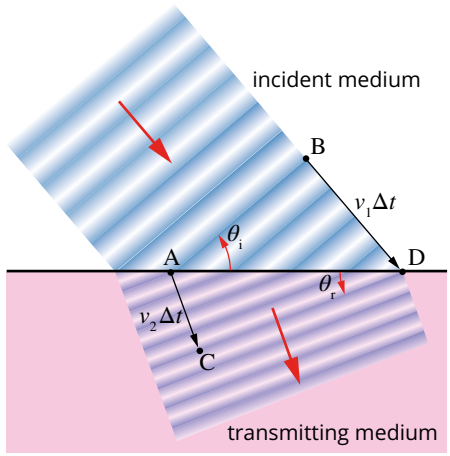


FIGURE 9.4.5 Wave refraction occurs because the distance A to C travelled by the wave in the transmitting medium is shorter than the distance B to D that it travels at the same time in the incident medium.

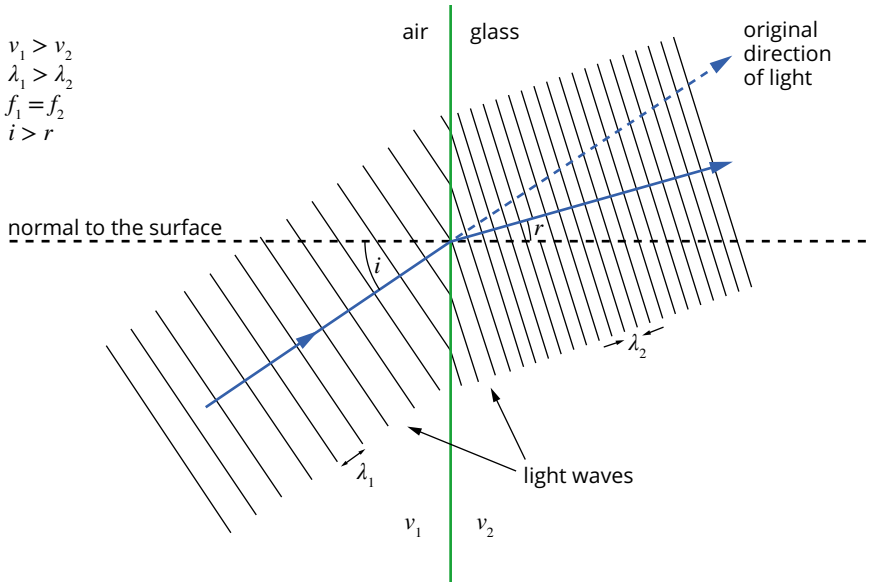


FIGURE 9.4.6 Light waves refract towards the normal when they slow down.

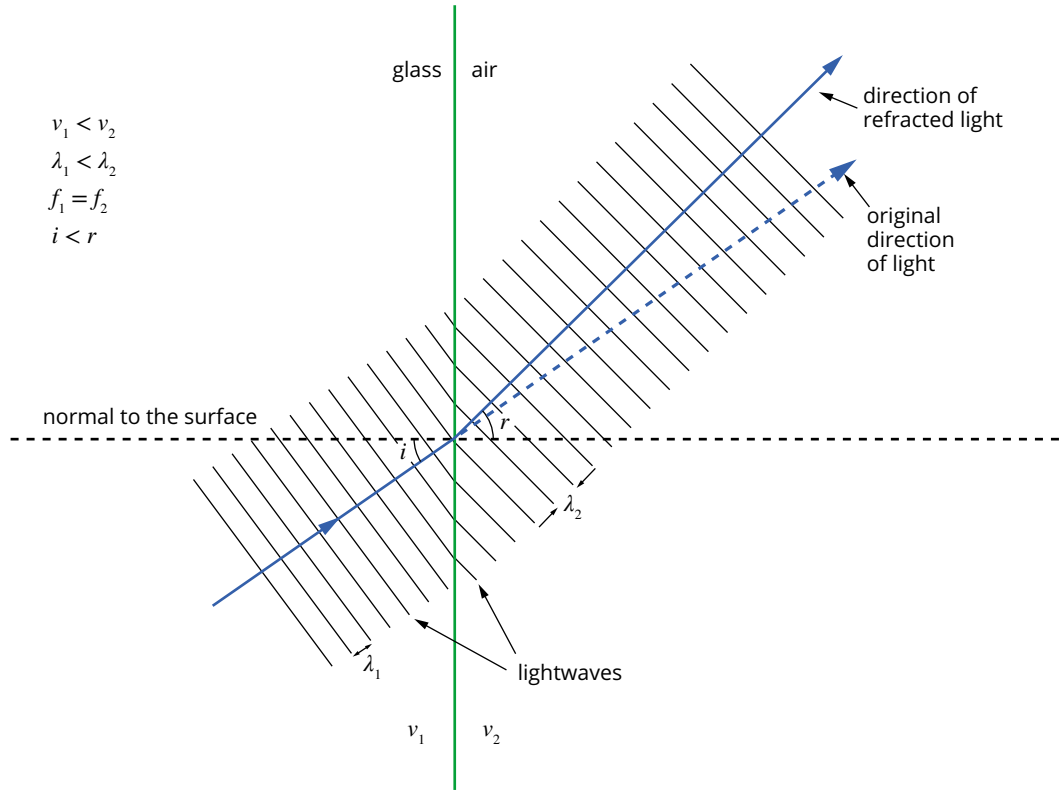


FIGURE 9.4.7 Light waves refract away from the normal when they speed up.

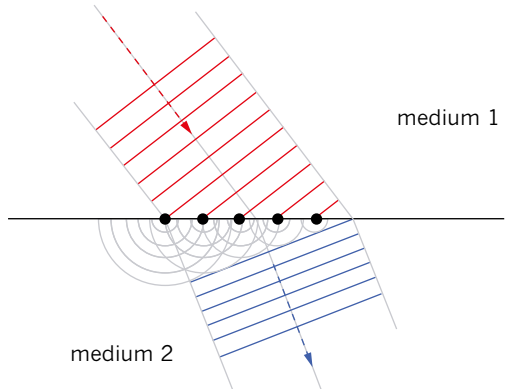
When light crosses the boundary of two media, the speed and wavelength of the wave changes in the same ratio. For example, when light travels from air into glass, the light wave slows down and the crests and troughs bunch up at a boundary so the same number of wavefronts pass per second.

This can be illustrated using the wave equation: $f = \frac{v}{\lambda}$. If the speed and the wavelength change in the same ratio, then these factors will cancel and the frequency will not change.

Worked example 9.4.2

REFRACTION OF LIGHT

Wavefronts travel through medium 1, as shown in the diagram below. The wavefronts refract (or bend) at the boundary between the two media and continue to travel through medium 2.



a State in which medium the waves are travelling faster.	
Thinking	**Working**
The wavefronts are further apart in medium 1 than in medium 2. If the frequency does not change, then the speed of the wave is dependent on the wavelength only (due to the wave equation). The distance between the wavefronts corresponds to the wavelength of a wave.	The waves are travelling faster in medium 1.
b State your observations in terms of comparing the angle of incidence and the angle of refraction.	
Thinking	**Working**
The angle of incidence, θ_i, is the angle measured between the normal line and the incident ray. The angle of refraction, θ_r, is the angle between the refracted ray and the normal line. The normal line, which is not evident in this diagram, is an imaginary line drawn perpendicular to the boundary at the point where the ray comes into contact with the boundary.	The angle of incidence is greater than the angle of refraction. The refracted ray bends towards the normal line.
c Explain your answer to the first part of the question using Huygens' principle.	
Thinking	**Working**
Applying Huygens' principle to explain your answer.	As each part of the incident wavefront in the top medium moves into the bottom medium, the distance travelled in the same time interval is less. This can be shown by the five dots, each representing a particle on the wavefront. Each secondary wavelet travels a shorter distance in medium 2 in one period. The wavefronts are closer together, indicating the speed of the wave is less (as the frequency remains unchanged).

➤ Try yourself 9.4.2

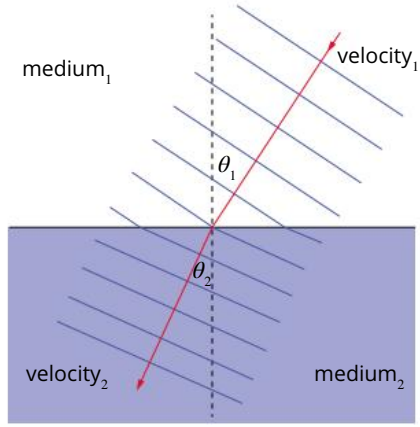
REFRACTION OF LIGHT

The labelled diagram below shows wavefronts travelling through two different media. Note the solid horizontal boundary line between the two media.

a Name the angle of incidence and the angle of refraction.

b Explain why the ray refracts.

c State in which medium the wave velocity is less, and explain your answer using Huygens' principle.



Apparent position of objects under water

Indigenous fishermen using spears know that when they see a fish in the water, the **real position** of the fish is not where they see the fish. They have learnt to aim a little lower than where they see the fish, or they may have a spear that has a number of spears evenly spread along the shaft, which increases the probability of striking a fish at its **real depth**.

The **apparent depth**, D_a, and the real depth, D_r, of the fish is shown in Figure 9.4.8. This difference between real depth and apparent depth is due to the refraction of the light rays travelling up from the fish through the water to the water–air boundary, and into the air above to the observer. The change in medium results in a change in velocity of the light waves; the light waves speed up in air, making the light ray bend, or refract, at the water–air boundary. In this case, the light ray speeds up and bends away from the imaginary normal line. Therefore the light rays are refracted at the water–air boundary before they enter the observer's eyes. So the fish appears at the apparent depth D_a and not the real depth D_r.

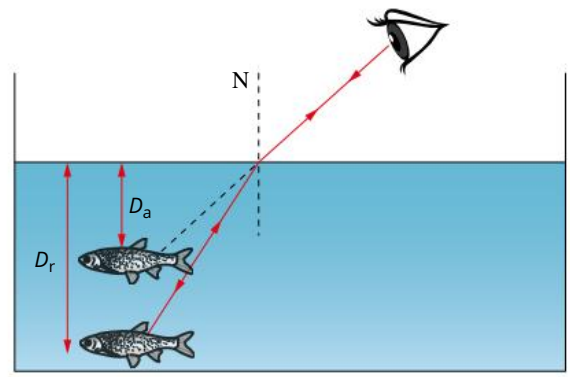


FIGURE 9.4.8 The apparent depth D_a of a fish compared to the real depth D_r as seen from above the air-water boundary.

Sun shape at sunrise and sunset

When the Sun is near the horizon during sunset, it appears to be more oval-shaped than circular, as shown in Figure 9.4.9. Notice how the shape of the Sun appears to distort as it approaches the horizon.

FIGURE 9.4.9 The shape of the Sun appears flatter as it approaches the horizon. It looks less circular and more oval-shaped.

During sunrise and sunset, light rays from the Sun travel a further distance through the atmosphere than at midday, when the Sun is directly overhead. The atmosphere consists of layers due to the air thinning with increasing altitude. This layered atmosphere structure continuously refracts the light rays until they reach the observer's eye. Refraction of light by these layers makes the Sun appear flattened or distorted.

At sunset and sunrise, the lower part of the Sun is closer to the horizon and is refracted more than the top part of the Sun (Figure 9.4.10). The observed effect is that the bottom of the Sun is lifted up more than the top. The Sun appears more oval in shape. The circular Sun is the object and the flatter, oval Sun is the image seen by the observer. The length of a day appears to be about 4 minutes longer than it actually is due to refraction of sunlight.

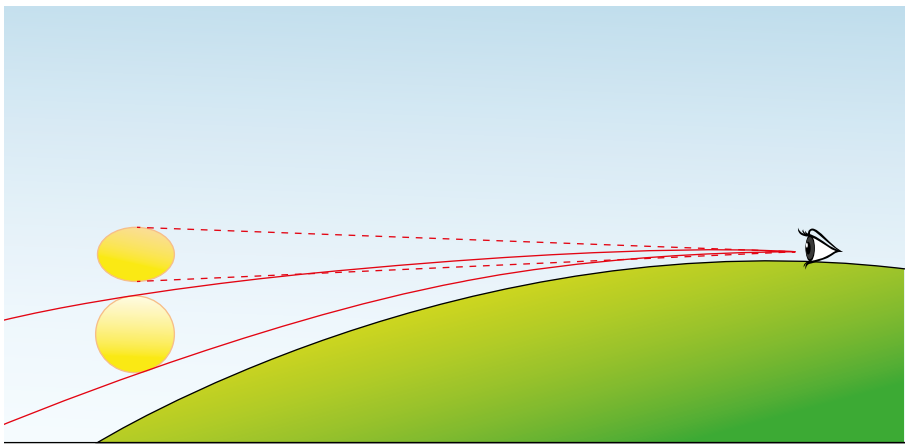


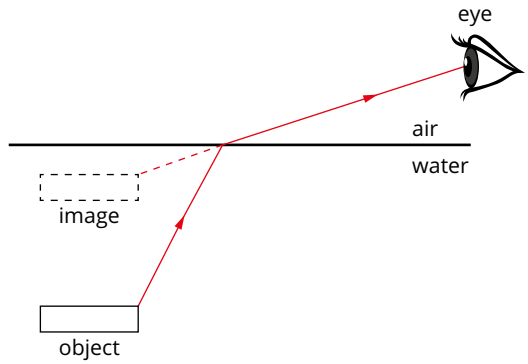
FIGURE 9.4.10 The actual position of the Sun (circular Sun) and the image seen (the flatter Sun)

Worked example 9.4.3

REFRACTION OF LIGHT AND APPARENT POSITION

When standing on the edge of a swimming pool and looking downwards into the water, is the apparent depth of the swimming pool deeper or shallower than its true depth?

Write a correct statement comparing the apparent depth and true depth of a swimming pool and include an explanation or justification for your thinking.

Thinking	Working
Incident light rays travelling upwards from the bottom of the pool refract at the water–air boundary. Light travels faster in air than water. The light rays refract away from the normal entering the observer's eye at a different (shallower) angle compared to the incident light rays. The observer sees the refracted rays of light.	Light rays from an object speed up in air, so the rays refract away from the imaginary normal line (vertical line) at the boundary. The image is seen to be shallower than the object. In this case the object is the bottom of the swimming pool.  Therefore the apparent depth as seen by the observer is shallower than the true depth of the swimming pool.

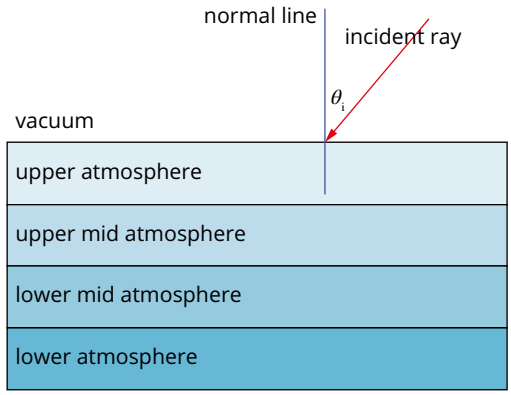
➤ Try yourself 9.4.3

REFRACTION OF LIGHT AND APPARENT POSITION

Sunlight is travelling through space (assume a vacuum) when it approaches Earth's upper atmosphere, which is slightly more dense than space. A single light ray strikes the boundary (interface) between the vacuum of space and the upper atmosphere at an arbitrary angle θ_i. The light ray refracts at this first boundary, and continues to pass through the four different layers shown in the diagram below. Assume the atmosphere becomes denser as altitude decreases, therefore slowing the light ray at each boundary.

Draw the path of the ray of light as it continues to travel through each atmospheric layer until it reaches the lower atmosphere.

Comment on the effect of the different layers of Earth's atmosphere on the path of the light ray.



OTHER EXAMPLES OF REFRACTION

Any wave that undergoes a change in wave velocity between two different media will refract. Two specific examples will be mentioned briefly, namely the refraction of seismic S-waves and P-waves in Earth's crust and mantle; and the refraction of sound waves in the differing temperature layers of Earth's atmosphere.

Seismic S-waves and P-waves

The velocities of both S-waves and P-waves depend on properties such as temperature and pressure of the media through which they travel. Seismic waves travel more quickly through denser materials and therefore generally travel more quickly with depth. When seismic waves travel between geological layers with differing seismic velocities, then refraction and reflection occur. These wave interactions provide evidence for the internal structure of Earth.

Figure 9.4.11 shows what happens when S-waves and P-waves travel through the Earth. S-waves travel through solid only (transverse waves) and the faster-moving P-waves travel through liquids and solids. Notice how both waves refract when travelling through Earth's mantle.

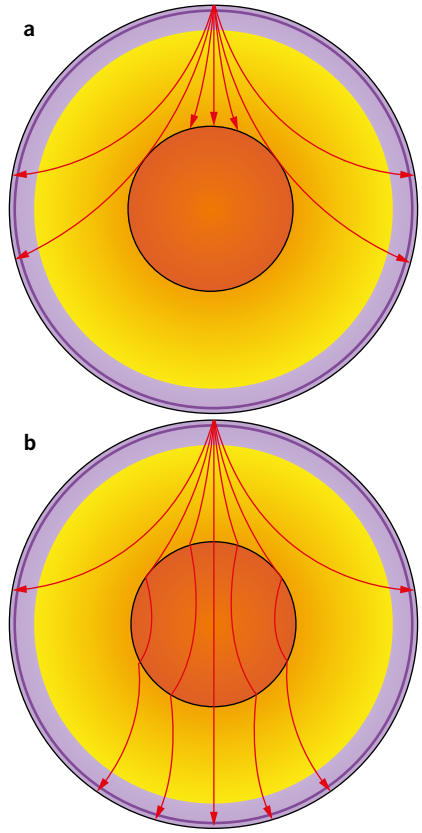


FIGURE 9.4.11 The path travelled by (a) seismic S-waves and (b) seismic P-waves passing through the Earth

Sound waves

Have you ever noticed that some sounds can be heard over long distances at particular times of the day? Fishermen notice this phenomenon very early in the morning as the Sun starts to rise and warm the upper layers of the air above a cool lake. Sounds from the other side of the lake can be heard, which cannot be heard later in the morning. This can be explained by Huygens' principle and the effect of differing air temperatures on the speed of sound.

The upper layers of air are warmer in the early morning due to the sunlight warming the air particles. The lower layers of air are cooler due to the cool surface of the lake. The layers of warmer air above cooler air are called a **thermal inversion**, as shown in Figure 9.4.12. Sound waves travel faster in warmer air than in cooler air. Following Huygens' principle, the upper part of the wavefront acts as a point source for secondary wavelets and travels a greater distance than the lower part of the wavefront. The effect is that sound waves refract downwards back to Earth as the secondary wavelets pass through the layers of air at different temperatures.

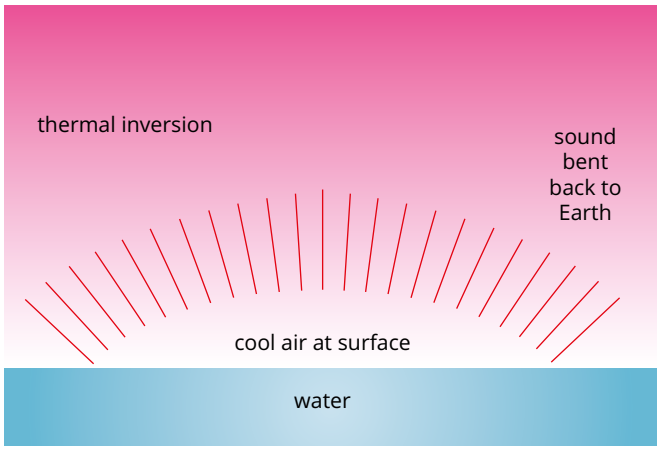


FIGURE 9.4.12 A thermal inversion refracts sound waves back down to Earth.

9.4 Review

SUMMARY

- Huygens' principle is the theoretical basis for explaining wave propagation in two dimensions.
- Refraction is the change in direction of a wave due to a change in velocity of the wave.
- When a wave travels from one medium to another medium, the direction of propagation of the wave can either refract towards the normal line (slow down) or refract away from the normal line (speed up).
- The angle of incidence is the angle between the incident ray and the imaginary normal line.
- The angle of refraction is the angle between the refracted ray and the imaginary normal line.
- The velocity of light and the wavelength of light can be affected by the type of medium; however, the frequency does not change.
- The wave model of light can explain phenomena such as the apparent position of objects that are under the water, and the shape of the Sun at sunrises and sunsets.
- Seismic waves refract in the mantle of the Earth with increasing depth, and increasing velocities of both P-waves and S-waves.
- Sound waves refract back towards Earth, when a thermal inversion occurs in the atmosphere.

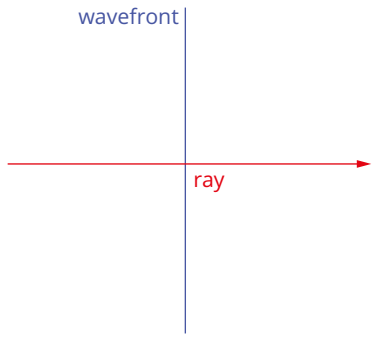
KEY QUESTIONS

Retrieval

1 Describe what happens when waves are refracted.

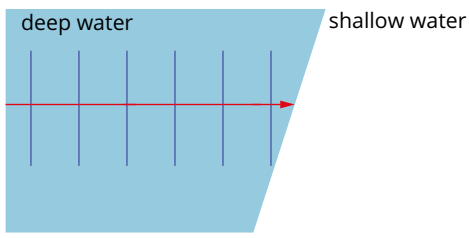
Comprehension

2 Use Huygens' principle to draw the wavefront of the plane wave shown after one period.



3 Draw the wavefront of a circular wave after one period using Huygens' principle. Start with a circular wavefront propagating outwards from a common centre for both wavefronts.

4 Water waves are travelling in deep water as shown, with the wavefronts and ray already drawn in the deep-water section. The boundary between deep water and shallow water is also shown. Sketch the direction of the wavefronts and the direction of the ray in the shallow water.



5 Wavefronts of light initially travelling in air are incident and parallel to an air–glass boundary (the angle of incidence of the light ray is 0°). Identify which one or more of the following statements is true regarding the wavefront and ray travelling through the glass.

A The wavefronts will not refract or bend as the wave slows down in the glass medium.

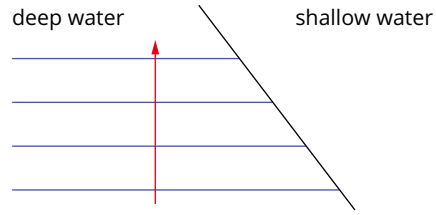
B The wavefronts will not refract or bend as the wave speeds up in the glass medium.

C The wavefronts will refract or bend as the wave slows down in the glass medium.

D The wavefronts will not refract or bend as the wave speeds up in the glass medium.

Analysis

6 Water waves are travelling from deep water up the page and into shallow water, as shown in the diagram. The wavefronts in the deep water, and the boundary between the deep and shallow water are sketched already. Sketch the wavefronts refracting in the shallow water, include a ray for direction. Label the angle of incidence θ_i and the angle of refraction θ_r.



7 Assess whether these statements are true or false regarding different types of waves and the angles of incidence and refraction. Rewrite the false statements to make them true.

a Water waves travel faster in deep water than in shallow water. The wavelength of a wave in deep water is greater than the wavelength of a water wave in shallow water.

b When light rays refract away from the normal line at a boundary between two different media, the light wave is travelling faster in this new medium.

c Sound waves will always refract down towards the Earth's surface, as the higher part of the wavefront travels faster than the lower part of the wavefront.

d The setting and rising Sun appears flatter than the afternoon Sun because light from the higher part of the Sun refracts more than that from the lower part of the Sun. The observed effect is that the top of the Sun is lowered more than the bottom of the Sun.

e The velocities of both seismic waves depend on the properties, such as temperature and pressure, of the media through which the seismic waves pass. Seismic waves travel more quickly through denser materials and therefore generally travel more quickly with depth.

9.5 Diffraction

BY THE END OF THIS MODULE, YOU SHOULD BE ABLE TO:

- define 'diffraction'
- recall the relationship between the wavelength and the aperture width for significant diffraction to occur
- apply Huygens' principle to sketch the wavefronts after passing through an opening or aperture
- recall light waves have a wavelength range from 400 nm to about 700 nm
- recall audible sound waves have a frequency range from 2 to 20 000 Hz for normal hearing
- state the theoretical limit on the resolution of optical telescopes and microscopes.

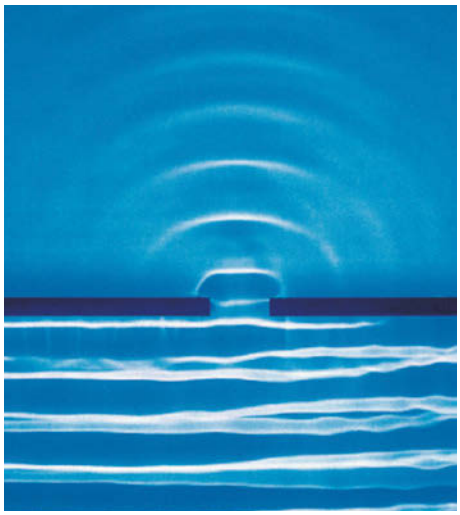


FIGURE 9.5.1 Water waves bend as they pass thorough an aperture. Sound waves will diffract as well, allowing you to hear around corners.

FIGURE 9.5.2 The way information is printed on a CD or DVD means that it creates structures small enough to cause light to diffract.

When light passes through an opening such as a window into a darker room, you expect to see the sharp shadow of the window on the floor of the room. You do not expect to see light bend around corners or appear in other parts of the room. When sound passes through a doorway, you expect it to travel to all parts of the room, to spread out and for all observers to hear the sound in all parts of the room.

So what is different between the behaviour of sound waves and light waves? Why does one wave appear to travel in a straight line, as a light ray, and the other wave seems to bend around corners and travel in all directions? In order to fully understand these observations, the wave property of diffraction needs to be considered.

DIFFRACTION

When a plane (straight) wave passes through a narrow opening or **aperture**, it **diffracts** (bends), as shown in Figure 9.5.1. Waves will also bend as they travel around obstacles. This kind of 'bending' phenomenon is known as diffraction. Huygens' principle, introduced in Module 9.4, will be used to explain the nature of wave propagation around obstacles and through narrow openings.

Diffraction is significant when the size of the opening or obstacle is similar to or smaller than the wavelength of the wave. This means that the diffraction of light is difficult to observe because the wavelength of light is very small.

Light waves range in wavelength from around 700 nm for red light to about 400 nm for violet light. One namometre (1 nm) is equal to 10^{-9} m or a one-millionth of a millimetre. This means that light waves are all less than one-thousandth of a millimetre in length. Light waves do not encounter many naturally occurring structures of this size, so diffraction is not easily observed. Usually, diffraction occurs with artificially constructed materials such as CDs or commercially produced diffraction gratings (Figure 9.5.2).

Sound waves range in frequency from 2 Hz to about 20 000 Hz for normal hearing. This corresponds to wavelengths from 17 mm to about 170 m. Any opening corresponding to these wavelengths, such as windows or door openings, could result in the diffraction of sound waves being observed. Or, more importantly, some sound waves could result in diffraction and others could not. To compare the wavelength of the sound wave produced and the size of the opening, you may need to use the wave equation $f = \frac{v}{\lambda}$.

Diffraction and slit width

When sound waves are diffracted around an opening, the size of the gap affects the degree of diffraction. If the wavelength is much smaller than the gap or obstacle, then the degree of diffraction is less. For example, Figure 9.5.3 shows the diffraction of water waves in a ripple tank.

In Figure 9.5.3a, the gap is similar in size to the wavelength, so significant diffraction occurs and the waves emerge as circular waves. In Figure 9.5.3b, the gap is much bigger than the wavelength, so diffraction only occurs at the edges.

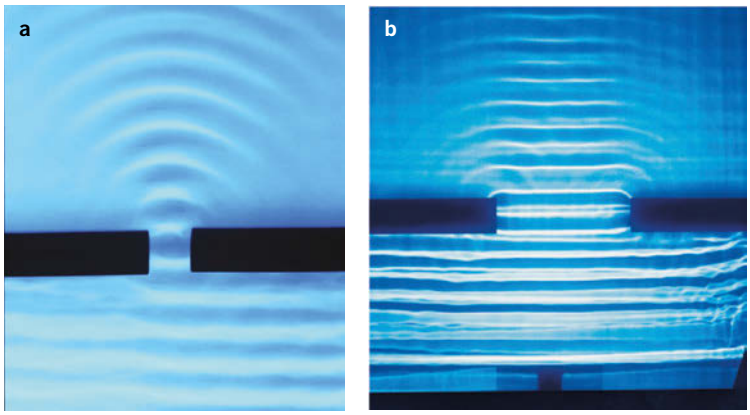


FIGURE 9.5.3 The diffraction of water waves in a ripple tank. (a) Significant diffraction occurs when the wavelength approximates the slit width ($\lambda \approx w$). (b) As the gap increases ($\lambda << w$), diffraction occurs mainly around the edges. It becomes less obvious, but is still present.

- If the wavelength of a sound wave is a similar size or larger than the width of a gap ($\lambda \geq w$), then significant diffraction occurs and the waves emerge as circular waves.
- If the wavelength of a sound wave is smaller than the width of a gap ($\lambda < w$), then less diffraction occurs.

Wavelengths comparable to or larger than the diameter of the obstacle or gap will produce significant diffraction. This can be expressed as the ratio $\frac{\lambda}{w} \geq 1$, where λ is the wavelength of the wave and w is the width of the gap.

Worked example 9.5.1

DIFFRACTION

A red neon laser emits light with a frequency of 4.5×10^{14} Hz. A white light source is a mixture of frequencies from 4.3×10^{14} Hz to 7.5×10^{14} Hz, with an average frequency of about 5.5×10^{14} Hz. Both light sources travel in air with a velocity of $3.00 \times 10^{8}\,\text{m s}^{-1}$.

Calculate the wavelength, using the wave equation, and the dimension of the opening for diffraction of these waves to occur. Give answers for both light sources in mm.

Thinking	Working
For the neon laser the frequency is 4.5×10^{14} Hz. Rearrange the wave equation to solve for λ. When converting from m into mm, multiply the number by 1000. This is the size of the slit for diffraction to occur.	$\lambda = \frac{v}{f}$ $= \frac{3.00 \times 10^{8}}{4.5 \times 10^{14}}$ $= 670 \times 10^{-9}\,\text{m}$ $= 670\,\text{nm}$ $= 6.7 \times 10^{-7}\,\text{m}$ $= 0.000\,67\,\text{mm}$
For white light the average frequency is 5.5×10^{14} Hz. Rearrange the wave equation to solve for λ. The average wavelength is about 545 nm. When converting from m into mm, multiply the number by 1000. Therefore this is the size of the slit needed for diffraction.	$\lambda = \frac{v}{f}$ $= \frac{3.00 \times 10^{8}}{5.5 \times 10^{14}}$ $= 545 \times 10^{-9}\,\text{m}$ $= 545\,\text{nm}$ $= 5.5 \times 10^{-7}\,\text{m}$ $= 0.000\,55\,\text{mm}$

➤ Try yourself 9.5.1

DIFFRACTION

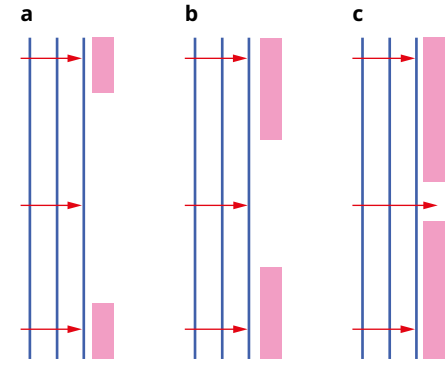
A piano produces a range of notes from 28 Hz to about 4200 Hz. The sound waves coming from a piano are diffracted around a doorway into the hallway. What dimensions must the doorway opening have? Assume the average frequency of sound heard coming from the piano is about 2000.0 Hz and the speed of sound in air is 340 m s^{-1}.

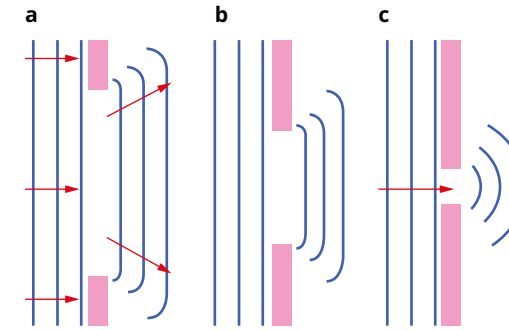
Explain what this calculation suggests about the sound waves heard in the hallway, and the diffraction of these waves.

Worked example 9.5.2

DIAGRAMS OF DIFFRACTION

In the three diagrams below, wavefronts are travelling towards openings of three different sizes. For each diagram, draw the wavefront pattern after passing through the opening. Take care to compare the wavelength, λ, of the wavefronts and the size of the opening, w.

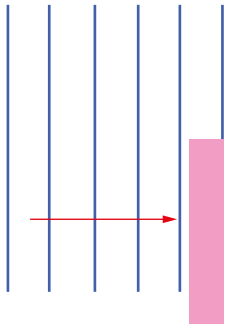


Thinking	Working
Compare the wavelength of the waves, λ, and the size of the opening, w. **a** The width of the gap is much greater than the wavelength, so diffraction occurs at the edge of the opening only. **b** The width of the gap is smaller, so more diffraction occurs. **c** The width of the gap is similar to the wavelength, so diffraction occurs, with circular concentric wavefronts.	

➤ Try yourself 9.5.2

DIAGRAMS OF DIFFRACTION

A wave travelling to the right strikes a barrier or edge, as shown in the diagram below. Sketch the resulting wavefront of the wave as the wave continues to travel past this barrier.



Diffraction and imaging

Diffraction can be a problem for scientists using microscopes and telescopes because it can result in blurred images. For example, light from two tiny objects or two very distant objects that are close together can be diffracted so much that the objects appear as one blurred object. When this happens, the objects are said to be unresolved. Essentially, the ratio $\frac{\lambda}{w}$ dictates how small an object can be to be clearly imaged by a particular instrument. Figure 9.5.4a shows the high-resolution image of stars in galaxy M33, taken with the orbiting Kepler space telescope.

This means that, as a general rule, optical microscopes cannot create images of objects that are smaller than the wavelength of the light they use; otherwise, diffraction effects are too significant. Using a green light of 514 nm allows objects in this range to be imaged clearly. The shorter the wavelength of light used to image a specimen, the more detail will be resolved.

Diffraction also places a theoretical limit on the **resolution** of optical telescopes. However, atmospheric distortion usually has a much larger effect on telescope images than diffraction. The Hubble Space Telescope, which sits above Earth's atmosphere, is not affected by atmospheric distortion. It can resolve images right down to its diffraction limit, i.e. where the separation of the stars is approximately equal to the wavelength of the light.

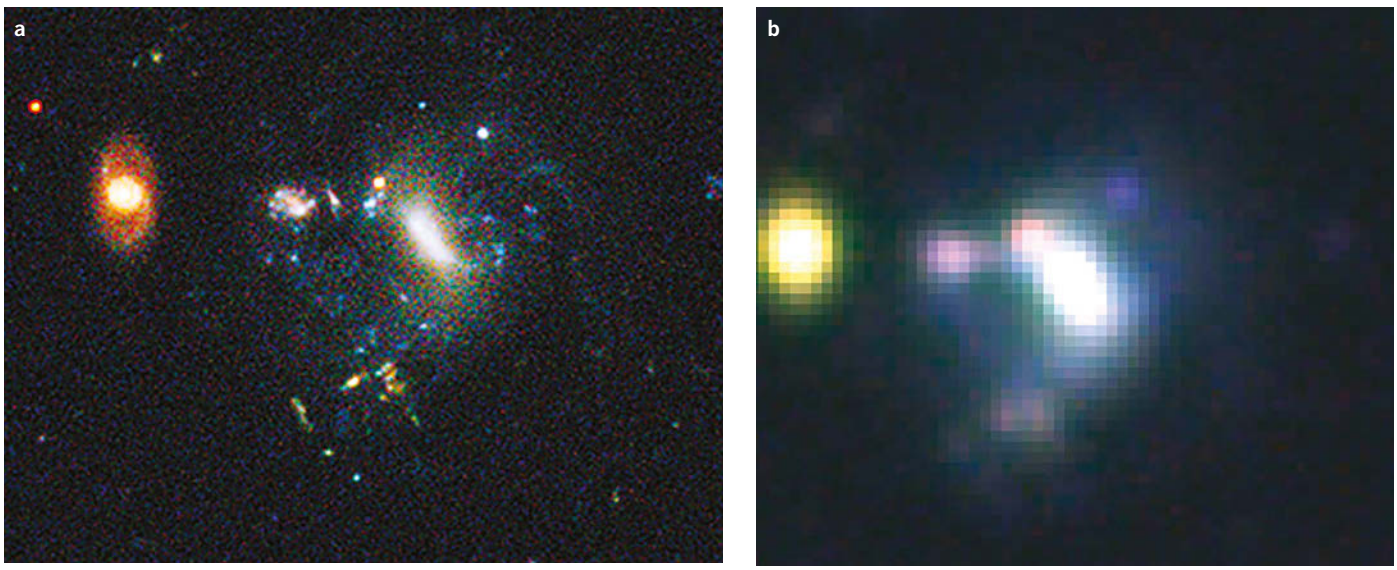


FIGURE 9.5.4 High- and low-resolution images of stars in the galaxy M33. (a) The high-resolution image shows several stars, compared to (b) the blurry low-resolution image of the same galaxy.

9.5 Review

SUMMARY

- When a plane (straight) wave passes through a narrow opening or meets a sharp object, it experiences diffraction.
- Significant diffraction occurs when the wavelength of the wave is similar to, or larger than, the size of the diffracting object.
- An application of Huygens' principle allows us to sketch the wavefronts after passing through an opening.
- Light waves have a wavelength range from about 400 nm to about 700 nm. Therefore openings of the order of 10^{-4} mm are needed for light waves to diffract.
- Audible sound waves have a frequency range from about 20 to 20 000 Hz for normal human hearing. Therefore openings of the range from 17 mm to 17 m are needed for these sound waves to diffract.
- Diffraction of light travelling from two tiny objects or two very distant objects close together may appear as one blurred object. In this case the objects are called 'unresolved'. This places a theoretical limit on the resolution of telescopes. For optical microscopes, using the shortest visible wavelength of light of 400 nm, the limit on the size of objects is about 400 nm or slightly smaller. This is the limit of resolution for the optical microscope.

KEY QUESTIONS

Retrieval

1 Define 'diffraction' and recall two examples where diffraction occurs.

2 Recall the conditions between the wavelength, λ, of a wave and the width of the opening, w, for diffraction to occur.

Comprehension

3 Identify which of the statements a–e are true and which are false. Rewrite the false statements to make them true.

a Visible light waves have a frequency range from 400 Hz to 800 Hz and require an opening with a width of about 10^{-2} mm for diffraction to occur.

b Water waves with a frequency of 0.2 Hz and a velocity of 0.5 m s^{-1} diffract around an opening with a width of 2.5 m.

c An acoustic guitar produces a middle C note with a frequency of 261.6 Hz. An opening with a width of 3.1 m or larger would cause this sound wave to diffract.

d A comparison between light waves and diffraction opening widths suggests that red light with a longer wavelength will diffract with a smaller opening width, compared to violet light.

e Any wave will only diffract if the dimensions of the opening, w, and the wavelength of the wave, λ, are identical.

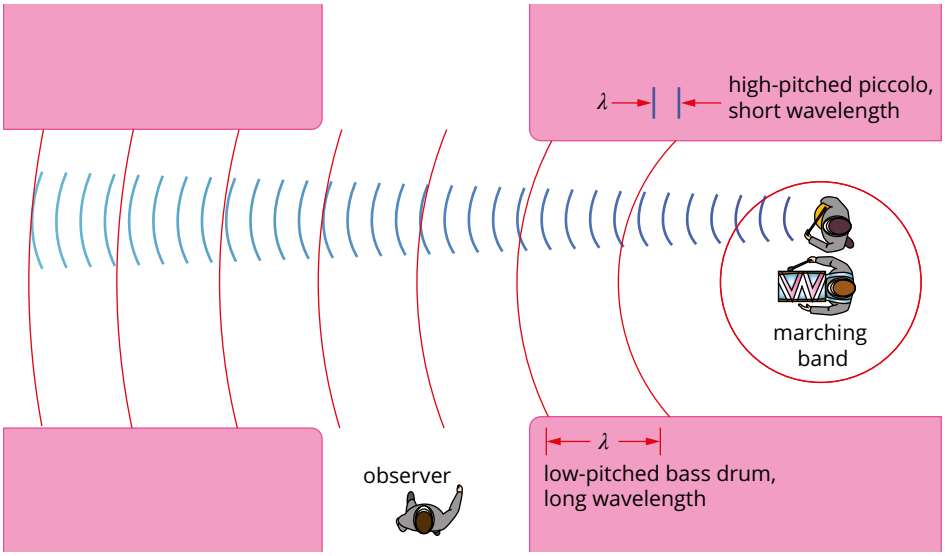
4 State the size opening width, in mm, that would be needed in order to produce significant diffraction of red light (wavelength of approximately 700 nm) in a diffraction experiment.

5 Explain what the theoretical limit for the resolution of images is with optical instruments.

Analysis

6 Doorways are approximately 1.0 metre wide. A guitar player produces a middle C note (C_4) with a frequency of 262 Hz and a listener is standing to one side of the doorway opening, not in direct line of the guitar player. Assess whether the listener would be able to hear this note due to the sound wave diffracting around the edge of the doorway. Assume the speed of sound in air is 340 m s^{-1}.

7 If a marching band is approaching on a cross street in a city, as shown below, determine which of these instruments you would hear first: the high-pitched piccolo with a short wavelength or the low-pitched bass drum with a long wavelength.



8 Differentiate between refraction and diffraction.

9.6 Interference and superposition

BY THE END OF THIS MODULE, YOU SHOULD BE ABLE TO:

- define the principle of superposition
- apply the principle of superposition to determine the resultant of two waves
- explain constructive and destructive interference of two simple waves
- apply the path difference relationship between two sources to determine whether constructive or destructive interference occurs.

The characteristic sounds of musical instruments, the human voice, or a combination of both at a musical concert, is due to the interaction of multiple mechanical waves. The interaction of these mechanical waves results in superposition. Superposition can be applied to waves whenever two or more waves travel through the same medium at the same time.

SUPERPOSITION

Imagine two transverse mechanical waves travelling towards each other along a string (Figure 9.6.1a). When the crest of one wave coincides with the crest of the other, the resulting displacement of the string is the vector sum of the two individual displacements (Figure 9.6.1b). The amplitude at this point is increased and the shape of the string resembles a combination of the two pulses. After they interact, the two pulses continue unaltered (Figure 9.6.1c). The resulting pattern is a consequence of the **principle of superposition**.

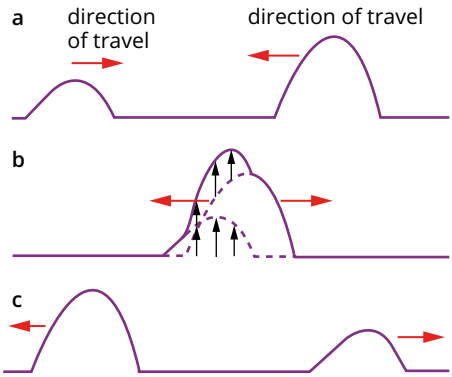


FIGURE 9.6.1 (a) Two wave pulses approach each other. (b) The pulses interact and constructive superposition occurs. (c) After the interaction, the pulses continue unaltered; they do not permanently affect each other.

When a pulse with a positive displacement meets a pulse with a negative displacement (Figure 9.6.2a), the resulting wave will have a smaller amplitude (Figure 9.6.2b). As in Figure 9.6.1, the resulting displacement of the string is the vector sum of the two individual displacements. The resulting pattern follows the principle of superposition. **Superposition** is also known as **interference** and the terms are often used interchangeably.

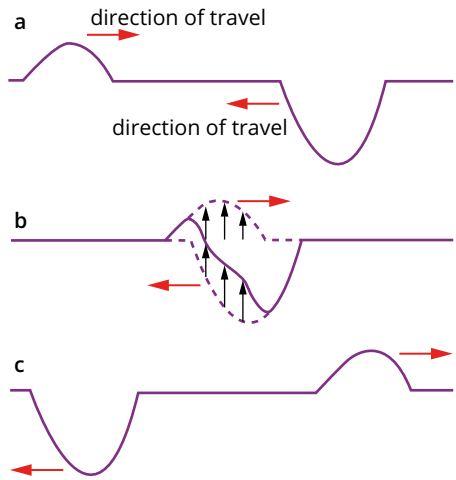


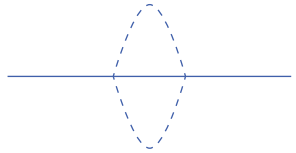
FIGURE 9.6.2 (a) Two wave pulses approach each other. (b) Superposition of the waves in the string shows destructive superposition. (c) The pulses continue unaltered. As in constructive superposition, the waves do not permanently affect each other.

Worked example 9.6.1

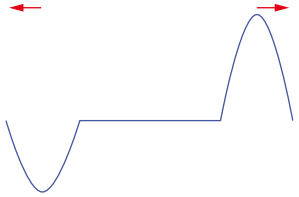
SUPERPOSITION

Two pulses travelling in a string are moving towards each other as shown below. As the pulses move towards each other they will interfere, producing an overlapping interference wave pattern and continue to move in the original directions. Draw the resulting interference pattern (when the pulses overlap) and the pulses after interference, for each example.

a pulses with identical amplitudes travelling towards each other

Thinking	Working
The diagram shows two pulses with the same amplitude but the pulse on the right is inverted (or upside down). When these two pulses overlap, the two pulses will destructively interfere, as the displacement of the pulse on the left will cancel out the displacement of the pulse on the right. After interference the pulses will continue to travel with the same amplitude and velocity as before superposition (if you ignore energy losses to the string).	pulses destructively interfere  pulses move away from other

b pulses with differing amplitudes travelling towards each other

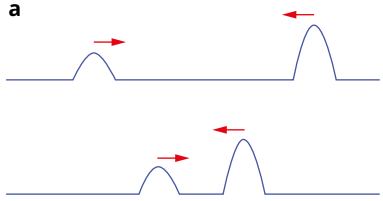
Thinking	Working
The diagram shows two pulses with different amplitudes. The pulse on the left has roughly twice the amplitude of the pulse on the right. When these pulses overlap, the two pulses will interfere through the addition of the separate pulse displacements. The displacement of the pulse on the left is larger and will produce an interference pulse pattern with a lower crest, due to superposition. After interference the pulses will continue to travel with the same amplitude and velocity as before superposition (again if you assume no energy losses in the string).	pulses interfere pulses move away from other 

➤ Try yourself 9.6.1

SUPERPOSITION

Two pulses are travelling along an elastic string (where no energy is lost to the string). In the diagrams for parts **a** and **b** below, the pulses are shown travelling towards each other during successive time intervals t_1 and t_2. Draw the pulse patterns in the string during and after interference between these pulses, for each diagram. Assume each time interval is identical and the pulses are travelling with a constant velocity, v.

a



b

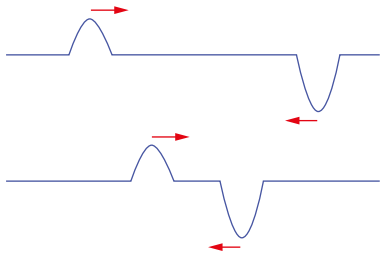


FIGURE 9.6.3 The ripples from raindrops striking the surface of a pond behave independently, regardless of whether they cross each other or not. Where the ripples meet, a complex wave will be seen as the result of the superposition of the component waves. After interacting, the component waves continue unaltered.

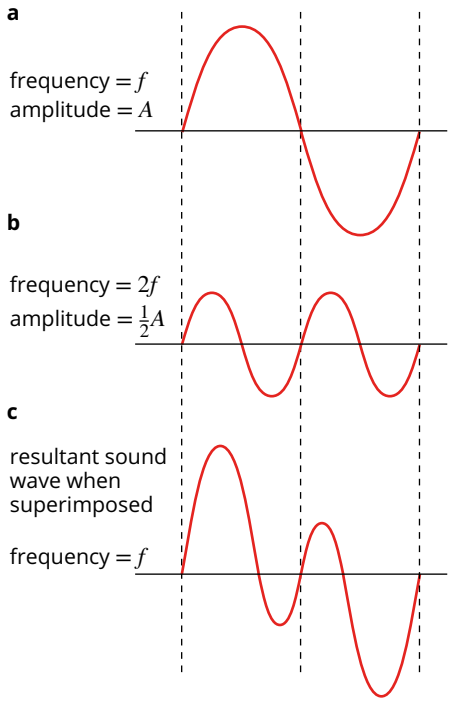


FIGURE 9.6.4 Two sound waves, one twice the frequency of the other, produce a complex wave of varying amplitude when they are superimposed.

INTERFERENCE

When two waves meet and superimpose, there will be places where constructive interference occurs and places where destructive interference occurs.

- **Constructive interference** is shown in Figure 9.6.1 (page 374), in which the two waves added together to produce a wave of larger magnitude.
- **Destructive interference** is shown in Figure 9.6.2 (page 374), in which positive and negative displacements produce a wave of smaller magnitude.

Although the wave pulses interact when they meet, passing through each other does not permanently alter the shape, amplitude or speed of either pulse. Just like transverse waves, longitudinal waves will also be superimposed as they interact.

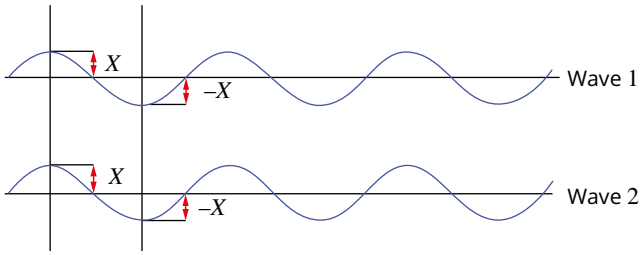
The effects of superposition can be seen in many everyday examples. The ripples in the pond in Figure 9.6.3 were caused by raindrops hitting the pond. Where two ripples meet, a complex wave results from the superposition of the two waves, after which the ripples continue unaltered. Similarly, in a crowded room, all the sounds reaching your ear have been superimposed, so that one complex sound wave arrives at the eardrum.

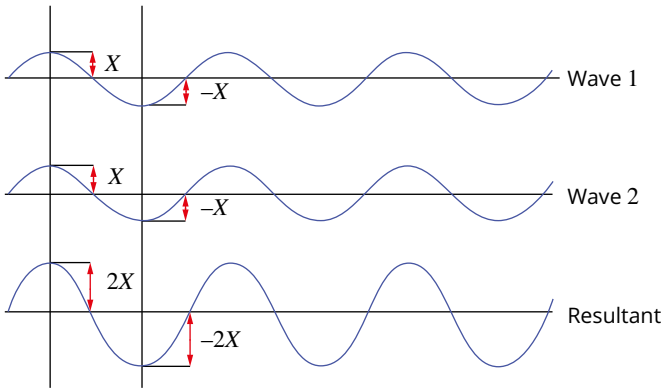
Superposition is important both theoretically and practically in the formation of complex sounds. Imagine two single-frequency sound waves, or pure tones, one of which is twice the frequency of the other. The two individual waves are added together to give a more complicated resultant sound wave, as shown in Figure 9.6.4. The sound wave with a greater amplitude will be the predominant sound heard. The quieter, higher frequency sound will combine with the louder sound to create the complex sound that you hear. Note that for Figure 9.6.4, a transverse wave is used to depict the sound wave. The crests represent compressions (areas of high pressure) and the troughs represent rarefactions (areas of low pressure). Showing longitudinal waves in this way makes features such as period, and therefore frequency, easier to see.

Worked example 9.6.2

INTERFERENCE

The graph shows two identical waves that arrive in phase. Note identical amplitudes and wavelengths, and all points on both waves are in phase. Use the principle of superposition to sketch the resultant wave produced from the interference of wave 1 and wave 2.

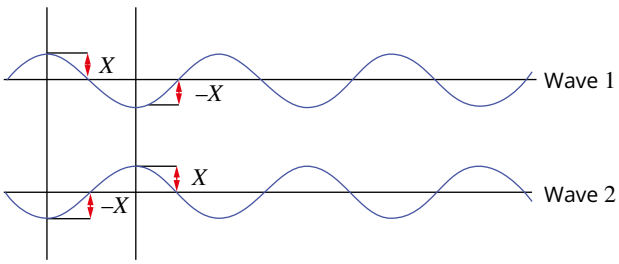


Thinking	Working
The crests of wave 1 correspond to the crests of wave 2. The troughs also correspond. The wavelengths are identical as are the amplitudes, *X* of each wave. The principle of superposition adds the displacements of waves at the same position or point. This is an example of complete constructive interference, with the resultant wave pattern having double the amplitude of the original waves. The resultant wave results from the addition of the displacements of wave 1 and wave 2. The resultant wave has twice the amplitude of the individual waves.	

➤ Try yourself 9.6.2

INTERFERENCE

The graph shows two identical waves that arrive exactly out of phase (or have a phase difference of 180°). Note identical amplitudes and wavelengths, but all points on the waves are out of phase. Use the principle of superposition to sketch the resultant wave produced from the interaction of wave 1 and wave 2.



Interference from two point sources

Interference from two point sources occurs when waves from both sources meet up and interfere. The resultant wave pattern at this point is dependent on the phase of each wave. If two crests meet up at a point, then the resultant wave at that point will be due to the constructive interference of both waves. This is also the case if two troughs meet at the same point, which produces a larger resultant wave due to constructive interference between the two wave sources.

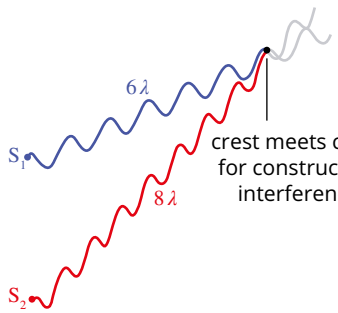


FIGURE 9.6.5 At a point a distance of 6λ from S_1 and 8λ from S_2 the two waves will interfere constructively. The path difference between the two waves is 2λ.

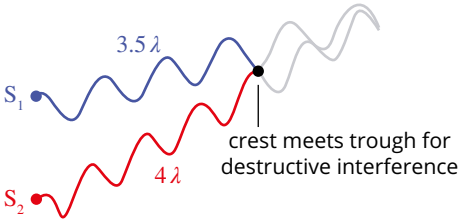


FIGURE 9.6.6 At a point a distance of 3.5λ from S_1 and 4λ from S_2 the two waves will interfere destructively. The path difference between the two waves is 0.5λ.

The conditions for constructive interference and destructive interference can be stated in terms of the path differences travelled by these identical waves.

- **Constructive interference occurs when the path difference = $n\lambda$ ($n = 0, 1, 2, \ldots$).**
- **Destructive interference occurs when the path difference = $(n + \frac{1}{2})\lambda$ ($n = 0, 1, 2, \ldots$).**

In Figure 9.6.5, two identical waves produced from sources S_1 and S_2 combine at a point some distance away from the individual sources. The point at which the two sources combine is exactly six wavelengths from S_1, and eight wavelengths away from S_2. If both S_1 and S_2 oscillate at the same frequency and have the same amplitude and wavelength, then the two waves will undergo complete constructive interference at this point.

Distance from $S_1 = 6\lambda$

Distance from $S_2 = 8\lambda$

The **path difference** between the two sources = 2λ (an integral number of wavelengths).

In Figure 9.6.6, two waves, produced from sources S_1 and S_2 combine at a point some distance away from the individual sources. The point at which the two sources combine is exactly a distance equal to three-and-a-half wavelengths away from S_1, and four wavelengths away from S_2. If both S_1 and S_2 oscillate at the same frequency and have the same amplitude and wavelength, then the two waves will undergo complete destructive interference at this point.

Distance from $S_1 = 3.5\lambda$

Distance from $S_2 = 4\lambda$

The path difference between the two sources = 0.5λ (not an integral number of wavelengths).

The conditions for complete constructive interference and complete destructive interference can be stated in terms of the path differences travelled by these identical waves.

In Figure 9.6.7, the darker lines represent crests from two identical sources S_1 and S_2, and the lighter lines represent troughs. This figure represents either transverse or compression (or longitudinal) waves.

The red lines represent complete constructive interference at:

- $m = 0$ (zero path difference)
- $m = 1$ (path difference = 1λ)
- $m = 2$ (path difference = 2λ).

The blue lines represent complete destructive interference at:

- $m = 0.5$ (path difference = 0.5λ)
- $m = 1.5$ (path difference = 1.5λ)
- $m = 2.5$ (path difference = 2.5λ).

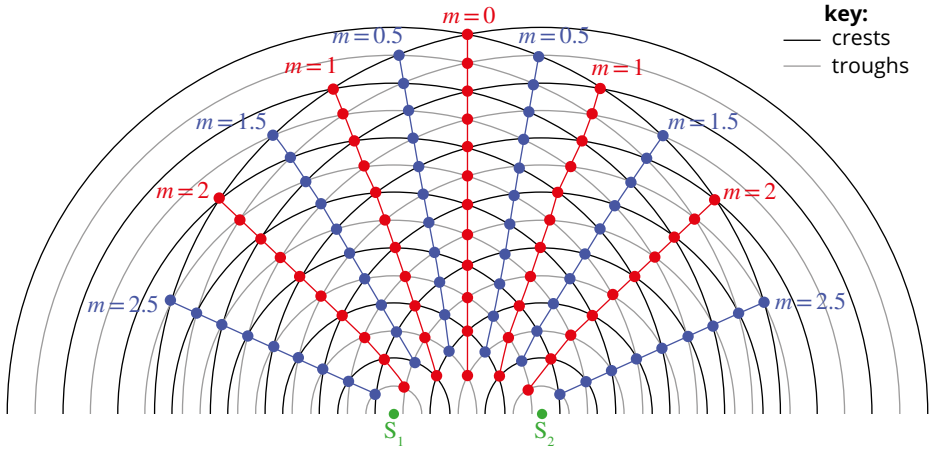


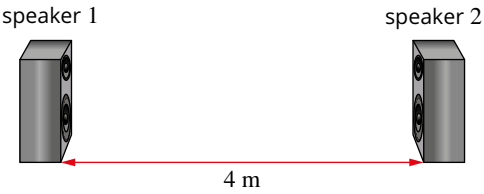
FIGURE 9.6.7 The path difference between two sources. If the path difference is $m = 0$, 1 or 2 (red lines), constructive interference is observed. If the path difference is $m = 0.5$, 1.5, 2.5 (blue lines), destructive interference is observed.

Worked example 9.6.3

INTERFERENCE FROM TWO POINT SOURCES

Two loudspeakers are positioned exactly 4.0 m apart and facing each other, as shown below. The speakers are producing identical sounds (equal amplitude and phase) with a frequency of 340 Hz. A person sits halfway between the two speakers.

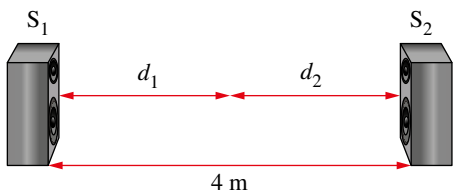
Assume the speed of sound in air is 340 m s^{-1}.



a Calculate the wavelength of these sound waves, using the wave equation.

Thinking	Working
Both the wave frequency and the wave velocity are known. Rearrange the wave equation to determine the wavelength of these sound waves.	$\lambda = \frac{v}{f}$ $= \frac{340}{340}$ $= 1.0\,\text{m}$

b In terms of wavelengths, determine how far this person is from each loudspeaker.

Thinking	Working
A person sitting halfway between the speakers is 2.0 m from each speaker. This is exactly 2 whole wavelengths from each speaker.	 $d_1 = 2.0\,\text{m}$ and $d_2 = 2.0\,\text{m}$ $d_1 = 2\lambda$ and $d_2 = 2\lambda$

c Determine the path difference between the two sound waves travelling towards the person.

Thinking	Working
The two sound waves travel the same distance in opposite directions: $2\,\text{m} = 2\lambda$ Path difference is calculated by subtracting the paths travelled by each sound wave.	Path difference $= 2\lambda - 2\lambda = 0$

d Identify whether the interference pattern produced (at the person's position) is a point of complete constructive or destructive interference between the two loudspeaker sounds. Explain what the person would hear.	
Thinking	**Working**
Refer to the interference conditions to determine whether complete constructive interference or complete destructive interference has occurred at this point. The two waves will meet at this point in phase. Constructive interference occurs.	Constructive interference occurs when the path difference $= n\lambda$ (where $n = 0, 1, 2, \ldots$). The person would notice constructive interference between the two sound waves, therefore the interference pattern would have twice the amplitude as the two individual travelling sound waves. So they would hear a noticeable increase in loudness of sound.

➤ Try yourself 9.6.3

INTERFERENCE FROM TWO POINT SOURCES

A second person sits 0.50 m from one of the speakers in Worked example 9.6.3.

a Calculate how far away this person is from the other speaker.

b Determine how far this person is from the speakers, in terms of wavelength.

c Determine the path difference between the two sound waves travelling towards this person.

d Identify whether the interference pattern produced (at that person's position) is a point of constructive or destructive interference between the two loudspeaker sounds. Explain what the person would hear.

9.6 Review

SUMMARY

- The principle of superposition states that when two or more waves interact, the resultant displacement or pressure at each point along the wave will be the vector sum of the displacements or pressures of the component waves.
- The shape of the medium during interference between two or more waves requires that the principle of superposition be applied for every point along the medium.
- Complete constructive interference occurs when overlapping identical waves are in phase. Complete destructive interference occurs when overlapping identical waves are 180° out of phase.
- Complete constructive interference occurs when the path difference between two waves is $n\lambda$.
- Complete destructive interference occurs when the path difference between two waves is $(n + \frac{1}{2})\lambda$.

KEY QUESTIONS

Retrieval

1 Recall the principle of superposition.

2 State the conditions between two identical waves for both destructive interference and constructive interference to occur.

Comprehension

3 Describe what happens to the resulting wave when two identical waves have a phase difference of the following:

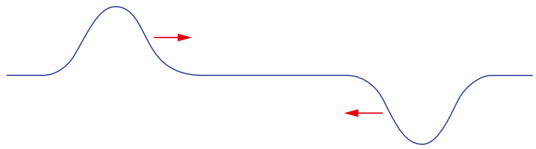
a 90°

b 180°

c 270°

d 360°

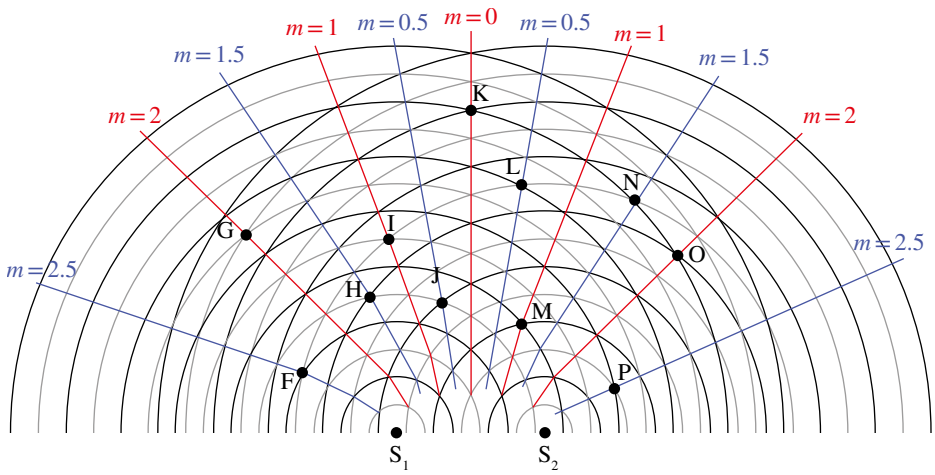
4 Draw a sequence of diagrams, for five time intervals, to demonstrate the principle of superposition for two pulses travelling towards each other in a light elastic string. Each time interval will advance the pulse shown by one complete pulse width. Use the first interval below and draw each subsequent time interval underneath the interval before.



5 A two-source interference pattern is shown below. Assuming the two sources produce the concentric wavefronts shown below, with dark lines indicating wavefronts representing crests (or compressions). Identify the letters that represent:

a constructive interference between the two sources S_1 and S_2

b destructive interference between the two sources S_1 and S_2.



9.6 Review *continued*

6 Determine which of the statements a–d are true and which are false. Rewrite the false statements to make them true.

- **a** Superposition will occur whether waves are in phase or not. If the waves are in phase they will produce a fixed interference pattern.
- **b** If two waves are in phase at a point then destructive interference occurs, and if the two waves are out of phase at a point then constructive interference occurs.
- **c** The principle of superposition occurs only for transverse waves, and not for longitudinal (or compression) waves.
- **d** One complete wave oscillation has a phase of 360°.

Analysis

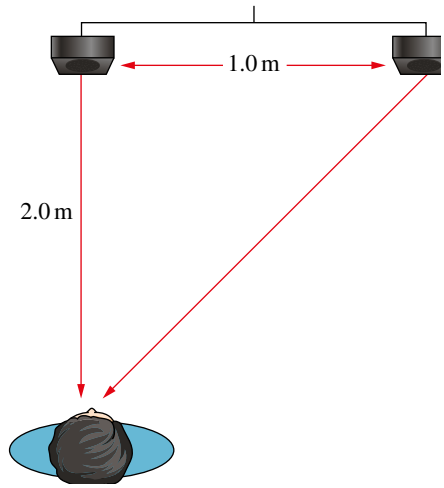
7 Two loudspeakers both emit sounds with a frequency of 680 Hz. The two sounds have equal amplitude and phase. The speakers are 2.0 m apart and face each other. Assume the speed of sound waves in air is $340\,m\,s^{-1}$.

- **a** Calculate the wavelength of the sound waves.
- **b** The amplitude of each sound is given by the symbol *A*. Calculate the amplitude of the sound halfway between the speakers (ignoring any amplitude reduction with distance).
- **c** Identify the other distance from either speaker at which constructive or destructive interference will be observed. Hint: Use the path difference relationships to answer this.

8 Identical waves leaving from two sources S_1 and S_2 arrive at a position X. The waves from both sources have a wavelength of 2.8 m. The position X is 8.4 m away from the first source and 9.8 m away from the second source. State the path difference between the two waves arriving at point X in terms of the wavelength. Explain what is observed at point X.

9 Two loudspeakers are 1.0 m apart, and produce the same signal. A listener is 2.0 m away from the left speaker and directly in front of this speaker, as shown in the diagram. Assume the speed of sound in air is $340\,m\,s^{-1}$ and the frequency of both speakers is 850 Hz. The listener starts to walk in a straight line towards the left speaker, and stops when standing 1.0 m away from it.

- **a** Determine the wavelength of the signal produced by each loudspeaker. State any assumptions made in your calculations.



- **b** Explain whether the listener would notice constructive or destructive interference at this point.

9.7 Standing waves

BY THE END OF THIS MODULE, YOU SHOULD BE ABLE TO:

- understand how standing waves are formed
- identify nodes and antinodes in a standing wave
- identify where standing waves occur in nature.

The properties of reflection and superposition of waves allows you to understand how the interaction between two or more waves produces standing waves. Unlike travelling transverse or compression (longitudinal) waves, there is no net transfer of energy in a standing wave in an ideal situation. Standing waves are noticeable in stringed musical instruments such as the guitar, cello, violin or piano. Standing waves can also be heard in musical instruments that have an air column, such as the flute, oboe or the large organ pipes of a cathedral.

The different standing wave patterns and corresponding frequencies produced in stringed and air-column instruments will be studied in further detail in Chapter 10. This module deals with the qualitative understanding of how a standing wave is produced. A comparison between standing waves and travelling waves will allow an understanding of these two different types of wave.

Standing waves are formed from the superposition of waves. They occur when two waves of the same amplitude and frequency are travelling in opposite directions towards each other in the same string. Usually, one wave is the reflection of the other. Standing waves are responsible for the wide variety of sounds associated with speech and music.

FORMATION OF STANDING WAVES IN A STRING

In Module 9.3, you learnt that when a wave pulse reaches a fixed end, it is reflected back 180° out of phase; that is, crests are reflected as troughs and troughs are reflected as crests.

Imagine creating a series of waves in a rope by shaking it vigorously. As you continue to shake the rope, waves will travel in both directions. The new waves travelling down the rope will interfere with those being reflected back along the rope. This kind of motion usually creates a random pattern and the waves die away quickly. Shaking the rope at just the right frequency, however, will create a new wave that interferes with the reflection in such a way that the two superimposed waves create a single, larger amplitude called a **standing wave**. A standing wave doesn't appear to be travelling along the rope. The rope simply seems to oscillate up and down with a fixed pattern. That is, is seems to be just 'flipping' up and down in a fixed pattern. This situation contrasts with a standard transverse wave, where every point on the rope has a maximum displacement at some time as the wave travels along the rope.

In Figure 9.7.1a–d, two waves (drawn in blue) are shown travelling in opposite directions towards each other along a rope. One of the waves is a string of pulses (shown as a solid line) and the other is its reflection (shown as a dashed line). The two waves superimpose when they meet and this is shown by the red line.

- In Figure 9.7.1a, at a particular point in time, the two waves are completely superimposed, resulting in a wave twice the original amplitude.
- In Figure 9.7.1b, after a time equal to $\frac{T}{4}$ (one-quarter of the period), the waves will each have moved $\frac{\lambda}{4}$, which means that they have moved $\frac{\lambda}{2}$ in relation to each other. The waves are completely out of phase and the resulting displacement is zero.
- In Figure 9.7.1c and Figure 9.7.1d, as more time goes by, the waves will continue to move past each other and completely superimpose again before cancelling again.

- In Figure 9.7.1e, the cycles shown in (a) to (d) form a standing wave. A standing wave swings between maximum displacements, creating antinodes (A) that are halfway between the stationary nodes (N). Regardless of the position of the component waves, these nodes stay in the same place. Successive nodal points are $\frac{\lambda}{2}$ apart, as are successive antinodal points.

The amplitude and frequency of each is the same, so the end result is a standing wave, as shown in Figure 9.7.1e. At the points where destructive interference occurs, the two waves totally cancel each other out and the rope will remain still. These are called **nodes**. Where the rope oscillates with maximum amplitude, constructive interference is occurring. These points on the standing wave are called **antinodes**.

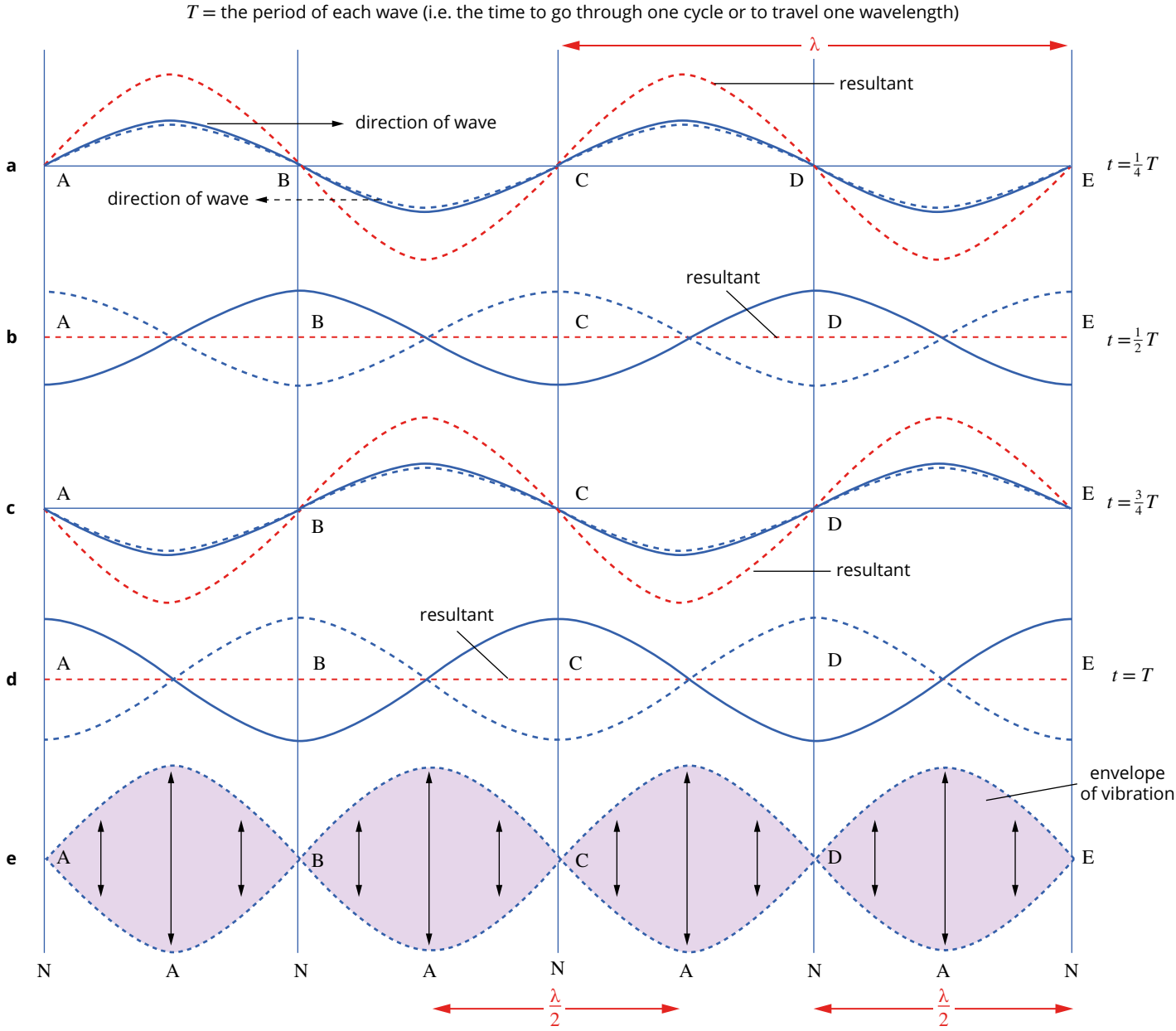


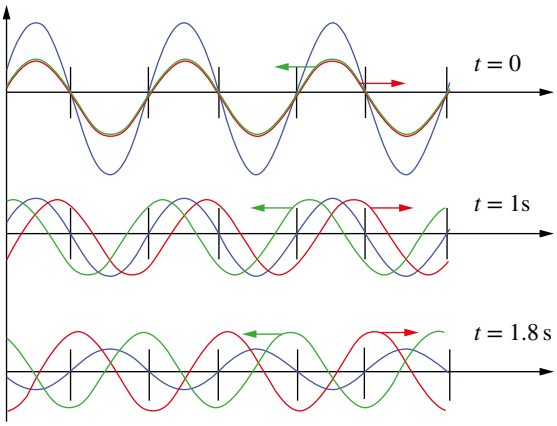
FIGURE 9.7.1 A standing wave is created in a rope from two waves travelling in opposite directions, each with the same amplitude and frequency.

Worked example 9.7.1

STANDING WAVES

The formation of standing waves can be shown graphically with the aid of a series of diagrams. In the diagram below, the red wave is moving to the right and the green wave is moving to the left. The blue wave is the resultant wave pattern due to the superposition of these red and green waves. Each successive graph is at a later time.

State how the positions of the antinodes (crests, and troughs) and the nodes (zero resultant displacement) move or don't move for each successive graph. Comment also on the amplitude of the separate points on the resultant blue standing wave.



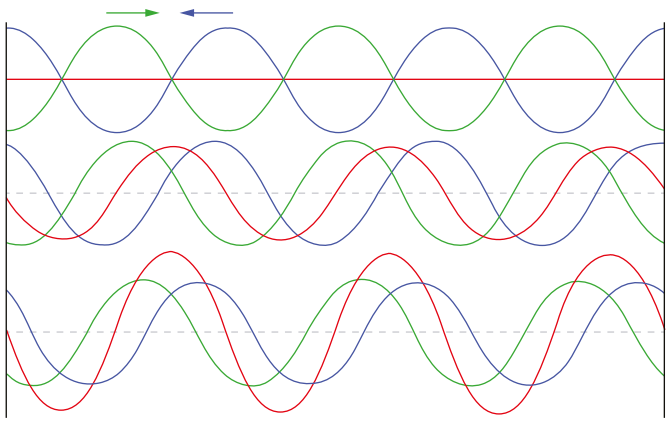
Thinking	Working
The red wave is moving to the right, and the green wave is moving to the left. The blue wave is the resultant wave pattern of the red and green waves. Look at the blue wave (the total displacement of the red and green waves) for each graph at identical positions.	The positions of antinodes (the crests and troughs) of the blue resultant wave do not change. The positions of the nodes (the points of zero displacement) of the blue standing wave do not change. The blue resultant wave pattern does not move to the left or the right, but oscillates about the rest position. Its minimum displacement is zero and its maximum displacement is twice the amplitude of the red and green waves. The amplitude of the points on the blue standing wave varies at every point along the standing wave.

➤ Try yourself 9.7.1

STANDING WAVES

The diagram below is a time sequence showing two waves interacting at three different times. The green wave is the incident wave and it reflects off the fixed boundary or wall to the right. As it reflects it undergoes a 180° phase change. The interference pattern between the green incident wave and blue reflected wave is represented as the red standing wave.

For the third time sequence (the bottom one) label the nodes, antinodes, and the wavelength relationship between successive nodes on the standing (resultant) wave.



Nodes and antinodes in a standing wave remain in a fixed position for a particular frequency of vibration.

It is important to note that the formation of a standing wave does not mean that the string or rope itself is stationary. It will continue to oscillate as further wave pulses travel up and down the rope. It is the relative position of the nodes and antinodes that remain unchanged. It is also important to note that standing waves are not a natural consequence of every wave reflection.

Standing waves are only produced by the superposition of two waves of equal amplitude and frequency, travelling in opposite directions. They are a result of **resonance** and occur only at the natural frequencies of vibration, or **resonant frequencies**, of the particular medium. As well as existing in the everyday world, standing waves also occur at the subatomic level.

Surface waves

The discussion in this module has been of two-dimensional standing waves, but standing waves may also form in three dimensions, such as in a section of Earth's crust. Standing waves will form as a result of resonance in any waveform.

Seismic surface waves travel along the boundary between materials, such as the Earth's crust and upper mantle. One type of surface wave is called the **Rayleigh wave**, or ground roll. Rayleigh waves are surface waves that travel as ripples with a motion like that of waves on the surface of water, although the restoring force is elastic rather than gravitational as it is for water waves. A phenomenon known as free oscillation of the Earth is the result of the superposition between two such surface waves travelling in opposite directions, creating a surface standing wave.

The first observations of free oscillations of the Earth were made during the 1960 Chile earthquake. Since then thousands of harmonics have been identified.

Standing waves in air columns

It is possible to produce longitudinal stationary waves in air columns, which create the sounds associated with wind instruments. Blowing over the hole of a flute or the reed of a saxophone produces vibrations that correspond to a range of frequencies that create sound waves in the tube.

Most musical wind instruments can be simplified as long cylindrical air tubes that can be either open at both ends or open at one end and closed at the other. Blowing across a reed or opening has the effect of sending a pressure sound wave down the cylindrical tube and causing a reflected sound wave to interfere with the incident sound wave, producing a standing wave in the air column. The length of the tube will determine the frequency of the sounds that will resonate.

- At the closed end of a pipe, the reflected wave is 180° out of phase with the original wave (phase change). The closed end will not allow longitudinal motion in the air. This produces a node in the standing wave.
- At the open end of a pipe, the reflected wave is in phase with the original wave. This produces an antinode in the standing wave.

A series of standing wave patterns produced in a musical instrument open at both ends is shown in Figure 9.7.2. Nodes are indicated with the letter N, and antinodes are shown with the letter A. These wave patterns will be examined in more detail in Chapter 10.

Standing waves can also form from the superposition of sound waves, when they are reflected at the walls of a room. The reflected waves interfere with the incident waves, producing patterns of constructive and destructive interference. This leads to a standing wave. At the surface of a wall, air particles do not have room to move, so an air–displacement node occurs. The bunching up of particles near the surface of the wall creates a pressure antinode, which is a region of greater pressure. Therefore the interference pattern for a pressure standing wave is a maximum or antinode at the surface of the wall and a node at the centre of the room.

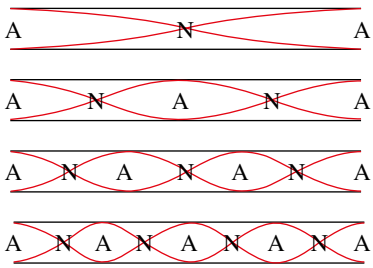


FIGURE 9.7.2 A series of standing wave patterns for a long cylindrical tube open at both ends

The two standing waves shown in Figure 9.7.3 are the longest wavelength standing waves in a room for a sound wave. The diagram on the left shows the air-pressure standing wave. The diagram on the right shows the air-displacement standing wave. Note that the pressure wave has a node where the displacement wave has an antinode, and vice versa. Both diagrams represent the standing wave for a note produced in the room.

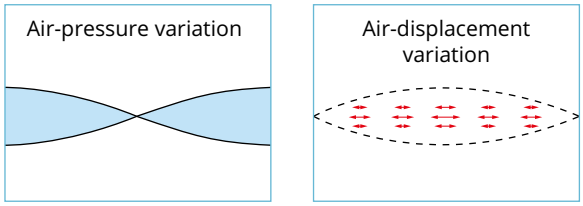


FIGURE 9.7.3 Air-pressure and air-displacement variation for a standing sound wave in a room

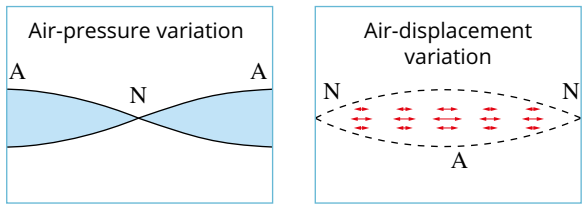
From this, the relationship between the room's dimensions and the wavelength of the longest wavelength standing wave can be found. The length of the room is equal to one-half of a wavelength for this standing wave pattern. Therefore the longest wavelength standing wave in a room is twice the room's length.

Worked example 9.7.2

WAVELENGTHS OF STANDING WAVES

The longest wavelength standing wave forms in a room that is 10.0 m across.

a Draw a diagram showing the air-pressure standing wave and the air-displacement standing wave. Label the nodes and antinodes.

Thinking	Working
Air particles do not have room to move at the surface of a wall. Therefore an air-displacement node occurs here. The bunching up of particles near the surface of the wall creates a greater region of pressure. Therefore a pressure antinode occurs here.	

b Calculate the maximum wavelength of the standing wave.

Thinking	Working
For a standing wave, the distance between two successive nodes is equal to half a wavelength.	$10.0\,\text{m} = \frac{\lambda}{2}$ $\lambda = 2 \times 10.0$ $= 20.0\,\text{m}$

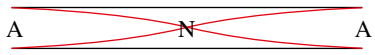
➤ Try yourself 9.7.2

WAVELENGTHS OF STANDING WAVES

A musical wind instrument that is open at both ends forms the standing wave shown in the diagram below. Nodes are indicated with the letter N, and antinodes are shown with the letter A.

a Determine whether this is an air-displacement or a pressure standing wave pattern.

b If the instrument is 20.0 cm long, calculate the maximum wavelength of the standing wave.



9.7 Review

SUMMARY

- Standing or stationary waves occur as a result of the interference between two waves of equal amplitude and frequency travelling in opposite directions.
- Points on a standing wave that remain still are called nodes.
- Points of maximum amplitude on a standing wave are called antinodes.
- The net transfer of energy in a standing wave is zero, unlike travelling waves.

KEY QUESTIONS

Retrieval

1 Recall how a standing wave is produced in a rope or string that is attached or fixed at the other end.

2 Recall the boundary conditions for an air-displacement standing wave in an air column. State where nodes and antinodes for air displacement will occur.

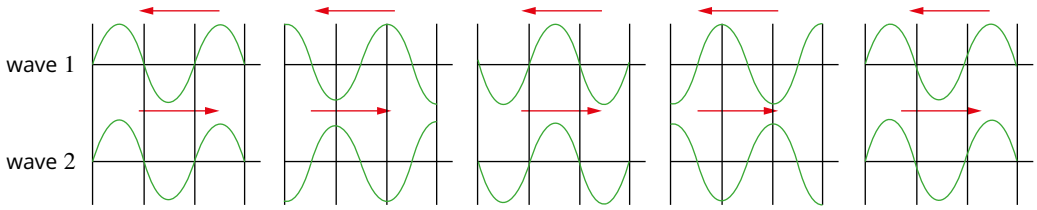
Comprehension

3 A transverse standing wave is produced on a rope. Explain whether the standing wave is actually standing still.

4 Explain the formation of nodes and antinodes on a standing wave.

5 Two identical waves moving in opposite directions are shown below at five different time intervals. The first time interval is $t = 0$ seconds and the fifth time interval is $t = T$ seconds. The waves are at a fixed location.

Discuss the resultant wave pattern formed for the five time intervals, in terms of constructive and destructive interference.



Analysis

6 Compare the properties of a travelling wave and a standing wave. A comparison of the amplitudes and energy transfer need to be clearly stated.

7 For each time interval in Question 5, draw the resultant standing wave pattern below wave 1 and wave 2.

Chapter review

09

KEY TERMS

absorbed
amplitude
angle of incidence
angle of reflection
antinodes
aperture
apparent depth
compression
constructive interference
crest
destructive interference
diffraction
diffuse reflection
dissipate
frequency
Huygens' principle
image
interference
incident ray
intensity
law of reflection
longitudinal wave
mechanical waves
medium
nodes
normal
object
particles
path difference
period
phase
phase change
plane wave
principle of superposition
propagation
pulse
P-wave
rarefaction
ray
Rayleigh wave
real depth
real position
reflection
refraction
resolution
resonance
resonant frequency
sinusoidal oscillation
standing waves
surface waves
S-wave
superposition
thermal inversion
torsional wave
transmitted
transverse wave
travelling wave
trough
tsunami
wavefront
wavelength

KEY QUESTIONS

Retrieval

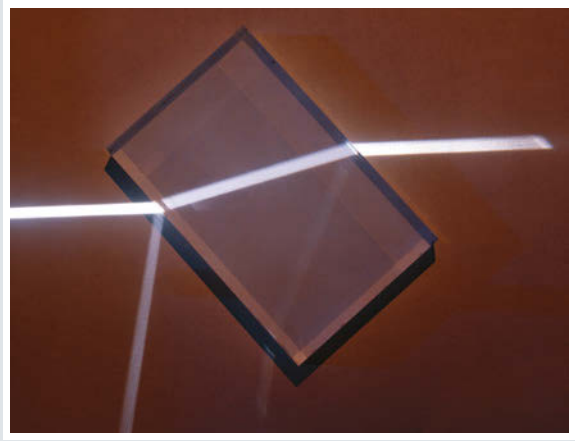
1 Describe the difference between a pulse and a travelling wave.

2 State which of the following three waves is not a mechanical wave: sound waves, water waves, light waves. Give a reason for your response.

3 **a** A pulse is sent along a rope that is fixed at one end. Recall what happens to the pulse when it is reflected at the fixed end of the rope.

b A pulse is sent along a rope that is open at one end. Describe what happens to the pulse when it is reflected at the open end of the rope.

4 Name the wave phenomenon the diagram below demonstrates.



Comprehension

5 You are watching the ripples on a pond after a stone has been dropped into it. Describe how the particles move on the surface of the water.

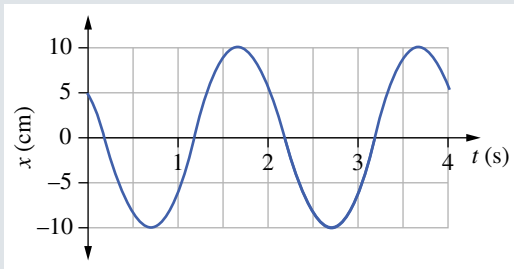
6 State and describe the similarities and differences between a transverse and a longitudinal wave.

7 Classify each of the waves listed below as either a transverse wave or longitudinal wave:
light waves, sound waves, seismic P-waves, seismic S-waves, vibration of a stringed instrument, ripples in a pond, tsunami waves.

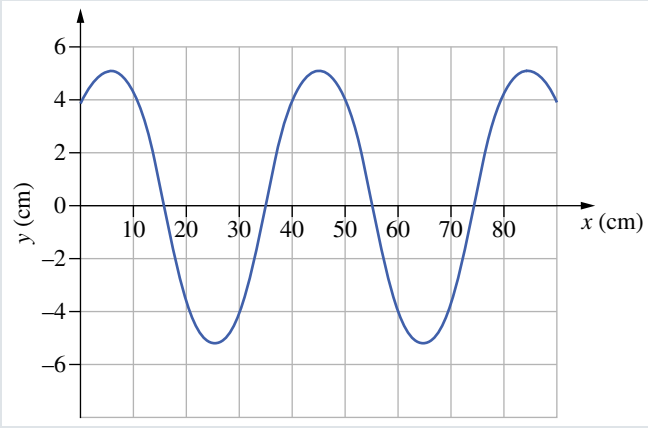
8 **a** Draw a transverse wave and label the crest, trough, amplitude and wavelength.

b Draw a longitudinal (compression) wave and label a compression, a rarefaction and the wavelength.

9 The displacement versus time graph below shows the variation of the displacement of a specific point on a wave with time. Identify which of the following wave characteristics can be determined from this type of graph: amplitude, frequency, period, wavelength, wave speed. Clearly state the values of these wave characteristics.



10 The displacement (y) versus position (x) graph shown below indicates the disturbance of any point on the rope at a specific moment in time. Identify which of the following wave characteristics can be determined from this type of graph: amplitude, frequency, period, wavelength, wave speed. Clearly state the values of these wave characteristics.



11 When sunlight shines on a house window, its energy can be transmitted, reflected or absorbed. Show the connection between each process and a statement below.

a The room inside the house is illuminated.

b You can see some of the sunlight from outside the house.

c The window glass would start to warm up.

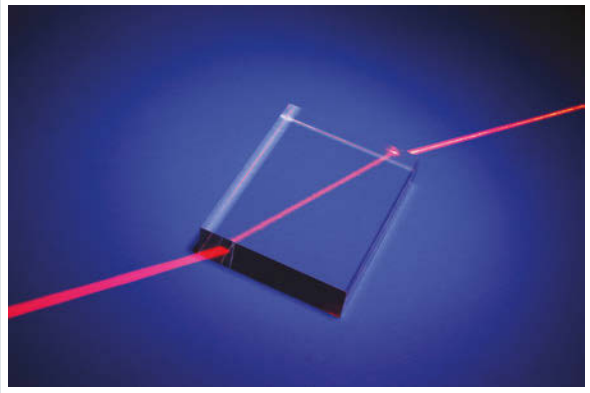
12 A person is standing in front of a mirror combing their hair. They notice that the image they are looking at is exactly the same distance behind the mirror as they are in front of the mirror. Explain the position of the apparent image, called the apparent position, using the wave model of light.

13 A light ray travelling in air strikes a glass boundary at an angle such that the angle between the light ray and the glass boundary is 90°.

a Explain what happens to the light ray as it passes into the glass, using the mechanical wave model of light. Explain whether the ray refracts.

b Determine whether the frequency of the light ray changes in the glass medium.

14 In the diagram shown, a light ray is travelling from medium 1 (air) into medium 2 (the glass prism). The light ray can be seen to change direction. Discuss why the light ray changes direction when it passes into medium 2.



15 A person is looking down at a fish below the surface of the water. Select the most correct statement regarding the apparent position and the real position of the fish.

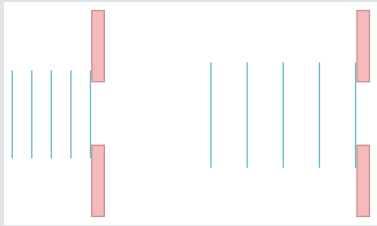
A The real position and the apparent position are identical, as the reflected light from the water surface and the incident light make the same angle with the water's surface.

B The apparent position of the fish would be lower and closer than the real position.

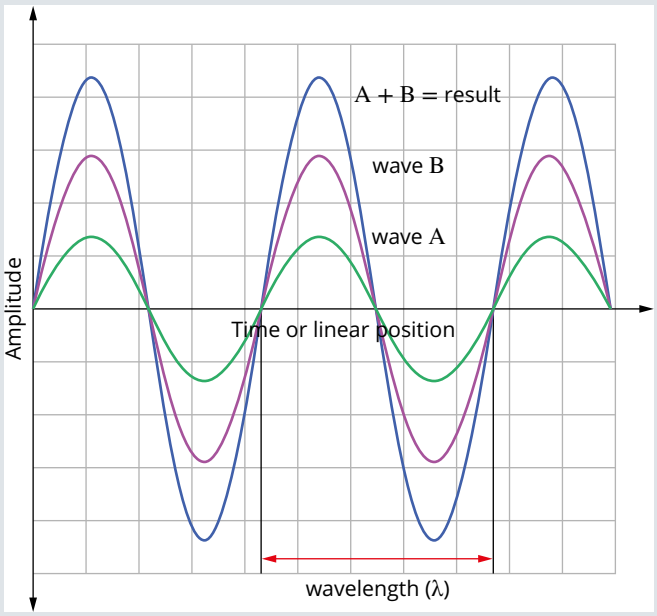
C The real position would be lower in the water than the apparent position.

D The apparent position would be lower and further than the real position of the fish.

16 In each of the two diagrams below, wavefronts are travelling towards a slit of a particular width. Draw the diffraction wave pattern after the waves have passed through the slits.

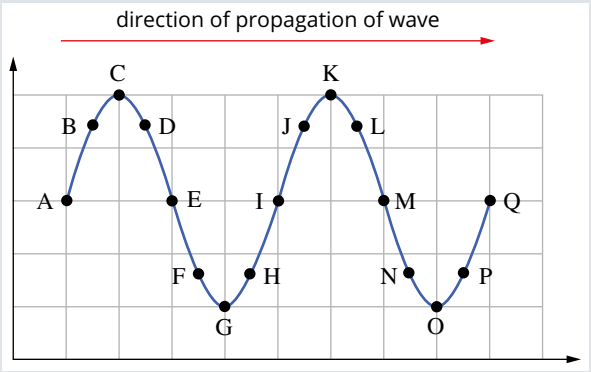


17 The diagram below shows the amplitude of wave A and wave B at a particular time (or linear position). The resultant wave pattern shows the combination of waves A + B. Name the principle and comment on the type of interference pattern this shows.
If one of the waves (A or B) is shifted 180° right or left, explain what would happen to the resultant wave pattern, and describe the type of interference pattern produced.



Analysis

18 A transverse wave is moving from the left to the right of the page. Determine the directions in which the particles B, D, F and K are moving at the moment in time shown on the graph.



19 A mechanical wave vibrator attached to a string operates at a frequency of 50.0 Hz. If the wave crests formed on the string are 5.0 cm apart, determine the speed of the waves in the string (in $m\,s^{-1}$).

20 Assume the speed of sound in water is approximately $1500\,m\,s^{-1}$ and the speed of sound in air is $340\,m\,s^{-1}$. If the frequency of a sound wave is 350 Hz, calculate the wavelength of this sound wave when it is transmitted in:

a water

b air.

21 A surfer sitting on a surfboard and bobbing up and down as water waves pass by counts 5 wave crests passing by in exactly 1 minute. He is on a crest when he starts counting. Use this information to determine:

a the period of these water waves, in seconds

b the frequency of the water waves in hertz.

22 Green light of frequency 5.66×10^{14} Hz is incident on a narrow slit. Determine the slit width in mm that is required for the green light to diffract. The speed of light is air is approximately $3.00 \times 10^{8}\,m\,s^{-1}$.

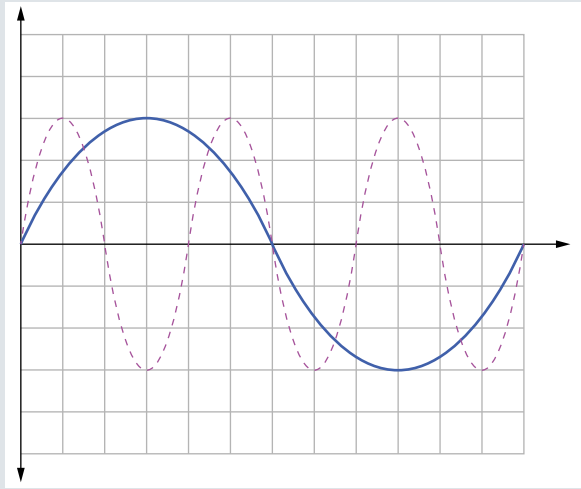
A 0.001 00 mm

B 0.005 30 mm

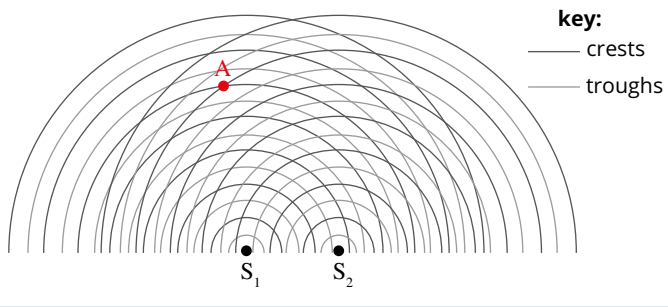
C 0.000 100 mm

D 0.000 530 mm

23 Two wave patterns are shown in the diagram below, the solid line represents one wave and the dashed line represents the second wave. Use the principle of superposition to draw the resultant wave pattern from a combination of the two waves.



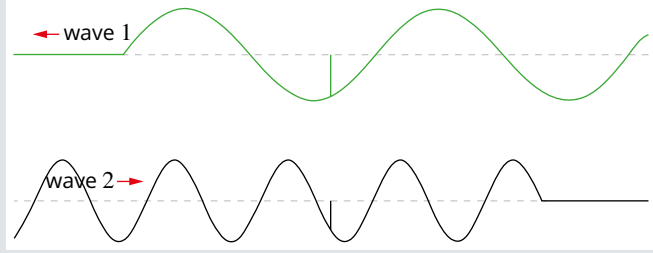
24 Two sources S_1 and S_2 are producing waves in phase with identical wavelengths. The wavefronts of both sources are shown and a key is provided for the crests and the troughs. The diagram shows a position marked in red and labelled A. Position A is a certain number of wavelengths from both sources. Determine whether destructive or constructive interference occurs between the two sources at the position A. Show all working.



25 Explain the formation of standing waves (in terms of superposition, constructive and destructive interference, and nodes and antinodes).

Knowledge utilisation

26 Two waves are travelling in different directions as shown in the figure below. At an instant in time these two waves produce a resultant wave due to the principle of superposition. Draw the resultant wave for the two waves shown at this instant.



27 Two speakers are mounted on a wall and are separated by 5.0 m. An observer is standing 30.0 m from the wall, directly in front of one of the speakers. Both speakers are driven by the same source, so the sound waves emitted from the speakers are in phase. Assume the speed of sound in air is 340 m s^{-1}. Assess whether the observer hears a quiet, loud or intermediate sound, if the speakers are driven at 850 Hz.

CHAPTER

10 Sound

Sound is an important manifestation of waves. Sound waves allow you to speak and hear, to create language and make music. Sound waves are used to investigate objects that you can't see, using technologies such as ultrasound and radar. The physics of waves allows us to determine the length of a violin string to create a certain note, or the location of keys on wind instruments to create a scale of notes. Acoustics is the science of sound including ultrasound and infrasound.

Syllabus subject matter

Topic 2 • Waves

WAVE PROPERTIES

- describe examples of transverse and longitudinal waves, such as sound, seismic waves and vibrations of stringed instruments
- solve problems involving the wavelength, frequency, period and velocity of a wave.

SOUND

- solve problems involving standing wave formation in pipes open at both ends, closed at one end, and on stretched strings
- define the concept of *resonance* in a mechanical system
- define the concept of *natural frequency*
- identify that energy is transferred efficiently in resonating systems.

SCIENCE AS A HUMAN ENDEAVOUR

- Noise pollution and acoustic design

Physics 2019 v1.2 General Senior Syllabus
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10.1 Sound waves

BY THE END OF THIS MODULE, YOU SHOULD BE ABLE TO:

- describe sound as a longitudinal, mechanical wave
- understand why the speed of sound is different in different materials and at different temperatures
- recognise that the sounds you hear are superpositions of sounds at different frequencies
- recognise that the lowest frequency produced by a string or pipe is known as the fundamental frequency and the higher frequencies are named as harmonics.

Most of us have seen science fiction movies that include epic space battles, explosions and sounds that can be heard across the galactic battlefield. In reality, sound is a **mechanical wave** that requires a **medium** to propagate through, which means that sound can't travel across the vast emptiness of the vacuum of space and battles would be eerily silent.

MODEL OF A SOUND WAVE

Sound is a mechanical wave. Mechanical waves transfer energy through vibrations in a medium, as seen in Module 9.1. You would usually experience sound moving through air. Sound cannot travel in vacuums and across space because there are no materials to transfer the energy of the sound wave.

Sound waves are modelled as a longitudinal wave with particles vibrating in the same dimension as the energy transfer (Module 9.2). Sound waves create compressions and rarefactions of the air molecules through which the wave travels (Figure 10.1.1). Recall that compressions are where the air molecules will come together and rarefactions are where the air molecules are spread apart.

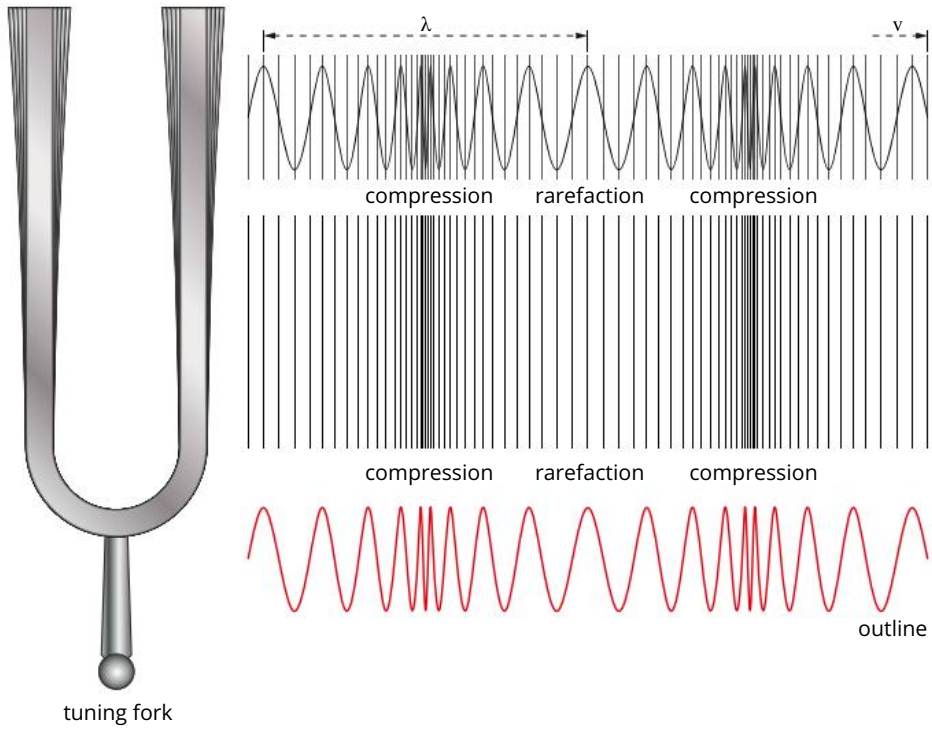


FIGURE 10.1.1 Sound is a longitudinal wave with compressions and rarefactions.

Sound waves are often drawn as transverse waves because the changes in wavelength and frequency are clearly visible, as shown in Figure 10.1.2.

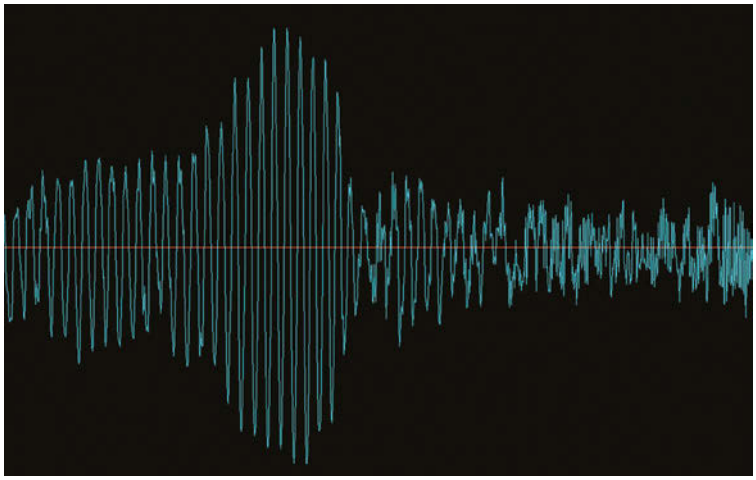


FIGURE 10.1.2 A whale song represented as a transverse wave. Changes in frequency and amplitude are more apparent when waves are represented in a transverse form.

SPEED OF SOUND

Sound is a mechanical wave, so the speed at which the wave travels depends on the material in which the sound wave travels. The stiffer the structure of the material, the faster the sound will travel. This stiffness is the **elastic modulus** of a material.

To understand why the stiffness of a material will affect the speed of sound, consider a model of matter as a series of balls and springs. The balls are the atoms and the springs are the bonds between them. The more spongy a spring, the slower energy travels through the spring; the stiffer the springs, the faster the energy travels through the ball–spring system. As the bonds between atoms become stiffer, the faster sound will travel through a material.

In different states of matter sound also travels at different speeds due to the matter's elastic modulus. Gases and liquids are more spongy than a solid, so will have a lower elastic modulus than a solid and a slower speed of sound. This means solids generally have the fastest speeds of sound, then liquids, then gases. It is easier to transfer energy between atoms in a solid than between the atoms in a gas. To see some examples of this increase in speed see Table 10.1.1.

TABLE 10.1.1 Speed of sound in some common materials

Material	Speed of sound (at 20°C) ($m s^{-1}$)
air	343
helium	927
methanol	1 143
fat	1 450
water	1 483
muscle	1 580
rubber	1 600
gold	3 240
bone	4 080
iron	5 130
Pyrex glass	5 640
diamond	12 000

FIGURE 10.1.3 An ultrasound being performed on a patient's hand and wrist.

FIGURE 10.1.4 Ultrasonic testing of gas cylinders. The technician is holding a transducer against the side of a cylinder. The transducer passes high-frequency sound waves through the metal and picks up any echoes. This allows the technician to assess the thickness of the cylinder wall and to check for any defects.

The speed of sound is used in ultrasonic imaging and testing. Ultrasound is often used to see inside the human body (Figure 10.1.3). Ultrasound can also be used to see inside machinery, to measure thicknesses and to detect faults in equipment (Figure 10.1.4).

To understand the effect of the speed of sound, consider what your voice sounds like if you breathe in some helium or balloon mix. (Be very careful if you try this!) What does your voice sound like? If you breathe in a gas more dense than air, your voice will sound lower.

The speed of sound in a material is also temperature dependent, as the temperature can affect the stiffness or elastic modulus of a material, especially for a gas. The temperature increase raises the stiffness of a material, increasing the speed of sound. Therefore as temperature increases, so does the speed of sound. Some examples of this temperature dependency can be seen in Table 10.1.2.

TABLE 10.1.2 Speed of sound in some common materials at different temperatures

Material	Temperature (K)	Speed of sound ($m\,s^{-1}$)
air	233	306
air	273	331
air	293	343
air	313	355
water	273	1403
water	293	1483
water	313	1526

$K = °C + 273$

The speed of sound waves can be linked with the frequency and wavelength of sound using the wave equation, allowing for the determination of the frequency or wavelength of the sound. Recall the wave equation from Chapter 9, which gives the relationship between frequency, velocity and wavelength.

$$v = f\lambda$$

where

v is speed ($m\,s^{-1}$)

f is frequency (Hz)

λ is wavelength (m)

Worked example 10.1.1

REVISITING THE WAVE EQUATION

A sound wave is travelling through water at 293 K. The sound wave has a frequency of 620 Hz. Calculate the wavelength, λ, of the sound wave.

Thinking	Working
Find the speed of sound in water at 293 K in Table 10.1.2: $v = 1483\,m\,s^{-1}$. As both v and f are known, the wavelength, λ, can be found. Rewrite the wave equation in terms of λ.	$v = f\lambda$ $\lambda = \frac{v}{f}$
Substitute the known values and solve.	$= \frac{1483}{620}$ $= 2.4\,m$

➤ Try yourself 10.1.1

REVISITING THE WAVE EQUATION

A sound wave is travelling through helium at 293 K and has a wavelength of 0.76 m. Calculate the frequency of the sound wave.

The speed of sound in a material depends on the elasticity and the temperature of the material.

- The stiffer the material, the faster the speed of sound in the material.
- The higher the temperature of the medium, the faster the speed of sound in the material.

THE SOUND BARRIER

Many modern aircraft are able to travel at the speed of sound in the air. Some land-based vehicles can also travel as fast. When something travels faster than the speed of sound, it is said to have broken the sound barrier. Travelling faster than the speed of sound creates shockwaves, which create a 'sonic boom' (Figure 10.1.5).

FIGURE 10.1.5 A sonic boom. A cloud forms behind the aircraft as it breaks the sound barrier by travelling faster than the speed of sound.

HARMONICS

Most sounds you hear are not just one frequency of sound. Sounds are often a combination of different frequencies, which are called **harmonics** (Module 9.6). These sound waves undergo superposition to create the sound waves that you hear. Sound waves have different combinations of frequencies and this is why you can distinguish the sounds of different musical instruments. To separate these frequencies, the waves can be analysed using a mathematical technique known as a fast Fourier transform. This will show what frequencies have been combined to make the wave. Fast Fourier transforms can be performed on many data logging interfaces (Figure 10.1.6).

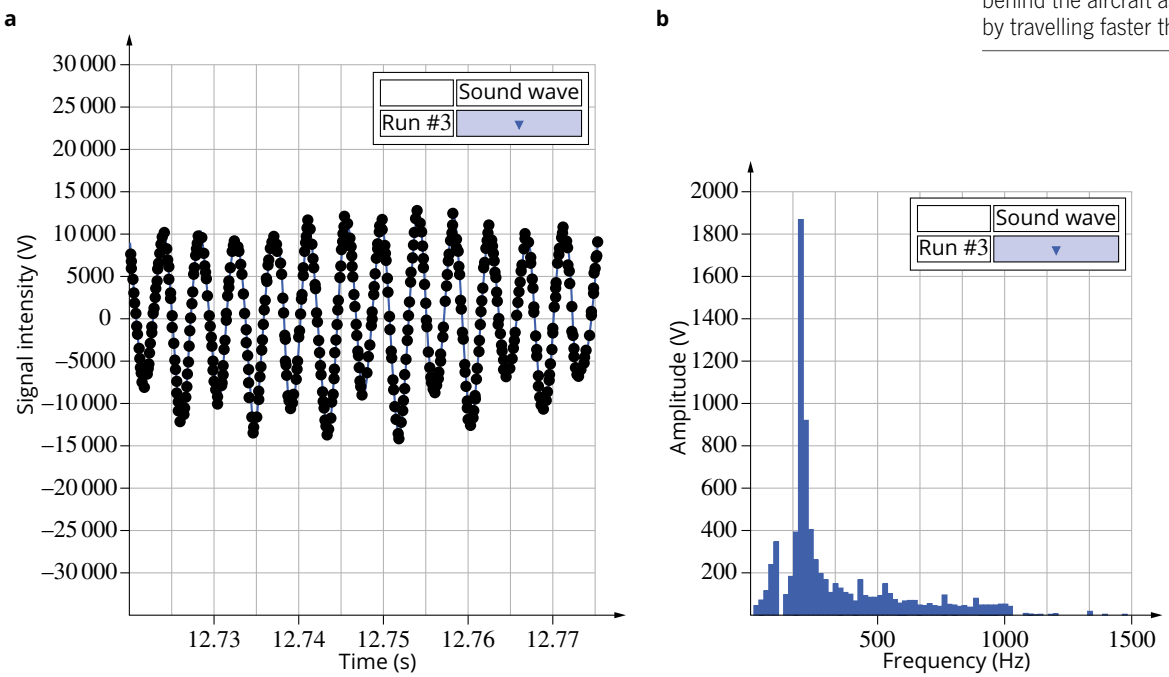


FIGURE 10.1.6 (a) A sound wave from a guitar. (b) The fast Fourier transforms of that sound wave showing what frequencies were combined to make that sound.

When producing sounds, many instruments actually create different harmonics (which will be explored in the following modules). The smallest or lowest of the frequencies for a given length of string or pipe is called the **fundamental** frequency or the first harmonic. The next frequency produced will be the second frequency or second harmonic, then the third frequency or the third harmonic and so on. Each of these frequencies produced is a multiple of the fundamental frequency.

10.1 Review

SUMMARY

- Sound waves are mechanical waves that require a medium to travel through.
- Sound waves are longitudinal waves.
- The speed of a sound wave depends on the medium the wave is travelling through and its temperature.
- The higher the temperature of a material, the faster sound can propagate through the material.
- The stiffer the material, the faster sound can propagate through it.
- Sounds often consist of a superposition of many sound waves of different frequencies.
- The lowest of these frequencies is known as the fundamental frequency or the first harmonic and all other waves produced by an instrument are a multiple of this fundamental frequency.
- The higher frequencies are named in increasing order harmonics (e.g. second harmonic, third harmonic).

KEY QUESTIONS

Retrieval

1 Draw a diagram of a sound wave, labelling a compression and a rarefaction.

2 Identify which of the materials has the fastest speed of sound.

A helium
B diamond
C water
D air at 20°C

3 State the name of the lowest frequency of an instrument.

Comprehension

4 Explain why sound cannot travel across a vacuum.

5 Explain why your voice sounds higher when you breathe in balloon gas (mostly helium). (Don't try this at home.)

6 Using the idea of harmonics, explain why it is possible to get a higher note on a wind instrument if you blow harder.

Analysis

7 A sound wave is travelling through iron and has a frequency of 400.0 Hz. Determine its wavelength.

8 A sound wave is travelling through water at 20°C. Determine how much faster it is compared to a wave travelling through air at the same temperature.

9 Sound waves generally travel faster in solids than in gases. Provide an explanation for this.

10 Sound is travelling through air at 343 $m\,s^{-1}$ with a wavelength of 0.78 m. Determine the period of the sound.

10.2 Strings

BY THE END OF THIS MODULE, YOU SHOULD BE ABLE TO:

- understand the creation of standing waves on a stretched string
- calculate the frequency and wavelength of the fundamental frequency and the harmonics generated by a stretched string fixed at both ends
- calculate the frequency and wavelength of the fundamental frequency and the harmonics generated by a stretched string fixed at one end.

Drawing a bow across a violin string causes the string to vibrate between the fixed bridge of the violin and the finger of the violinist (Figure 10.2.1). The simplest vibration will have maximum amplitude at the centre of the string, halfway between the bridge and the finger. This is a very simple example of a transverse standing wave.

FIGURE 10.2.1 Transverse standing waves can form along a violin string when the string is bowed by the violinist.

STANDING WAVES

Recall from Module 9.7 that standing waves are formed from the superposition of waves. They occur when two waves of the same amplitude and frequency are travelling in opposite directions towards each other in the same string. Usually, one wave is the reflection of the other. Standing waves are responsible for the wide variety of sounds associated with speech and music. A wave pulse is reflected back 180° out of phase when it reaches a fixed end, as discussed in Module 9.3. Crests are reflected as troughs and troughs are reflected as crests. For a continuous wave this can produce a standing wave for certain frequencies.

The nodes in a standing wave, where the waves have interfered destructively, are stationary. The antinodes of a standing wave, where the two waves have interfered constructively, also have a stationary point on the string, but they oscillate with the maximum amplitude. Nodes and antinodes in a standing wave remain in a fixed position for a particular frequency of vibration. Figure 10.2.2 illustrates a series of possible standing waves in a rope with both ends fixed, corresponding to three different frequencies. The distance between nodes is one-half of a wavelength. Assume that the tension in the rope is kept the same in all three standing waves.

- Figure 10.2.2a shows the lowest frequency of vibration, which produces a standing wave with one antinode in the centre of the rope. Note one-half of a wavelength is shown here, so the wavelength, λ, is twice the length of the string.
- Figure 10.2.2b shows waves produced at two times the original frequency. Note that one wavelength is shown here, so the wavelength, λ, is equal to the length of the string.
- Figure 10.2.2c shows waves produced at three times the original frequency. Note that one-and-a-half wavelengths are shown here, so the wavelength, λ, is two-thirds of the length of the string.

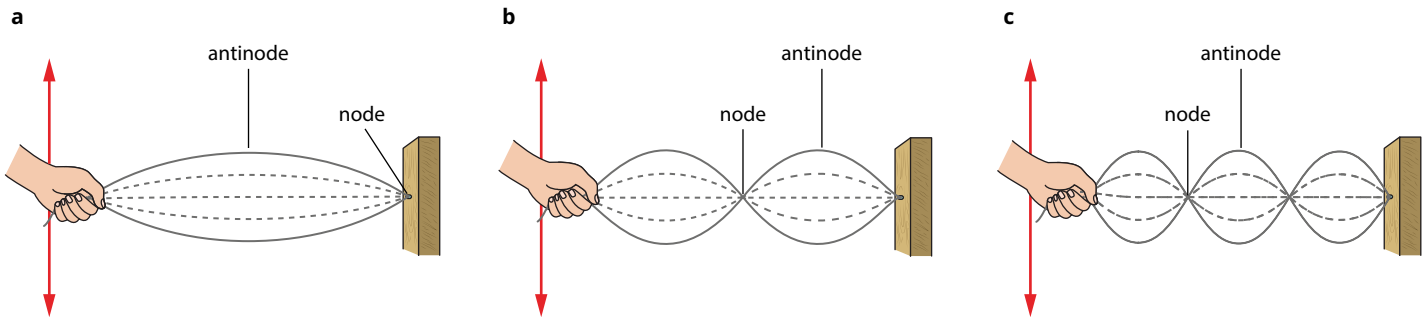


FIGURE 10.2.2 A rope vibrated at three different resonant frequencies, illustrating the standing waves produced at each frequency.

The rope could also vibrate at a frequency four times that of the original and so on. The frequencies at which standing waves are produced are called the resonant frequencies of the rope. It is important to note that the formation of a standing wave does not mean that the string or rope itself is stationary. It will continue to oscillate as further wave pulses travel up and down the rope. It is the relative position of the nodes and antinodes that remain unchanged. It is also important to note that standing waves are not a natural consequence of every wave reflection.

Standing waves are only produced by the superposition of two waves of equal amplitude and frequency, travelling in opposite directions. Standing waves are a result of resonance and occur only at the natural frequencies of vibration, or resonant frequencies, of the particular medium.

Harmonics and the fundamental frequency

The resonant frequencies produced in the complex vibrations of multiple standing waves are called harmonics. The lowest and simplest form of vibration has one antinode and is called the fundamental frequency (Figure 10.2.2a). Higher-level harmonics are called the second harmonic (Figure 10.2.2b) and third harmonic (Figure 10.2.2c) and so on.

The fundamental frequency usually has the greatest amplitude, so it has the greatest influence on the sound. The amplitude generally decreases for each subsequent harmonic. Usually all possible harmonics are produced in a string simultaneously, and the instrument and the air around it also vibrate to create the complex mixture of frequencies, which are heard as an instrumental note.

STRING FIXED AT BOTH ENDS

Instruments in the string family, in their most basic form, consist of a set of tensioned strings of different densities, fixed at both ends. The string family includes instruments such as the violin, viola, cello, double bass, guitar, ukulele, harp, zither and piano. A selection of some of string instruments can be seen in Figure 10.2.3. The instruments are plucked, bowed or struck to create vibrations in the form of standing waves in the strings. A standing wave, with the help of resonance with the body of the instrument, transfers this wave energy to the air, through which it travels to our ears for us to enjoy. Figure 10.2.4 is an example of a standing wave on a string.

FIGURE 10.2.3 A selection of string instruments. From the left, a violin, viola, cello and a double bass.

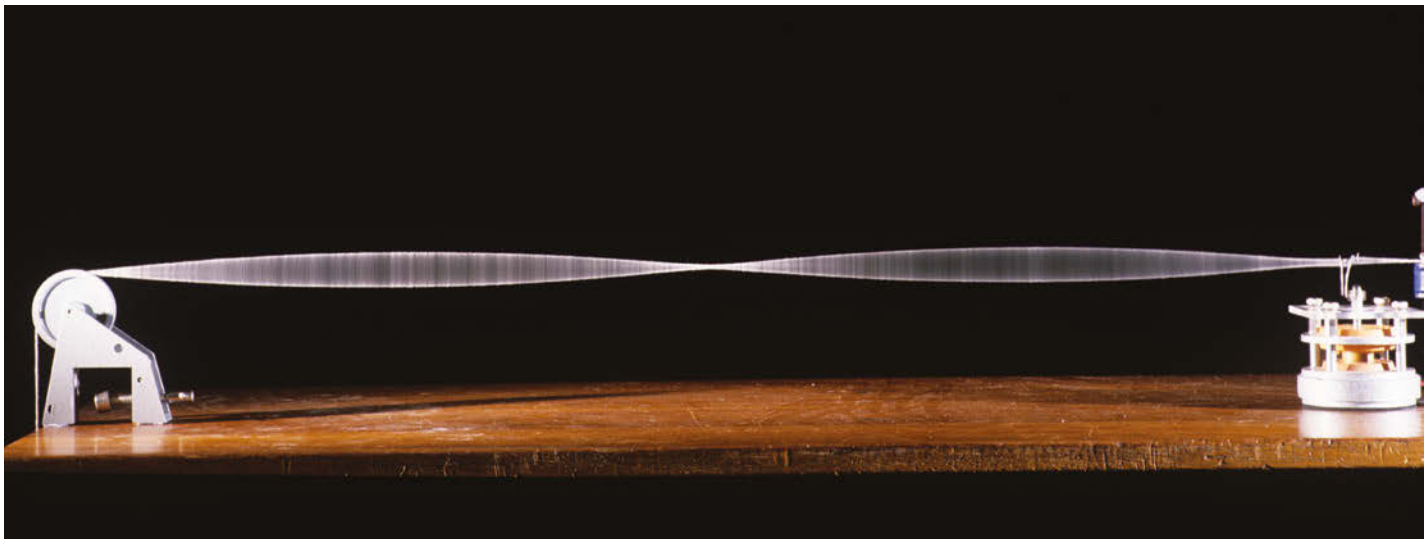


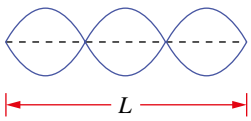
FIGURE 10.2.4 A standing wave on a vibrating string. Note the position of the nodes at each end and in the middle, with the antinodes in between the nodes. You can observe this in the laboratory using a standing wave generator.

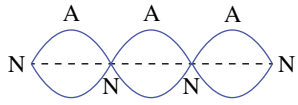
A standing wave, and its pattern of notes and antinodes, in a string fixed at both ends is examined in Worked example 10.2.1.

Worked example 10.2.1

STANDING WAVES

A standing wave pattern in a string fixed at both ends to a wall is shown in the diagram. The distance between the two fixed points on the wall is a length L.

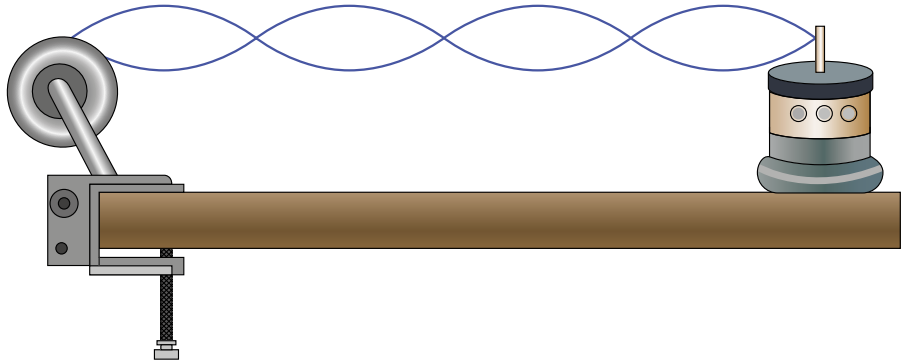


Thinking	Working
a Determine how many nodes and antinodes there are in the standing wave pattern.	
Nodes, N, are points of zero displacement. Antinodes, A, are points of maximum displacement.	This standing wave pattern has four nodes and three antinodes. 
b State the relationship between the length, L, and the wavelength, λ, for this standing wave.	
The distance between nodes is one-half of a wavelength. This standing wave diagram has three antinodes and four nodes. This corresponds to three one-half wavelengths.	$L = \frac{3\lambda}{2}$ or $\lambda = \frac{2L}{3}$

➤ Try yourself 10.2.1

STANDING WAVES

In the figure below a mechanical wave generator attached to a light string is vibrating and producing standing wave patterns in the string. The distance between the wave generator and the other end is 1.0 m. Label the nodes N and the antinodes A for this standing wave pattern, and then find the wavelength of the standing wave pattern.



A variety of waves can be created from the strings of a musical instrument. The waves travel along the string in both directions and reflect from the fixed ends. Most of these vibrations will interfere in a random fashion and die away. However, those corresponding to resonant frequencies of the string will form standing waves and remain.

In a musical instrument with a string fixed at both ends, the resonant frequencies or harmonics can be calculated from the relationship between the length of the string, L, and the wavelength, λ, in a standing wave.

The first harmonic, or fundamental frequency, has one antinode in the centre of the string:

$$\lambda = \frac{2L}{1} = 2L$$

The second harmonic will have two antinodes:

$$\lambda = \frac{2L}{2} = L$$

The third harmonic will have three antinodes:

$$\lambda = \frac{2L}{3}$$

And so, in general, for any harmonic:

$$\lambda = \frac{2L}{n} \text{ and } L = \frac{n\lambda}{2}$$

The relationship between wavelength, λ, and string length, L, is shown in Figure 10.2.5.

For a string fixed at both ends:

$\lambda = \frac{2L}{n}$ and $L = \frac{n\lambda}{2}$

where

λ is the wavelength (m)

L is the length of the string (m)

n is the number of the harmonic, which is also the number of antinodes (1, 2, 3, 4, …).

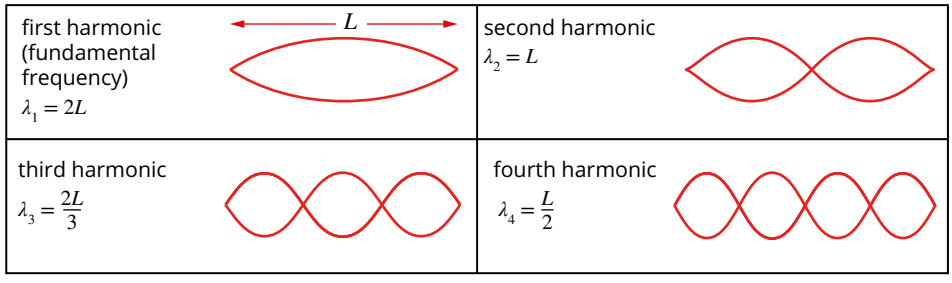


FIGURE 10.2.5 The first four resonant frequencies, or harmonics, in a stretched string fixed at both ends. The ends are fixed so they will always be nodal points.

The wave equation $v = f\lambda$ gives the relationship between frequency, velocity and string length.

For the first harmonic, or fundamental frequency ($\lambda = 2L$):

$$v = f\lambda \text{ and so } f = \frac{v}{\lambda} = \frac{v}{2L}$$

For the second harmonic ($\lambda = L$):

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

For the third harmonic $\lambda = \frac{2L}{3}$:

$$f = \frac{v}{\lambda} = \frac{v}{1} \times \frac{3}{2L} = \frac{3v}{2L}$$

And so, in general, for a string fixed at both ends:

$$f = \frac{nv}{2L}$$

> **For a string fixed at both ends:**
> $f = \frac{nv}{2L}$
> where
> f is the frequency of the wave (Hz)
> n is the number of the harmonic, which is also the number of antinodes (1, 2, 3, 4, …)
> v is the velocity of the wave ($m\,s^{-1}$)
> L is the length of the string (m).

Worked example 10.2.2

FUNDAMENTAL FREQUENCY FOR STRINGS FIXED AT BOTH ENDS

A violin string, fixed at both ends, has a length of 22 cm. It is vibrating at its fundamental mode of vibration at a frequency of 880 Hz.

a Determine the wavelength of the fundamental frequency.

Thinking	Working
Identify the length of the string, L, in metres and the harmonic number, n.	$L = 22\,cm = 0.22\,m$ $n = 1$
Recall that for any frequency $\lambda = \frac{2L}{n}$. Substitute the known values and solve for λ.	$\lambda = \frac{2L}{n}$ $= \frac{2 \times 0.22}{1}$ $= 0.44\ m$

b Determine the wavelength of the second harmonic.

Thinking	Working
Identify the length of the string, L, in metres and the harmonic number, n.	$L = 22\,cm = 0.22\,m$ $n = 2$
Recall that for any frequency $\lambda = \frac{2L}{n}$. Substitute the known values and solve for λ.	$\lambda = \frac{2L}{n}$ $= \frac{2 \times 0.22}{2}$ $= 0.22\ m$

> **You may see the equations for the wavelength and frequency of waves in a string written with L as the subject. For example,**
> $\lambda = \frac{2L}{n}$
> may be written as
> $L = \frac{n\lambda}{2}$
> By rearranging one of these, you can see that the two forms of the equation are equivalent. Use the form that is most helpful for you in answering questions. You will usually be asked to find the wavelength or frequency of a wave or harmonic, so you would usually use an equation with λ or f as the subject.

➤ Try yourself 10.2.2

FUNDAMENTAL FREQUENCY FOR STRINGS FIXED AT BOTH ENDS

A standing wave in a string is found to have a wavelength of 0.50 m for the fundamental frequency of vibration. Assume that the tension of the string is not changed and that the string is fixed at both ends.

a Determine the length of the string.

b Determine the wavelength of the third harmonic.

STRING FIXED AT ONLY ONE END

A flexible string fixed at one end cannot create enough tension for the efficient energy transfer required to create a sound. However, in musical instruments this can be achieved by using stiff materials such as metal. An example of an instrument

FIGURE 10.2.6 A kalimba or African thumb piano. The metal tines are fixed at one end and free to move at the other end as a string with one fixed end.

that functions like a string fixed at only one end is the kalimba or thumb piano (Figure 10.2.6). The stiff metal strings, called tines, are fixed at one end but free to move at the other end. This creates a system of a string with only one fixed end, which makes a sound when plucked.

The standing waves that form in a string with only one fixed end are shown in Figure 10.2.7. Note that only odd-numbered harmonics are possible, because only these satisfy the condition of having a node at the fixed end and an antinode at the free end. A node will always form at the fixed end (the left-hand side of Figure 10.2.7) and an antinode will always form at the free end (the right-hand side of Figure 10.2.7) of the string.

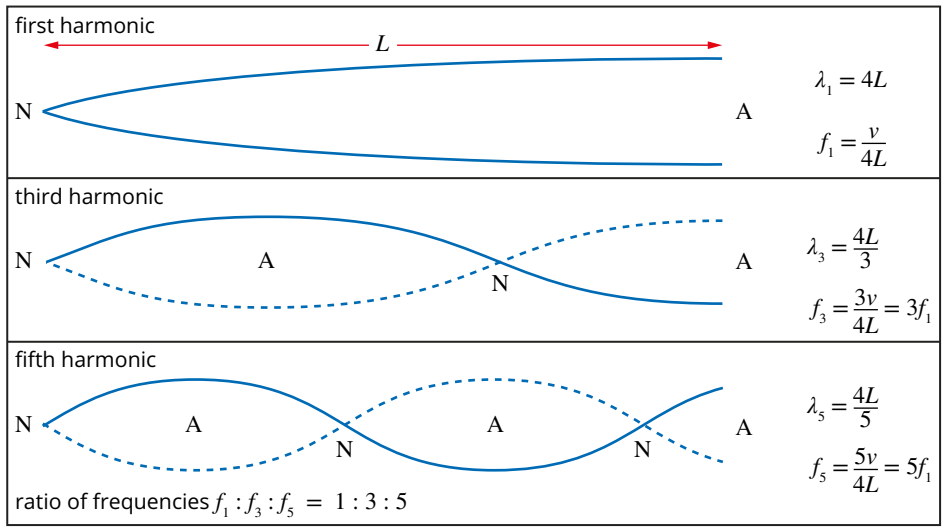


FIGURE 10.2.7 The lower harmonics for a string that is fixed at one end (the left-hand side) and free to move at the other end (the right-hand side).

For a string fixed at only one end:

$\lambda = \frac{4L}{n}$ and $L = \frac{n\lambda}{4}$

where

λ is the wavelength (m)

L is the length of the string (m)

n is the number of the harmonic, odd-number integers only (1, 3, 5, …).

In general, for a string fixed at only one end, the frequency in terms of velocity is:

$f = \frac{nv}{4L}$

where

f is the frequency of the wave (Hz)

n is the number of the harmonic (1, 3, 5, …)

v is the velocity of the wave ($m\,s^{-1}$)

L is the length of the string (m).

The first harmonic, or fundamental frequency, will have a wavelength four times the length of the string:

$$\lambda = 4 \times L$$

The next simplest harmonic that can form will have a wavelength:

$$\lambda = \frac{4 \times L}{3}$$

The next harmonic that can form will have a wavelength:

$$\lambda = \frac{4 \times L}{5}$$

And so, in general, for a string fixed at one end:

$$\lambda = \frac{4L}{n} \text{ and } L = \frac{n\lambda}{4}$$

Substituting the wave equation $v = f\lambda$ into the equation for a string fixed at only one end gives the frequency in terms of velocity:

$$\lambda = \frac{4L}{n}$$
$$\frac{v}{f} = \frac{4L}{n}$$
$$f = \frac{nv}{4L}$$

Odd-numbered harmonics (1, 3, 5, ...) will form because the conditions necessary for a standing wave to form are only met under the circumstances where there is an antinode at the free end and a node at the fixed end. The ratio of the wavelengths of the harmonics will be 1 : 3 : 5 and so on. This means the wavelength of the third harmonic is $\frac{1}{3}$ the length of the fundamental frequency (the first harmonic), the fifth harmonic is $\frac{1}{5}$ the length of the fundamental frequency and so on.

Even-numbered harmonics (2, 4, 6, …) will not form. The equations for a standing wave on a string fixed at one end can be modified to incorporate this. The modified formula is:

$$\lambda = \frac{4L}{2n-1}$$

and $$L = \frac{(2n-1)\lambda}{4}$$

Note that for this equation, n is defined slightly differently from that for strings fixed at both ends. For this equation, n is the next harmonic in the sequence, not the harmonic number.

Although it won't be considered in this unit, it should be noted that the resonant frequencies of a string correspond to a particular tension and mass per unit length. Tightening or loosening the string will change the wavelengths and resonant frequencies for that string (i.e. the instrument will need tuning by adjusting the tension of the string). Heavier strings of a particular length will have different resonant frequencies than lighter strings of the same length and tension.

Worked example 10.2.3

FUNDAMENTAL FREQUENCY FOR STRINGS FIXED AT ONE END

A thumb piano is a musical instrument from Africa. It consists of a wooden board with several metal tines attached, which are struck with the thumb to make a sound. It can be modelled as a string with one fixed end.
A thumb piano tine, fixed at one end, has a length of 5.0 cm.

a Calculate the wavelength of the fundamental frequency.

Thinking	Working
Identify the length of the string, L, in metres and the harmonic number, n.	$L = 5.0\,\text{cm} = 0.05\,\text{m}$ $n = 1$
Recall that for any frequency, for a string fixed at only one end $\lambda = \frac{4L}{n}$. Substitute the values from the question and solve for λ.	$\lambda = \frac{4L}{n}$ $= \frac{4 \times 0.05}{1}$ $= 0.20\,\text{m}$

b Calculate the wavelength of the third harmonic.

Thinking	Working
Identify the length of the string, L, in metres and the harmonic number, n.	$L = 5.0\,\text{cm} = 0.05\,\text{m}$ $n = 3$
Recall that for any frequency $\lambda = \frac{4L}{n}$. Substitute the values from the question and solve for λ.	$\lambda = \frac{4L}{n}$ $= \frac{4 \times 0.05}{3}$ $= 0.067\,\text{m}$

➤ Try yourself 10.2.3

FUNDAMENTAL FREQUENCY FOR STRINGS FIXED AT ONE END

A standing wave in a tine on a thumb piano is found to have a wavelength of 0.080 m for the fundamental frequency of vibration.

a Determine the length of the tine.

b Determine the wavelength of the fifth harmonic.

The discussion in this section has only included two-dimensional standing waves, but standing waves may also form in three dimensions, such as in a section of Earth's crust. Standing waves will form as a result of resonance in any waveform.

10.2 Review

SUMMARY

- Standing or stationary waves occur as a result of resonance at the natural frequency of vibration.
- Points on a standing wave that remain still are called nodes.
- Points of maximum amplitude on a standing wave are called antinodes.
- The standing wave frequencies are referred to as harmonics. The simplest mode is referred to as the fundamental frequency.
- In a string fixed at both ends, the wavelength of the standing waves corresponding to the various harmonics is:

$$\lambda = \frac{2L}{n}$$

and the frequency is:

$$f = \frac{nv}{2L}$$

Length of string is:

$$L = \frac{n\lambda}{2}$$

All harmonics may be present.

- In a string fixed at only one end, the wavelength of the standing waves corresponding to the various harmonics is:

$$\lambda = \frac{4L}{n}$$

and the frequency is:

$$f = \frac{nv}{4L}$$

Length of string is:

$$L = \frac{n\lambda}{4}$$

Only odd-numbered harmonics may be present.

- A modified version of the equation for the wavelength for a string fixed at one end, taking into account that only odd-numbered harmonics are present, is:

$$\lambda = \frac{4L}{2n-1}$$

where n is the next harmonic in the sequence.

Length of string is:

$$L = \frac{(2n-1)\lambda}{4}$$

KEY QUESTIONS

Retrieval

1 A transverse standing wave is produced using a rope. State whether the standing wave actually is standing still. Explain your answer.

2 Describe how superposition and interference are related to the formation of standing waves in a stretched slinky spring.

Comprehension

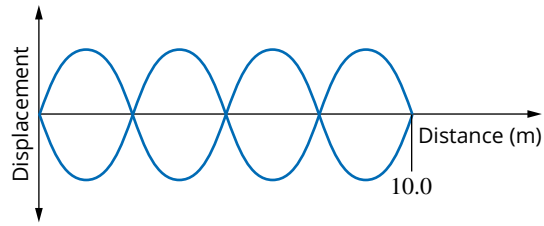
3 A standing wave is produced in a rope fixed at one end by vibrating the rope with five times the frequency that produces the fundamental or first harmonic. Discuss how much larger or smaller the wavelength of this standing wave is compared to that of the fundamental or first harmonic.

Analysis

4 Calculate the length of a string fixed at both ends when the wavelength of the fourth harmonic is 0.75 m.

5 Calculate the wavelength of the fundamental mode of a standing wave on a string 0.40 m long and fixed at one end.

6 A standing wave pattern in a string is shown over a distance of 10.0 m. Calculate the length of the string that would generate the first harmonic if a standing wave of the same wavelength as the pattern shown in the diagram below was produced.



7 The fundamental frequency of a violin string is 350 Hz and the velocity of the waves along it is 387 m s^{-1}. Calculate the wavelength of the new fundamental frequency when a finger is pressed to shorten the string to $\frac{2}{3}$ its original length.

The following information relates to questions **8**–**10**.

A metal string (at constant tension) of length 50.0 cm is plucked, creating a wave pulse. The speed of the transverse wave created is 300.0 m s^{-1}. Both ends of the string are fixed.

8 Calculate the frequency of the fundamental frequency.

9 Calculate the frequency of the second harmonic.

10 Calculate the frequency of the third harmonic.

10.3 Pipes

BY THE END OF THIS MODULE, YOU SHOULD BE ABLE TO:

- understand the creation of standing waves in a pipe
- calculate the frequency and wavelength of the fundamental frequency and the harmonics generated by a pipe with both ends open
- calculate the frequency and wavelength of the fundamental frequency and the harmonics generated by a pipe with one open end and one closed end.

In Module 9.7, you learnt that longitudinal stationary waves are also possible in air columns. These create the sounds associated with wind instruments. Blowing over the hole of a flute (Figure 10.3.1) or the reed of a saxophone (Figure 10.3.2) produces vibrations that correspond to a range of frequencies that create sound waves in the pipe.

The compressions and rarefactions of the sound waves, confined within the tube, reflect from both open and closed ends. This creates the right conditions for resonance and the formation of standing waves. The length of the pipe will determine the frequency of the sounds that will resonate.

The open end of a pipe corresponds to the fixed end of a string in that the reflected wave is fully inverted (i.e. it undergoes a 180° change of phase). At a closed end there is no change of phase. The reflected wave is in phase with the original wave.

FIGURE 10.3.1 Blowing over the mouthpiece of a flute and controlling the length of the flute with the keys enables a particular note to be produced.

FIGURE 10.3.2 Blowing into the mouthpiece of a saxophone vibrates the reed that is attached to the mouthpiece, which creates a vibration in the air column. Using the keys to control the length of the saxophone produces particular notes.

FIGURE 10.3.3 A piccolo and flute. A piccolo is a small flute that produces sounds higher (higher frequency) than a flute due to its shorter length.

PIPES WITH BOTH ENDS OPEN

A flute is an example of a musical instrument with two open ends. Not only can you control the length of the instrument using the keys but, like many instruments, flutes come in several lengths to provide different length pipes (Figure 10.3.3). The flautist blows across the embouchure hole, creating the vibration in the air column. This sets up a standing wave from the mouthpiece to the first open key (hole).

At the open end of a pipe, the wave forms an antinode with the reflected wave fully inverted (i.e. undergoes a 180° change of phase). In a pipe with two open ends, an antinode is formed at each end of the pipe.

As for the strings in Module 10.2, a large variety of waves are created in the pipe when a vibration is added to the air column within the pipe. These waves will reflect from the open ends of the pipe, but only the frequency that corresponds to a resonant frequency of the length of the instrument will create standing waves and therefore create the sound you hear. These standing waves are (as for strings) termed harmonics and add in superposition, with the resultant sound being a combination of a series of harmonics.

In a wind instrument, it is not always the fundamental frequency that dominates the sound heard. The control the flow of air from a player's mouth to the instrument can often determine which harmonic has the greatest amplitude. These harmonics correspond to octaves to a musician.

The resonant frequencies or harmonics in a pipe of length L can be calculated in the same way that harmonics were calculated for a string with two fixed ends.

The first harmonic, or fundamental frequency, has two antinodes, one at each end of the pipe, and a node in the centre of the pipe and

$$\lambda = 2 \times L$$

The second harmonic will have two nodes and

$$\lambda = L = \frac{2L}{2}$$

The third harmonic will have three nodes

$$\lambda = \frac{2L}{3}$$

And so, in general, for any harmonic:

$$\lambda = \frac{2L}{n}$$

and

$$L = \frac{n\lambda}{2}$$

The relationship between wavelength, λ, and pipe length, L, is shown in Figure 10.3.4.

For a pipe with two open ends:

$\lambda = \frac{2L}{n}$ and $L = \frac{n\lambda}{2}$

where

λ is the wavelength (m)

L is the length of the pipe (m)

n is the number of the harmonic, which is also the number of nodes (1, 2, 3, 4, …).

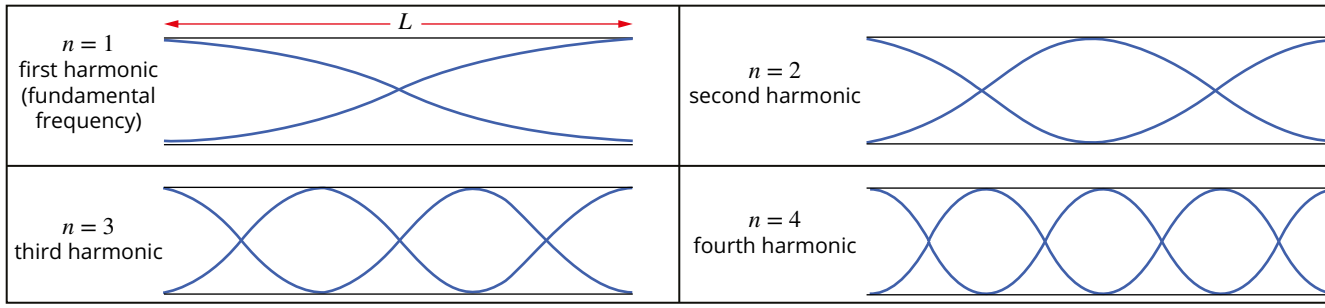


FIGURE 10.3.4 The first four resonant frequencies, or harmonics, in a pipe with two open ends. The ends are open so they will always be antinodal points.

Using the wave equation $v = f\lambda$ gives the relationship between frequency, velocity and pipe length.

For the first harmonic, or fundamental frequency ($\lambda = 2L$):

$$v = f\lambda \text{ and so } f = \frac{v}{\lambda} = \frac{v}{2L}$$

For the second harmonic ($\lambda = L$):

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

For the third harmonic ($\lambda = \frac{2L}{3}$):

$$f = \frac{v}{\lambda} = \frac{3v}{2L}$$

And so, in general, for a pipe with two open ends:

$$f = \frac{nv}{2L}$$

For a pipe with two open ends:

$f = \frac{nv}{2L}$

where

f is the frequency of the wave (Hz)

n is the number of the harmonic, which is also the number of nodes (1, 2, 3, 4, …)

v is the velocity of the wave ($m\,s^{-1}$)

L is the length of the pipe (m).

Worked example 10.3.1

FUNDAMENTAL FREQUENCY FOR PIPES WITH TWO OPEN ENDS

A flute is a 66 cm long pipe with two open ends.

a Calculate the wavelength of the fundamental frequency.

Thinking	Working
Identify the length of the pipe, L, in metres and the harmonic number, n.	$L = 66\,cm = 0.66\,m$ $n = 1$
For the first harmonic, or fundamental frequency, $\lambda = 2L$.	$\lambda = 2L$ $= 2 \times 0.66$ $= 1.3\,m$

b Calculate the wavelength of the second harmonic.

Thinking	Working
Identify the length of the pipe, L, in metres and the harmonic number, n.	$L = 66\,cm = 0.66\,m$ $n = 2$
Recall that for any frequency $\lambda = \frac{2L}{n}$. Substitute the values from the question and solve for λ.	$\lambda = \frac{2L}{n}$ $= \frac{2 \times 0.66}{2}$ $= 0.66\,m$

➤ Try yourself 10.3.1

FUNDAMENTAL FREQUENCY FOR PIPES WITH TWO OPEN ENDS

A standing wave in a flute is found to have a wavelength of 0.38 m for the fundamental frequency of vibration. Assume that the flute is a pipe with two open ends.

a Calculate the length of the flute.

b Calculate the wavelength of the fourth harmonic.

PIPE WITH ONE OPEN END AND ONE CLOSED END

Many woodwind and brass instruments are examples of a pipe with one closed end and one open end. This includes instruments such as clarinets, oboes, saxophones, trumpets, trombones and French horns (Figure 10.3.5). The mouthpiece of these instruments acts as a closed end with node and the bell of the instrument (the other end) acts as an open end of a pipe. Recall that the open end of a pipe results in the reflected wave being fully inverted (i.e. undergoes a 180° change of phase). In contrast, at a closed end there is no change of phase. The reflected wave is in phase with the original wave.

FIGURE 10.3.5 A variety of instruments that have one closed end and one open end. From the left: a French horn, a clarinet, a bassoon and an oboe.

The closed end of the pipe creates a node, so a pipe with one open end and one closed end has one end as a node and the other as an antinode. This is the same as in the case for a string with one fixed end, and results in the same equations to find lengths and wavelengths, as seen in Module 10.2.

For a pipe with one open end and one closed end:

$$\lambda = \frac{4L}{n} \text{ and } L = \frac{n\lambda}{4}$$

where

λ is the wavelength (m)

n is the number of the harmonic (1, 3, 5, ...)

L is the length of the pipe (m).

In general, for a pipe with one open end and one closed end, the frequency in terms of velocity is:

$$f = \frac{nv}{4L}$$

where

f is the frequency of the wave (Hz)

n is the number of the harmonic, which is also the number of nodes (1, 3, 5, ...)

v is the velocity of the wave (m s^{-1})

L is the length of the pipe (m).

Odd-numbered harmonics (1, 3, 5, ...) will form because the conditions necessary for a standing wave to form are only met in circumstances where there is an antinode at the open end and a node at the closed end. The ratio of the wavelengths of the harmonics will be 1 : 3 : 5, … This means that the wavelength of the third harmonic is $\frac{1}{3}$ the length of the fundamental frequency (the first harmonic), the fifth harmonic is $\frac{1}{5}$ the length of the fundamental frequency, and so on.

Even-numbered harmonics (2, 4, 6, …) will not form. The equations introduced above can be modified to incorporate this. The modified formula is:

$$\lambda = \frac{4L}{2n-1} \text{ and } L = \frac{(2n-1)\lambda}{4}$$

For a pipe with one open end and one closed end:

$$\lambda = \frac{4L}{2n-1} \text{ and } L = \frac{(2n-1)\lambda}{4}$$

where

λ is the wavelength (m)

L is the length of the pipe (m)

n is an integer (1, 2, 3, 4, …).

Note that for this equation, n is defined slightly differently from that for strings fixed at both ends. For this equation, n is the next harmonic in the sequence, not the harmonic number.

Worked example 10.3.2

FUNDAMENTAL FREQUENCY FOR PIPES WITH AN OPEN AND A CLOSED END

A clarinet is an example of a pipe with an open and a closed end. The length of the bass clarinet is 101.6 cm.

a Calculate the wavelength of the fundamental frequency.

Thinking	Working
Identify the length of the pipe, L, in metres and the harmonic number, n.	$L = 101.6\,\text{cm} = 1.016\,\text{m}$ $n = 1$
Recall that for any frequency, $\lambda = \frac{4L}{n}$. Substitute the values from the question and solve for λ.	$\lambda = \frac{4L}{n}$ $= \frac{4 \times 1.016}{1}$ $= 4.064\,\text{m}$

b Calculate the frequency of the third harmonic. (Use the speed of sound as 343 m s^{-1}.)

Thinking	Working
Identify the length of the pipe, L, in metres the harmonic number, n, and the speed of the wave, v.	$L = 4.064\,\text{m}$ $n = 3$ $v = 343\,\text{m s}^{-1}$
Recall that $f = \frac{nv}{4L}$. Substitute the known values and solve for f.	$f = \frac{nv}{4L}$ $= \frac{3 \times 343}{4 \times 1.016}$ $= 253\,\text{Hz}$

➤ Try yourself 10.3.2

FUNDAMENTAL FREQUENCY FOR PIPES WITH AN OPEN AND A CLOSED END

A trombone is a pipe with an open end and a closed end. The fundamental frequency of a trombone is 31 Hz. (Use the speed of sound as 343 m s^{-1}.)

a Calculate the total length of the pipe of the trombone.

b Calculate the wavelength of the third harmonic.

10.3 Review

SUMMARY

- In a pipe with two open ends, the wavelength of the standing waves corresponding to the various harmonics is:

$$\lambda = \frac{2L}{n}$$

and the frequency is:

$$f = \frac{nv}{2L}$$

Length of pipe is:

$$L = \frac{n\lambda}{2}$$

All harmonics may be present.

- In a pipe closed at one end, the wavelength of the standing waves corresponding to the various harmonics is:

$$\lambda = \frac{4L}{n}$$

and the frequency is:

$$f = \frac{nv}{4L}$$

Length of pipe is:

$$L = \frac{n\lambda}{4}$$

Only odd-numbered harmonics may be present.

KEY QUESTIONS

Retrieval

1 State what part of a standing wave occurs at each end, for a string with fixed ends.

Comprehension

2 Draw the fundamental frequency and the second harmonic for a wave in a pipe with two open ends.

3 If a standing wave could be made in a pipe with two closed ends, sketch what the fundamental frequency would look like.

4 Explain why are there no stringed instruments with one fixed end and one free end.

Analysis

5 A clarinet (pipe with one closed end) plays a note at 540 Hz. Assume this is the fundamental frequency. Calculate the effective length of the clarinet, if the speed of sound in the clarinet is 343 $m\,s^{-1}$.

6 Calculate the frequency of the second harmonic for a pipe with two open ends, if the pipe is 47 cm long. (Assume the speed of sound in the pipe is 343 $m\,s^{-1}$.)

7 A pipe with one closed end has a fundamental wavelength of 2.8 m. Calculate the frequency of the third harmonic. (Assume the speed of sound of 343 $m\,s^{-1}$.)

8 A string with two fixed ends produces notes with a frequency of 400.0 Hz, 800.0 Hz and 1200.0 Hz. Determine the longest length of the string that can produce these frequencies. (Assume the speed of sound is 343 $m\,s^{-1}$.)

9 A 4.23 m organ pipe with two open ends is played with a speed of sound of 343 $m\,s^{-1}$. Calculate the fundamental frequency and, thus, the period of this note.

10.4 Resonance and natural frequency

BY THE END OF THIS MODULE, YOU SHOULD BE ABLE TO:

- recognise resonance in mechanical systems
- recognise resonance in a musical instrument
- describe what is an object's natural frequency
- identify whether an energy transfer is efficient in a resonating system.

You may have heard about singers who supposedly can break glass by singing particularly high notes. Figure 10.4.1 shows a glass being broken in this way. All objects that can vibrate tend to do so at a specific frequency known as their natural or resonant frequency. Resonance occurs when an object is exposed to vibrations at a frequency equal to its resonant frequency. Resonance occurs when a weak vibration from one object causes a strong vibration in another. If the amplitude of the vibrations becomes too large, then the object can be destroyed. Resonance can happen for any kind of wave, not just sound waves. The energy transfer that occurs with resonance is very efficient and leads to a large increase in amplitude.

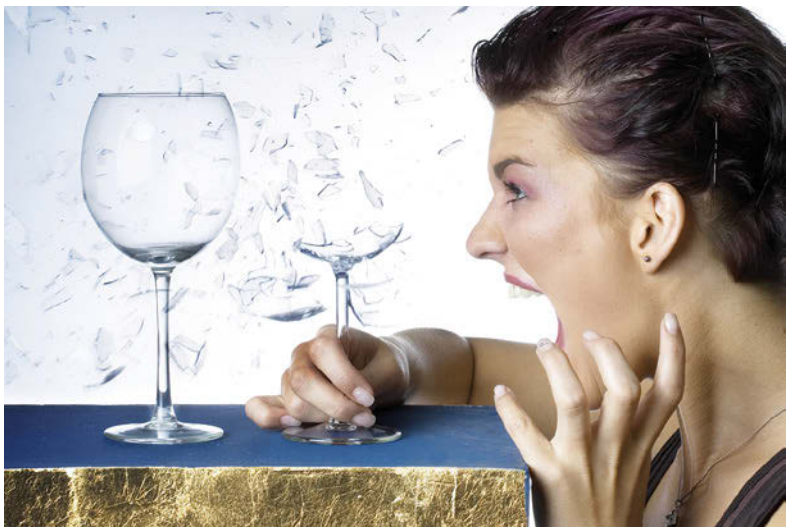


FIGURE 10.4.1 A glass can be destroyed by the vibrations caused by a singer emitting a sound of the same frequency as the resonant frequency of the glass.

A swing pushed once and left to swing or oscillate freely is an example of an object vibrating at its natural frequency. The frequency at which it moves backwards and forwards depends entirely on the design of the swing, especially on the length of its supporting ropes. In time, the oscillations will fade away as the energy is transferred to the supporting frame and the air.

If you watch a swing in motion, it is possible to determine its natural oscillating frequency. It is then possible to push the swing at exactly the right time so that you match its natural oscillation. The additional energy you add by pushing will increase the amplitude of the swing rather than work against it. Over time, the amplitude will increase and the swing will go higher and higher, and resonate (Figure 10.4.2). The swing can only be pushed at one particular rate to generate this increase in amplitude (i.e. to get the swing to resonate). If the rate is faster or slower, the forcing frequency that you are providing will not match the natural frequency of the swing and you will fight against it, rather than assist.

WS 2.2.4 PA 2.2.2

FIGURE 10.4.2 If you push a swing at its natural frequency, the amplitude of the swing increases, allowing it to swing higher.

FIGURE 10.4.3 The sound box of a stringed instrument is tuned to resonate for the range of frequencies of the vibrations being produced by the strings. When a string is plucked or bowed, the airspace inside the box vibrates in resonance with the natural frequency and the sound is amplified.

Other examples of resonant frequency that you may have encountered are blowing air across the mouthpiece of a flute or drawing a bow across a string of a violin in just the right place (Figure 10.4.3). In each case, a clearly amplified sound is heard when the frequency of the forcing vibration matches a natural resonant frequency of the instrument.

Resonance can be quite destructive in a mechanical system. Like the wine glass in Figure 10.4.1, the increased amplitude in a vibration caused by resonance can cause violent vibrations beyond the device's capacity, leading to catastrophic failure. Resonance disaster can occur if the mechanical resonance of different components matches the natural frequencies of other components, thereby increasing their amplitudes until the components fail. In the design process, these natural frequencies need to be considered to avoid resonance disaster.

Acoustics consider resonance in the design process. For example, useful forms of resonance are maximised in the design of a concert hall, but resonance is minimised in systems where the vibrations produced can cause destruction. In musical instruments and loudspeakers, resonance is a desired effect. The sounding boards of pianos and the enclosures of loudspeakers are designed to enhance and amplify particular frequencies. In other systems, such as car exhaust systems and suspension bridges, resonance is not desirable, and care is taken to design a system that prevents vibrations.

Two very significant effects occur when the natural resonant frequency of an object is matched by the forcing frequency.

- **The amplitude of the oscillations within the resonating object will increase dramatically.**
- **The maximum possible energy from the source creating the forced vibration is transferred to the resonating object.**

Noise pollution and acoustic design

The world around us is full of unwanted noise, from road noise, air traffic noise, industrial noise and simply noise from other people. These levels of noise are monitored and minimised to avoid unnecessary noise (Figure 10.4.4). Acoustical engineers use their understanding of the behaviour of sound waves to reduce noise pollution and the effects of noise pollution. Reflection, refraction, diffraction and interference of sound waves all need to be considered in designing structures to minimise noise pollution.

One of the most common ways to control noise is with the choice of building materials. Different materials will absorb the energy of the wave by different amounts. The more spongy the material, the more it dampens the energy of the sound wave, reducing the amplitude of the wave. This is why insulation or foam can be useful in reducing noise.

Noise transfer also depends on the density of a material. The denser the material, the more energy of the sound wave it will absorb, and the more it reduces the noise level. So building materials such as brick, thick glass and concrete are quite useful for shielding from and reducing unwanted noise.

A common method used to minimise noise reflection (and transfer) inside a room is to cover the walls (and, if necessary, the floor and ceiling) in foam or other soft structures, which not only reduces reflection of sound but also dampens the sound. These structures are known as sound baffles. An example of this can be seen in Figure 10.4.5. The room is designed to minimise sound reflections or echoes. Notice how the foam is not flat. The foam coating the walls is moulded into pyramids so the waves can't reflect from the foam as the sharp point disrupts any reflections.

FIGURE 10.4.4 Using a sound level meter to measure the noise levels in decibels.

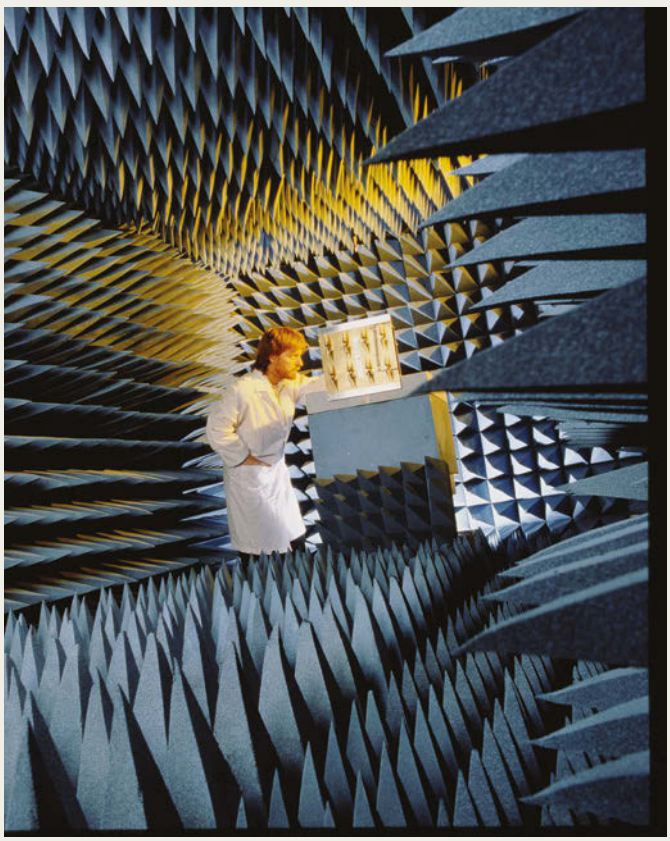


FIGURE 10.4.5 A scientist setting up an experiment in an anechoic (echo-free) chamber. The foam pyramids covering the walls, floor and ceiling absorb the sound waves, preventing echoes or reflections.

To reduce noise, engineers often need to consider and minimise mechanical vibrations, which create sound waves. One way to minimise mechanical vibrations, especially with machinery, is to isolate the source of the vibrations. This isolation prevents transmission of the vibrations to other surfaces, which would then also vibrate. Springs, rubber mats and cork are often used to provide this isolation. An example of vibration isolation can be seen in Figure 10.4.6, in which the equipment is specially mounted on isolation blocks to stop the transmission of any vibrations. The same understanding of wave behaviour is used by acoustical engineers to optimise wanted sound in concert halls (Figure 10.4.7) and cinemas, in railway announcements, and in ultrasound applications such as medicine and non-destructive industrial testing.

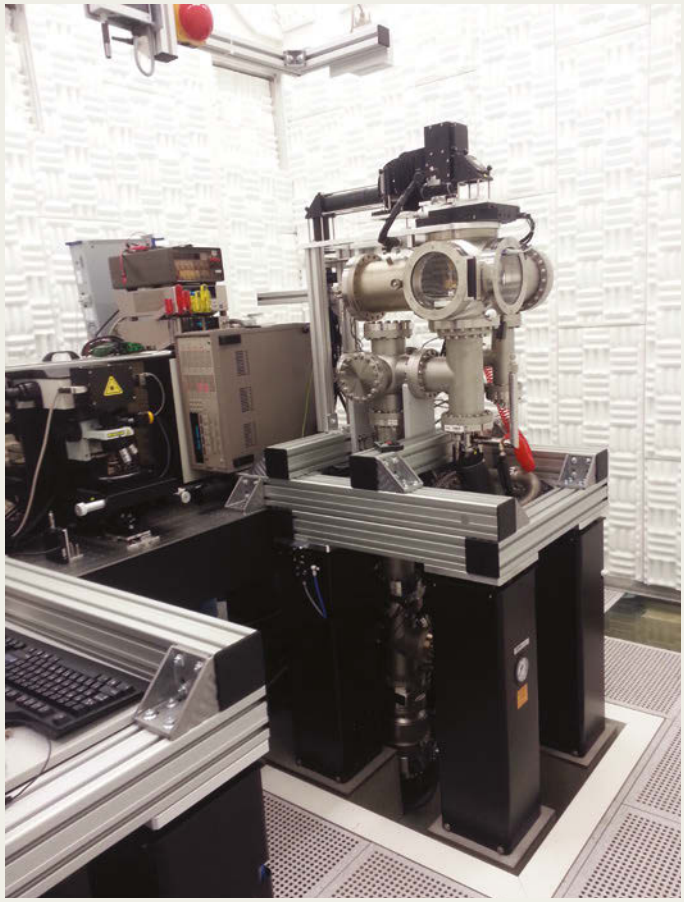


FIGURE 10.4.6 A noise-free laboratory at IBM Research. The acoustic dampening panels can be seen on the walls. The equipment is mounted on vibration isolating blocks to isolate it from any vibrations in the room and to isolate the different pieces of equipment from each other.

FIGURE 10.4.7 Modelling concert hall acoustics with a scale model. Laser beams (red) are being used to test the acoustics and find any acoustic defects.

Review

1. List the sort of materials that an acoustical engineer might coat walls with to minimise reflection of sound.
2. Explain why walls are often built around busy freeways.
3. Discuss the features of cars that minimise the road noise you hear in the car.

10.4 Review

SUMMARY

- All objects that can vibrate tend to do so at a specific frequency known as their natural or resonant frequency.
- Resonance occurs when the frequency of a forcing vibration equals the natural frequency of an object.
- Two special effects occur with resonance:
  - The amplitude of vibration increases.
  - The maximum possible energy from the source is transferred to the resonating object.
- Musical instruments are designed to use resonance to produce a clear, loud sound.

KEY QUESTIONS

Retrieval

1 Explain resonance.

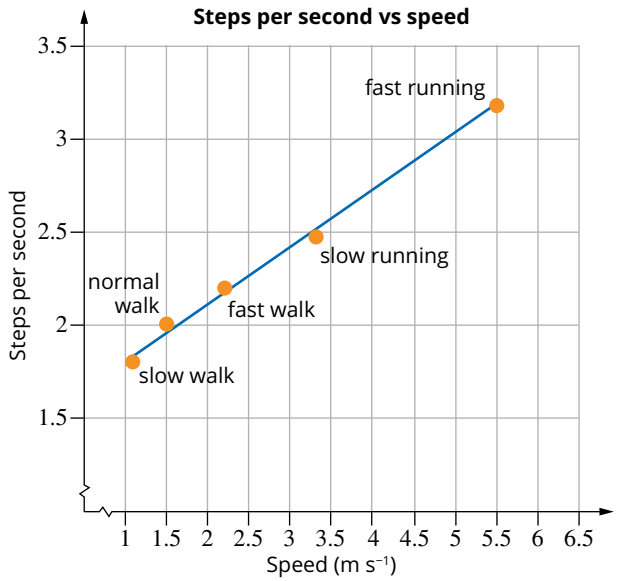
Comprehension

2 Explain why resonance can result in damage to built structures.

Analysis

3 On a swing, if you don't have someone to push you, you can also swing higher by swinging your legs and body with the natural frequency of the swing. Consider how this works.

4 A footbridge over a river has a natural frequency of oscillation from side to side of approximately 1 Hz. When pedestrians walk at a pace that produces an oscillation in the bridge close to the natural frequency of the footbridge, resonance will occur. The graph displays relevant data about pedestrians walking or running. A pedestrian completes 1 cycle of their motion every 2 steps. Determine which activity of the pedestrians is most likely to cause damage to the footbridge over time. Explain your answer.



Chapter review

10

KEY TERMS

elastic modulus
fundamental
harmonic

KEY QUESTIONS

Retrieval

1 Identify which of the following best describes sound.
- **A** transverse wave
- **B** electromagnetic wave
- **C** longitudinal wave
- **D** Mexican wave

2 Identify the material through which sound travels the fastest.
- **A** helium
- **B** iron
- **C** air at 20°C
- **D** gold

3 True or False: Most sounds you hear are a combination of different frequencies.

4 A stretched string with two fixed ends has a fundamental frequency of 150 Hz. Identify the frequency of the third harmonic.
- **A** 600 Hz
- **B** 300 Hz
- **C** 50 Hz
- **D** 450 Hz

5 Recall which harmonics are possible for a string with a free end.
- **A** all harmonics
- **B** even harmonics ($n = 2, 4, 6, \ldots$)
- **C** odd harmonics ($n = 1, 3, 5, \ldots$)
- **D** no harmonics, just the fundamental frequency

6 Indicate what the ends of a standing wave will be in a pipe with two open ends.
- **A** both nodes
- **B** both antinodes
- **C** one node and one antinode

7 Indicate how a musician changes the length of a wind instrument, which acts a pipe, to change the wavelength.
- **A** taking pieces on/off the instrument
- **B** opening and closing keys/holes
- **C** blowing harder

Comprehension

8 Resonance occurs when the frequency of a forcing vibration exactly equals the natural frequency of vibration of an object. Two special effects occur. Identify and explain which one of the following responses relating to these effects of resonance is true.
- **A** The amplitude of vibration will decrease.
- **B** The amplitude of vibration will increase.
- **C** The frequency of vibration will increase.
- **D** The frequency of vibration will decrease.

9 Explain whether the speed of sound increases or decreases as the temperature of the medium increases.

10 Explain what a harmonic is.

11 Draw (to scale) the standing wave patterns for the first, second and third harmonics on a string (fixed at both ends) 10 cm long.

12 Many instruments come in different sizes such as soprano, alto, tenor and bass. Explain why all these sizes are made.

13 Describe the concept of resonance and why it would need to be considered when designing structures such as buildings or bridges.

Analysis

14 The sonar on a submarine sends out a signal with a frequency of 32 kHz. If the wave travels at 1400 $m\,s^{-1}$ in sea water, calculate the wavelength of the signal.

15 Assuming the speed of sound in water is 1500 $m\,s^{-1}$, calculate the wavelength of a sound at a frequency of 300.0 Hz.

16 The sound wave from Question **15** is now produced in air, where the speed of sound is 340 $m\,s^{-1}$. Determine the wavelength now.

17 A string with two fixed ends has a length of 7.2 cm. Determine the longest wavelength that can be produced on this string.

18 A piccolo (a small flute) is a pipe with two open ends. Its length is 32 cm. Calculate:
- **a** the fundamental wavelength
- **b** the second harmonic.

19 A soprano saxophone is a pipe with one closed end and has a length of 40.0 cm. Calculate the wavelength of the third harmonic.

The following information relates to questions **20** and **21**.

A signal generator is attached to a string vibrator producing vibrations down a string fixed at one end and free to move at the other. The string is kept at constant tension. The effective length of the string is 85 cm. The speed of the vibrations along the string is 340 $m\,s^{-1}$.

20 Determine the lowest frequency of vibration that will produce a standing wave in the string.

21 Calculate the frequency of vibration of the third harmonic.

22 Echolocation uses the speed of sound to determine how far away an object is. On boats, they often use echo sounders to see how deep the water is or to locate fish. The echo sounder sends out a sound wave and detects the echo or reflection. The time between the sound and its echo is how long the wave takes to go from the boat to the bottom of the ocean and back. Determine how long it takes to receive a signal, if the water is 800.0 m deep and at a temperature of 20°C.

23 A flute (a pipe with two open ends) has a length of 66 cm.

Hint: the speeds of sound for different temperatures are in Table 10.1.2.

a Determine the frequency of the third harmonic if the air in the flute is at 20°C.

b Determine the frequency of the third harmonic if the air in the flute is now at 0°C.

c Using your answers to parts **a** and **b**, discuss why it is important to 'warm up' a musical instrument before adjusting the instrument to match frequencies with other instruments.

24 You can blow across the top of a test tube to create a sound. Blowing across the top causes a vibration in the air in the test tube. A test tube is a closed tube (one open end and one closed end). You can change the length by putting some water into the test tube.

a The empty test tube is 15 cm long. Calculate its fundamental wavelength.

b Determine the height of water that needs to be added to the tube to create a fundamental wavelength half of that in part **a**.

25 A pipe with one closed end is filled with air that resonates with a 400.0 Hz tuning fork. The length that corresponds to the fundamental frequency is 21 cm. Calculate the speed of sound in the pipe.

26 On a string with only one fixed end the wavelength of the fundamental frequency is 30.0 cm.

a For the same length string, calculate the wavelength of the fundamental frequency if the string has two fixed ends.

b Determine the relationship between the fundamental frequency on a string with only one fixed end and that on a string with both fixed ends.

c Determine whether this relationship holds for all harmonics.

27 A flute (a pipe with two open ends) produces a fundamental frequency of 440 Hz with a speed of sound of 350 $m\,s^{-1}$.

a Calculate the length of the flute.

b Calculate the length of a clarinet (a pipe with one closed end) that would produce the same fundamental frequency (same speed of sound).

28 An earthquake causes a footbridge to oscillate up and down with a fundamental frequency once every 4.0 s. The motion of the footbridge can be considered to be like that of a string fixed at both ends. Determine the frequency of the second harmonic for this footbridge.

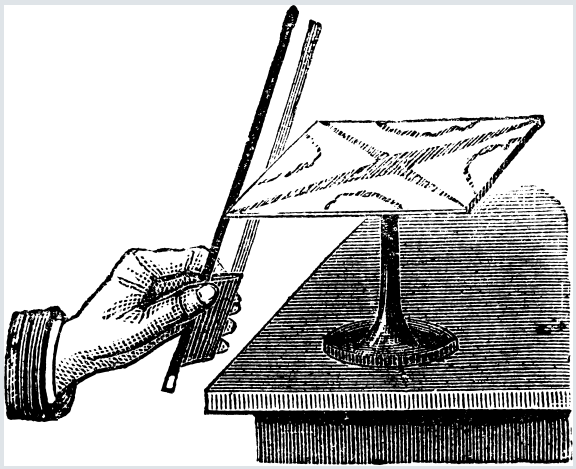
29 The velocity of waves in a particular string at constant tension is 78 $m\,s^{-1}$. The string is fixed at both ends. If a particular frequency of a standing wave formed in the string is 428 Hz, calculate how far apart two adjacent antinodes would be.

30 Use the internet to research how resonance is used to help protect large buildings in earthquake-prone areas.

Knowledge utilisation

31 The speed of sound can be measured by taking advantage of echoes. Design an experiment to use echoes to measure the speed of sound.

32 An interesting way to visualise sound, and as an engaging science demonstration, is the use of Chladni plates, shown below. Research how these work and design a demonstration to use these.



CHAPTER

11 Light

A model is a system that is used to build a picture or an analogy for an observed phenomenon. In this chapter you will explore models for the behaviour of light. A good model will fit and explain all known observations and ideally will be able to predict new behaviours. This chapter looks at the development of a wave model to explain the nature of light and its application to key observations.

Syllabus subject matter

Topic 2 • Waves

LIGHT

- recall that light is not modelled as a mechanical wave, because it can travel through a vacuum
- recall that a wave model of light can explain reflection, refraction, total internal reflection, dispersion, diffraction and interference
- describe polarisation using a transverse wave model
- use ray diagrams to demonstrate the reflection and refraction of light
- solve problems involving the reflection of light on plane mirrors
- define Snell's law
- solve problems involving the refraction of light at the boundary between two mediums
- recall that the speed of light in a vacuum is $c = 3 \times 10^8 \text{ m s}^{-1}$
- contrast the speed of light and the speed of mechanical waves
- define the concept of intensity
- solve problems involving the proportional relationship between intensity of light and the inverse-square of the distance from the source.

MANDATORY PRACTICAL

- Conduct an experiment to determine the refractive index of a transparent substance.

SCIENCE AS A HUMAN ENDEAVOUR

- Development of the wave theory of light

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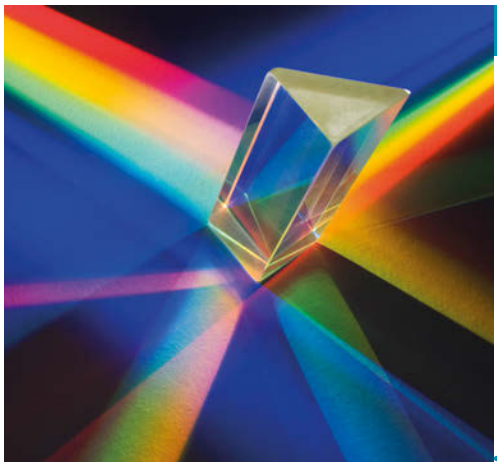
11.1 Light as a wave



BY THE END OF THIS MODULE, YOU SHOULD BE ABLE TO:

- describe two models for the nature of light
- explain the propagation of light by particles and waves
- describe reflection and refraction as evidence for both the particle and wave models of light
- state that whether light can be modelled as a particle or wave depends upon the speed of light
- explain, using Michelson and Morley's experiment, that light cannot be a mechanical wave because it doesn't need a medium in which to travel
- state that a transverse wave model of light can be used to explain other wave behaviours of light.

In Chapter 9 you studied the general properties of waves and in Chapter 10 you learnt about the behaviour of sound waves. So now the question that can be asked is: Is light also wave?

If a wave is defined as the sum of its properties, does light exhibit all of the properties known to belong to waves?

Curiosity about the nature of light has occupied the minds of physicists for centuries. The beginning of human interest in the nature of light dates back to the ancient Greek, Arabian and Chinese philosophers. In the early 19th century, evidence suggested that light could be modelled as a wave because it exhibited the same set of properties as other phenomena that had already been defined as waves: water waves, sound waves, vibrations in springs and strings. If light exhibits sufficient properties in common with these known waves, then surely it too could be assumed to 'be' a wave?

Recall from Chapter 9 that light cannot be a mechanical wave because a mechanical wave needs a medium in which to travel. Light can travel through a vacuum and does not need a medium. This observation resulted in two conflicting theories.

- The famous English scientist Sir Isaac Newton explained light in terms of particles or 'corpuscles', with each different colour of the **spectrum** representing a different type of particle.
- The lesser-known scientists, at least in current times, Robert Hooke (from England) and Christiaan Huygens (from Holland) proposed an alternative model that described light as a type of wave, similar to the water waves observed in the ocean.

A key point of difference between the two theories was that Newton's **corpuscular** theory suggested that light would speed up as it travelled through a solid material such as glass. In comparison, the wave theory predicted that light would be slower in glass than in air.

Unfortunately, at the time it was impossible to measure the speed of light accurately, so the question was not resolved scientifically. Newton's reputation meant that for many years his corpuscular theory was considered correct.

It was not until the early 19th century that experiments first convincingly demonstrated the wave properties of light.

MODELLING WITH PARTICLES

Light streaming through trees on a misty morning, the projector's beam in a dusty cinema, our limited view when peeping through a keyhole and the distinct shape of shadows are all evidence for the straight-line or rectilinear path of light. These examples provide evidence that when transmitted in a uniform medium, light travels in straight lines. A uniform medium is a substance that is unchanging in its constitution. Our awareness of the **rectilinear propagation** of light enables us to judge the distance to objects. The mechanism by which our eyes and brain interpret a three-dimensional world is complex, but it relies on the assumption that light in a uniform medium travels in straight lines.

The following simple experiment can be performed to demonstrate that light travels a straight path in a uniform medium. Make a pinhole in each of three identical pieces of card. Place card A close to a light source, and position card B a little further away, as shown in Figure 11.1.1. Then, holding card C in front of your eye so that you can always see through the hole, adjust its position so that you can see the light from the lamp. This will only be possible when all three pinholes lie in the same line and are **collinear**. The conclusion that can be drawn is that light must travel in straight lines.

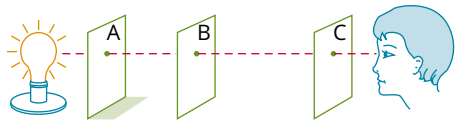


FIGURE 11.1.1 Light from the lamp can only be seen if the pinholes lie in a straight line. This means that light must travel from the lamp to the eye along a straight line.

The above property of light was first modelled by considering that light was particle-like in nature. Consider a beam of light shining from a powerful torch. Rays can represent the direction of travel of the light 'particles'. The idea of a light ray is a useful concept, as it can successfully model the behaviour of light. A beam of light can be thought of as a bundle of rays. A strong light source, such as the Sun, could therefore be thought of as producing a very large number of light rays.

MODELLING LIGHT AS A TRANSVERSE WAVE

During the 17th century, when Newton was studying the nature of light, it was known that light had the following properties:

- Light travels in straight lines in a uniform medium (referred to as linear propagation).
- Light obeys the law of reflection.
- Light obeys Snell's law of refraction.

Reflection and refraction, along with other wave behaviours of light, will be investigated in more depth in later modules of this chapter.

Huygens' principle

Recall from Module 9.4 that Huygens' principle states that each point on a plane or circular wavefront can be considered as a source of secondary wavelets (i.e. small waves). These wavelets spread out in the forward direction at the same speed as the source wave.

Huygens noted that the envelope or common tangent of the wavelets becomes the new wavefront. The path of a point on any one wavelet will be in a straight line and accounts for the straight line rays observed as light travels from a source. Light could be modelled as a transverse wave.

Modelling reflection

Reflection can be modelled either as particles or as a wave. If light is considered to be a wave, reflecting light behaves just as water waves do when striking a barrier. The laws of reflection are obeyed and the reflection of light is modelled just as effectively as with a particle approach, as shown in Figure 11.1.2.

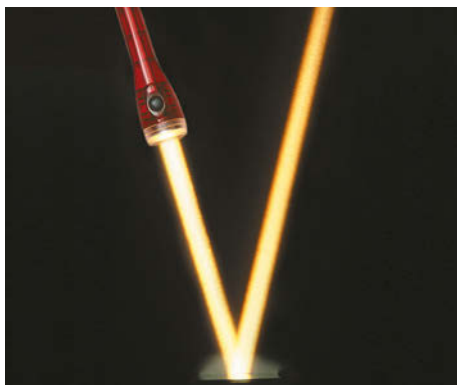


FIGURE 11.1.2 The reflection of light can be modelled by considering light as a wave, as Huygens predicted.

Modelling refraction

Modelling refraction of light as a wave was not as simple. The bending or change of direction of light as it passes from one medium to another is called refraction (Figure 11.1.3). **Refraction** occurs because light changes speed as it enters a medium with a different **optical density**. Various common phenomena are caused by refraction. Examples include the bend that appears in a straw when it is standing in a glass of water, the strangely shortened appearance of your legs as you stand in a waist-deep swimming pool, and the 'puddles of water' that you see on the road ahead on a warm day.

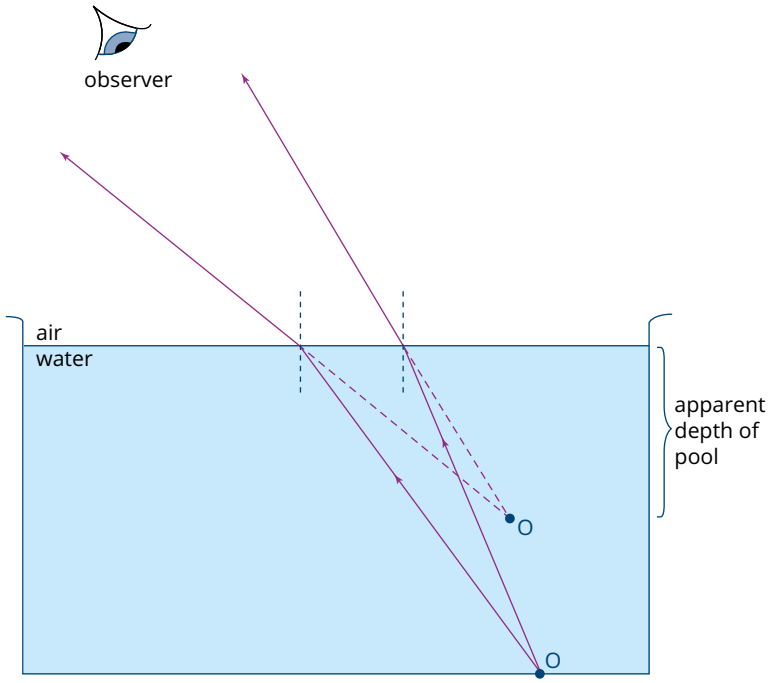


FIGURE 11.1.3 The apparent depth of a body of water appears less than its actual depth because of refraction. Light rays from a point at the bottom of the pool are refracted at the water's surface. The observer perceives these rays to have come from an elevated location and interprets this as an indication of shallow water.

In Module 9.4 you studied the refraction of waves, including light waves. However, refraction can be modelled by either the movement of particles or by that of waves. Newton's particle (or 'corpuscular') model was the more popular and most of the progress in understanding the nature of light during the 18th century was made based on his theories. Newton's prestige also added weight to his arguments. After all, he had been shown to be right so many times before, so why would he be wrong now?

It seemed that the only way to separate the two competing theories was to determine the speed of light in both air and another transparent medium, such as glass. For refraction to occur with the light bending towards the normal, it would have to speed up in the optically denser medium for light to be particles. If light was slower in air, then the particle theory wave model would be vindicated. Newton was unable to measure the speed of light and assumed that it was similar to that of other mechanical wave phenomena such as sound (at about 20°C) and that, like sound, light would travel faster in the denser medium.

It was not until 1850 that relatively accurate measurements could confirm that the speed of light was approximately $3 \times 10^8 \,\mathrm{m\,s^{-1}}$—many magnitudes higher than the speed of sound—and light slowed down when travelling through an optically denser medium. Huygens' wave model appeared to be vindicated. Light could be modelled as a transverse wave.

By then, however, the wave nature of light was well established by the work of other scientists observing and measuring wave-based behaviours of light such as dispersion, diffraction, interference and polarisation and Newton's particle model was all but forgotten.

Development of the wave theory of light

From as long ago as ancient Greek times, scientists have argued about the nature of light and attempted to measure the speed of light.

Aristotle wrote that light was able to travel instantaneously from one point to another. Empedocles, another Greek scientist, disagreed and stated that because light moved then it must take some time, albeit very little, to travel. The question remained unresolved as the technology to measure the speed of light simply didn't exist.

In 1667, Galileo Galilei, the Italian scientist and astronomer, attempted to measure the speed of light using lanterns. Two people holding covered lanterns stood on the tops of hills about 1 km apart. The first lantern was uncovered. When the second person saw the flash of light, the second lantern was uncovered. By finding the time between the two observations, the speed of the light between the two observers could be found. However, the distances were too small and Galileo was only able to state that light travelled at least 10 times the speed of sound.

In 1728, James Bradley, an English physicist, used calculations of the apparent change in position of stars due to Earth's orbit around the Sun. His calculations suggested a value of $3.01 \times 10^8\,m\,s^{-1}$—incredibly this was within 1% of the value used today, despite relatively rudimentary instrumentation. It wasn't until the late 1800s that the American scientists Albert Michelson and Edward Morley determined a more accurate value of $2.999\,10 \times 10^8\,m\,s^{-1}$.

Today, the *defined* value for the speed of light in a vacuum is $2.997\,924\,58 \times 10^8\,m\,s^{-1}$.

This is considered to be a constant value in a vacuum throughout the universe (Figure 11.1.4). However, some recent experiments suggest that there may be some special conditions under which light will travel at a different speed.

Mechanical waves need a medium in which to travel. By the end of the 19th century, a transverse wave model for light was accepted but it was believed that like other waves, light needed a medium in which to travel, called the **aether**.

FIGURE 11.1.4 A photo from the Hubble Space Telescope of the illuminated dust shell around an exploding star. Light from this distant source travels at the same speed in a vacuum as it does everywhere else in the universe.

Michelson and Morley had tried without success to find the speed of the Earth as it moved through this aether. Their experiment was designed to measure the speed of light from a star at two different times in the year, 6 months apart. They expected to find a difference in the values they obtained because at one time, the Earth would have been travelling towards the star, and 6 months later the Earth would be on the other side of its orbit, and therefore travelling away from the star.

To do this, Michelson and Morley built what is now called a Michelson interferometer. It essentially consisted of a light source, a half-silvered glass plate, two mirrors and a telescope. The half-silvered glass acts as a beam splitter, allowing some light to pass and reflecting the rest. The mirrors were placed at right angles to each other and at equal distance from the glass plate, which is oriented at an angle of 45° relative to the two mirrors. The arrangement of an interferometer is shown in Figure 11.1.5.

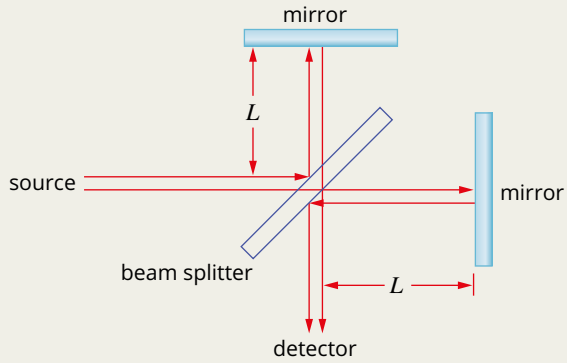


FIGURE 11.1.5 A diagram of the arrangement of the mirrors and beam splitter in the Michelson interferometer.

Michelson and Morley were able to measure the speed of light by looking for a change in the interference fringes produced between light that had passed through the two arms of the interferometer. If light travels in the same direction as the aether, it would speed up; if it was travelling in the opposite direction to the aether, its speed would slow down. This means that as Michelson and Morley altered the orientation of the interferometer, the interference pattern produced should also change. Instead, the Michelson–Morley experiment found that there was no effect on the interference patterns produced and it is now one of the most famous failed experiments.

Not only were Michelson and Morley unable to see any effect on the interference patterns produced, they also obtained the same value for the speed of light, approximately $3.00 \times 10^8 \, \text{m s}^{-1}$, regardless of when they took their measurements. That the speed of light was unchanged was considered a strange result. Intuition would suggest that the speed of light from the star relative to Earth should be higher when Earth was moving towards it, and lower as Earth moved away.

To explain the result, it took a tremendous revolution in mechanics in which Newton's mechanics had to be replaced by Einstein's theory of special relativity for fast-moving bodies. Newton's work is now seen as part of a bigger, more encompassing theory.

Review

1. In 1850, Michelson and Morley determined the speed of light. State the speed of light.
2. In 1772, James Bradley determined the speed of light within 1% of the value used today. Describe the method he used.
3. Early scientists investigating the nature of light thought it travelled through an aether. Describe what the aether was.
4. Michelson's and Morley's interferometer included a half-silvered mirror that acted as a beam splitter, allowing some light through and reflecting the rest. Explain why a beam splitter was included in the design.
5. The experiment performed by Michelson and Morley was designed to demonstrate the existence or otherwise of an aether. Explain why this was important in understanding the nature of light.

11.1 Review

SUMMARY

- In the 1600s, two models for the nature of light were proposed: particles and waves.
- Newton explained light in terms of particles or 'corpuscles', with each different colour of the spectrum representing a different type of particle.
- Huygens proposed a wave model in which the wavefront of a plane wave can be considered a source of secondary wavelets.
- Rays can be used to represent the direction in which light travels.
- Reflection and refraction both provide further evidence for a model of light as either particles or waves.
- Measurements of the speed of light confirmed its speed as approximately $3 \times 10^8 \,\text{m}\,\text{s}^{-1}$. This is many magnitudes faster than mechanical waves such as sound.
- Measurement of the reduction in the speed of light when refracting in a more optically dense medium confirmed a wave model for light.
- Michelson and Morley's experiments measured the speed of light and confirmed both the wave nature of light and that light was not a mechanical wave. No medium is needed for its propagation.
- Further investigations confirmed that a transverse wave model for light could explain other wave properties including dispersion, diffraction, interference and polarisation.

KEY QUESTIONS

Retrieval

1 In the 1600s, two models for light were proposed: a particle model and a wave model. Name the first scientist to publish a wave model for light.

2 List three observed behaviours of light that can be explained either by a particle or by a wave model.

3 State the graphical method by which the straight-line propagation of light can be represented.

4 The apparent depth of a body of water appears less than its actual depth when viewed from above. Identify the behaviour of light that contributes to this observation.

Comprehension

5 A bright beam of light could be modelled by either particles or waves. Describe the physical change that allows each model to explain a brighter light source.

6 Refraction can be explained in part by either a wave model or a particle model of light. Describe what the key difference was that established that the refraction of light could be explained by a wave model rather than by the particle model.

7 Huygens proposed a wave model for light based on the propagation of wavelets. Describe the observed behaviour of light that this model sought to explain.

Analysis

8 Consider the different observed behaviours of light noted in this module. Sort each behaviour as supporting either a particle or a wave model. Include any specific constraints that apply for the behaviour to apply to the particular model.

Supports particle model	Supports wave model

11.2 The electromagnetic spectrum

BY THE END OF THIS MODULE, YOU SHOULD BE ABLE TO:

- define light as an electromagnetic, transverse wave needing no medium in which to travel
- explain that visible light is only one small part of the electromagnetic spectrum
- describe the regions and properties of other sections of the electromagnetic spectrum.

By the late 1600s, light was known to involve the transfer of energy from one place to another. In Isaac Newton's time a corpuscular (particle) model and a wave model for light seemed equally valid. In spite of considerable experimentation by scientists it was not until the early 1800s that one model prevailed.

Thomas Young discovered that sources of light were able to interfere with each other, just like sound waves and water waves. It was this finding that led to a universally accepted wave theory for light. Furthermore, with the work of Michelson and Morley and others, the speed of light had been measured for the first time, and the wave model of refraction could be validated. Meanwhile, another area of physics had been developing. By the 1860s, investigations led to the finding that **visible light** was just one of the many forms of **electromagnetic radiation** (EMR).

ELECTROMAGNETIC RADIATION

Electricity and magnetism were once considered to be completely separate phenomena. It was discovered that:

- a moving charge will create a magnetic field
- a changing magnetic field can be used to create electricity.

In 1864 James Clerk Maxwell used mathematical equations to describe how charges moving periodically in a conductor would set up alternating electric fields and magnetic fields in the nearby region. Maxwell knew that the magnetic and electric fields travelled through space. He calculated their speed and found it to be $3.0 \times 10^8\,\text{m s}^{-1}$, exactly the same as the speed of light! He went further to devise mathematical expressions to describe the magnetic and electric fields. The solution to these expressions was found to be the same as the equation of a wave. Maxwell had demonstrated that light is an electromagnetic wave.

Today we know that the **electromagnetic spectrum** includes a wide range of frequencies (or wavelengths). The many forms of EMR are essentially the same, differing only in their frequency and therefore their wavelength. All electromagnetic waves are created by accelerating charges that result in rapidly changing magnetic and electric fields travelling out from the source at the speed of light, as shown in Figure 11.2.1.

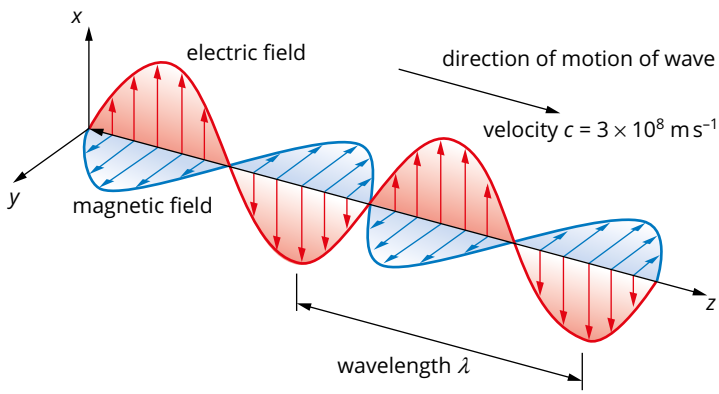


FIGURE 11.2.1
As all electromagnetic waves travel with the same velocity, the only thing that differentiates one form of EMR from another is the frequency and wavelength.

Note that the electric field component and the magnetic field component are at right angles to each other and to their direction of travel. Electromagnetic radiation meets the description of a transverse wave as discussed in the earlier chapters on mechanical waves.

The electromagnetic spectrum is roughly divided into seven categories, depending on how the radiation is produced and the frequency of the waves. Energy carried by the EMR is proportional to the frequency.

- High-frequency, short-wavelength gamma rays are at the high-energy end of the spectrum.
- Low-frequency, long-wavelength radio waves carry the least energy.
- Human eyes can respond to EMR of frequencies between approximately 400×10^{12} Hz and 800×10^{12} Hz. These frequencies are referred to as the visible light section of the electromagnetic spectrum.

Recall from Chapter 9 that for any wave the relationship between its frequency, f, and its wavelength, λ, is given by $v = f\lambda$, where v is the velocity of the wave in a given medium.

All EMR travels at a speed of $3 \times 10^8\,\text{m s}^{-1}$ in a vacuum, and so this significant speed has been allocated the special symbol c.

Figure 11.2.2 shows the different categories of EMR. Note the vast range of frequencies and wavelengths, λ. The range of frequencies (or wavelengths) constituting visible light occurs near the middle of the spectrum. Our eyes cannot perceive any wavelengths of EMR outside of this range.

For all electromagnetic radiation:

$f = \frac{c}{\lambda}$

where

f is the frequency of the EMR (Hz)
c is the speed of EMR approximately $3 \times 10^8\,\text{m s}^{-1}$
λ is the wavelength of the EMR (m).

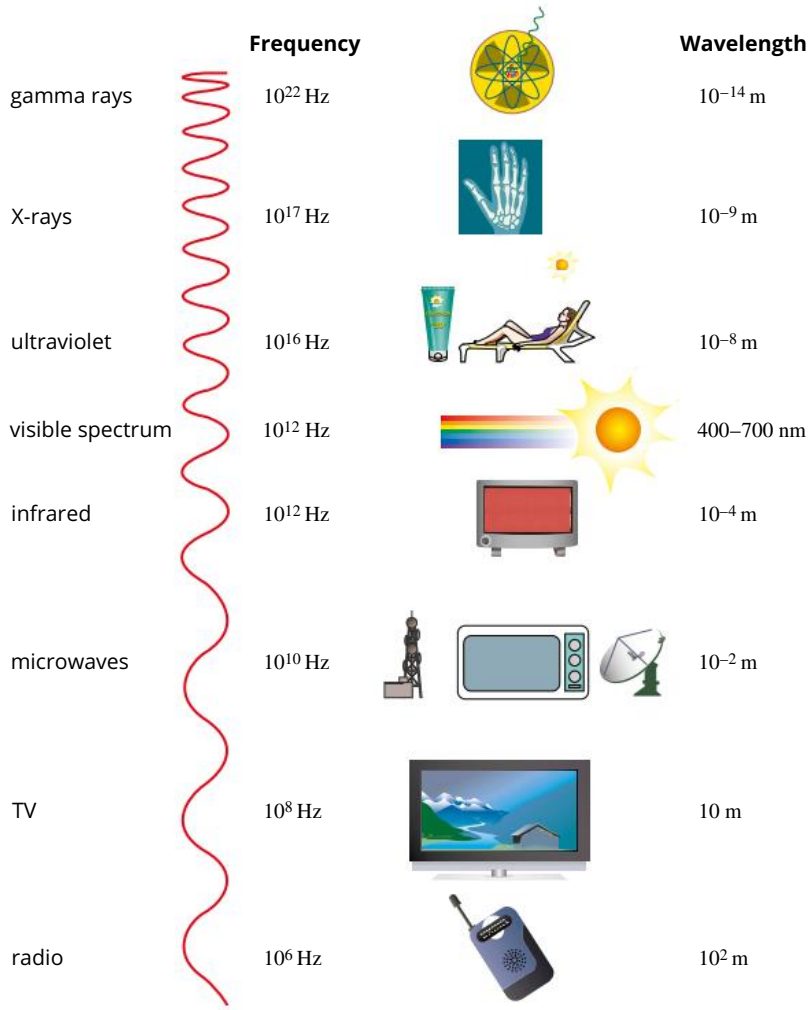


FIGURE 11.2.2 The electromagnetic spectrum. In this representation the radio wave section of the spectrum is broken down into two sections: TV and radio.

Worked example 11.2.1

APPLYING THE WAVE EQUATION TO EMR

A sample of sodium burned in a flame produces light with a wavelength of 589 nm. Determine whether the frequency of this light is within the visible range.

Thinking	Working
Recall the special case of the wave equation for EMR.	$f = \frac{c}{\lambda}$
Substitute the appropriate known values into the formula and solve.	$c = 3.0 \times 10^8\,\text{m s}^{-1}$ $\lambda = 589\,\text{nm} = 589 \times 10^{-9}\,\text{m}$ $f = \frac{3.0 \times 10^8}{589 \times 10^{-9}}$ $= 5.09 \times 10^{14}$ $= 509 \times 10^{12}\,\text{Hz}$ This frequency is in the visible range of the EMR spectrum.

➤ Try yourself 11.2.1

APPLYING THE WAVE EQUATION TO EMR

A sample of copper burned in a flame produces light with a wavelength of 492 nm. Determine whether the frequency of this light is within the visible range.

VISIBLE LIGHT

Within the visible section of the spectrum, our eyes are responsive to many different colours of light from the deepest red through to the brightest violet. In fact, the human eye can distinguish about 10 million different colours.

Coloured light, different wavelengths

Each variation in colour or shade is caused by light of a different wavelength. Traditionally the colours quoted as making up the visible spectrum are red, orange, yellow, green, blue and violet, present in approximately equal proportions. However, as shown in Figure 11.2.3, the actual allocation of separate names for the colours is not as clear-cut as many people think, because the colours merge into one another. The wavelengths associated with visible light are very small. They range from approximately 390 nanometres (or 390×10^{-9} m) for violet light to about 780 nanometres for red light.

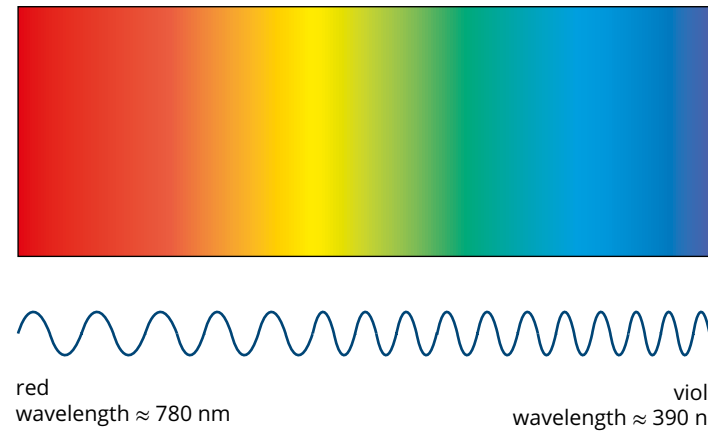


FIGURE 11.2.3 Visible light is one category of EMR. The spectrum of visible light contains a myriad of colours. Each different colour or hue is light of a different wavelength.

The colour of an object that we see is actually a physiological response to the particular wavelength(s) of light entering our eyes. Our colour-sensing system, consisting of the eye, nerve conductors and the brain, can discriminate between millions of different colours. However, different combinations of wavelengths of light can evoke the same response from our brain. In other words, there are a number of different ways in which to make an object appear a particular shade of colour.

The colour of an object is determined by the colours of light it reflects and absorbs when white light, evenly distributed across the visible spectrum, is shone upon it. When an incident ray of light strikes the surface of an object it may be absorbed, transmitted and/or reflected.

- If all of the white light falling on a surface is reflected, then the object will appear white.
- If all of the white light falling on a surface is absorbed, then the object will appear black because no light is reflected.
- If all of the white light falling on a surface is absorbed except for blue, then the object will appear blue because this is the only light that is reflected.

You perceive light as white light if it contains roughly equal amounts of each of the colours of the visible spectrum. The page of this book appears white because it is reflecting all of the colours (wavelengths) of visible light in roughly equal proportions.

Sunlight, incandescent light and fluorescent light all produce the same general sensation of white light. The light from incandescent and fluorescent globes does not appear to be as white as sunlight. This is because sunlight is very evenly distributed across the spectrum, but an incandescent source radiates considerably more red light than blue, and a fluorescent source favours blue light.

NON-VISIBLE FORMS OF EMR

The electromagnetic spectrum is divided into seven different categories based on the frequencies of the different categories. The boundaries or each section shouldn't be thought of as an exact number, but they do provide a convenient means of identifying the properties of the frequencies of EMR in each section. Visible light, for example, is the category of EMR that is visible to the human eye.

Radio waves

Accelerating a positive or negative charge can produce EMR. Electrons oscillating in a conducting wire, such as an antenna, produce the radio waves that bring sports broadcasts to your car. These long-wavelength, low-energy electromagnetic waves blanket the surrounding region, and aerials can receive the signal many kilometres from the source. As a result of the radio waves, electrons in the receiving aerial will oscillate, producing a current that can be amplified. Radio waves can be transmitted over very long distances, including around the Earth, by reflection from layers of atmosphere.

Radio waves are the lowest energy EMR, so they are also the most common form of energy emitted by interstellar objects. They are a major focus of studies seeking to determine the evolution, shape and size of our universe (Figure 11.2.4).

Microwaves

Microwaves are EMR ranging from about 1 mm to about 10 cm. The microwaves that cook your dinner are produced by the spin of an electron or nucleus. Microwave links are also used for communication between particular locations over long distances, and radar equipment uses microwaves of centimetre wavelengths to locate distant objects by measuring the strength and direction of reflected signals.

Infrared waves

Infrared or heat radiation includes the wavelengths that are emitted by every object at a temperature above absolute zero. When you feel the warmth of the Sun or a heater, your skin is detecting infrared radiation. The hotter the object, the more radiation that is emitted and the higher the frequency of the radiation.

Night scopes and infrared spy satellites create an image by sensing infrared radiation and converting it into a visible picture.

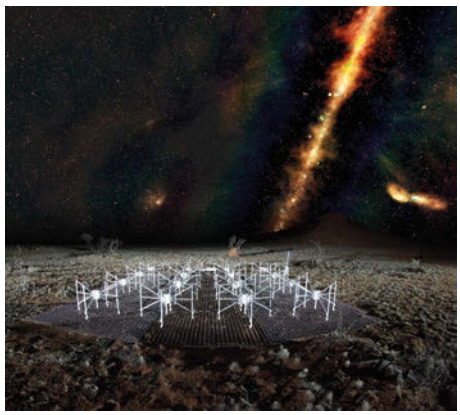


FIGURE 11.2.4 The Murchison Widefield Array (MWA) is a low-frequency radio telescope located in Western Australia, operating between 80 and 300 MHz and conducting large-scale surveys of the southern sky. This composite image shows a section of the MWA, the Milky Way and the radio galaxy Centaraus A.

Ultraviolet waves

Ultraviolet waves have wavelengths shorter than the violet that our eyes can see, but no greater than about 10 nm. Many insects and birds can detect ultraviolet light that is commonly reflected from flowers, allowing potential pollen sources to be located. Although ultraviolet light is less energetic than gamma rays and X-rays, it is known to cause skin cancer, particularly with increased time of exposure.

X-ray waves

X-rays initially got their name as a result of scientists not knowing what they were when they were first detected. They are produced when fast-moving electrons are fired into an atom. X-rays are high-energy radiation that can pass through body tissue and so are used in medical diagnosis. In industry, X-rays are used for safety testing, security, quality control and, increasingly, as a means of investigating structures at the subatomic level, including that of DNA.

Gamma-ray waves

The highest energy, shortest wavelength radiation is the gamma ray, produced within the nucleus of an atom. Gamma rays are one of three types of emissions that result from radioactive decay. Gamma rays are able to penetrate through a considerable depth of most materials and require dense materials to absorb them.

11.2 Review

SUMMARY

- Electromagnetic radiation (EMR) can be modelled as a transverse wave propagated by electrical and magnetic fields at right angles to each other. Hence, it doesn't need a medium in which to travel.
- Visible light is only a small part of the electromagnetic spectrum. The many forms of EMR are essentially the same, their properties differing as a result of their frequency and, hence, wavelength.
- All EMR travels at a speed of $3.0 \times 10^8\,m\,s^{-1}$ in a vacuum.
- White light contains red, orange, yellow, green, blue and violet light in approximately equal proportions.
- From longest to shortest wavelength, the parts of the electromagnetic spectrum are radio waves, microwaves, infrared radiation, visible light, ultraviolet radiation, X-rays and gamma rays.

KEY QUESTIONS

Retrieval

1 List three different categories of electromagnetic radiation.

2 Name two properties that are common to all forms of electromagnetic radiation.

3 State the approximate range of frequencies included in the EMR category of visible light.

4 List the seven categories of electromagnetic radiation in order from longest wavelength to shortest wavelength.

Comprehension

5 Two sources of electromagnetic radiation have wavelengths of 450 nm and 780 nm respectively. Explain why the 780 nm radiation has the lower energy.

6 Describe a use for X-rays. State the particular property of X-rays that makes them suitable for this purpose.

7 Determine whether radio waves or microwaves have the higher frequency. Explain your answer.

Analysis

8 Calculate the wavelength of:
- **a** microwaves of frequency 3.0×10^{10} Hz.
- **b** ultraviolet radiation of frequency 1.0×10^{15} Hz.

9 Infrared radiation has wavelengths between 700.0 nm and 1.00 mm. Calculate the corresponding range of frequencies of infrared radiation, based on the limiting values of 700.0 nm and 1.00 mm.

11.3 Reflection of light

BY THE END OF THIS MODULE, YOU SHOULD BE ABLE TO:

- state that a wave model of light can explain reflection
- state the law of reflection
- apply the ray and wave models to the reflection of light
- use ray diagrams to demonstrate the reflection of light
- use ray diagrams and the mirror formula to solve problems involving the reflection of light on plane and curved mirrors.

MODELLING REFLECTION

The reflection of waves was explained in Chapter 9. Light has been observed to obey the same laws of reflection that apply to waves and so evidence is provided for the argument that light is a wave.

Using a wave model, the reflection of light would be represented as a series of wavefronts striking a surface and then being reflected on the surface. However, it is far more common to model the reflection of light using ray diagrams and the conventions associated with them, as shown in Figure 11.3.1. Creating a model for the path of light and the formation of images in optical systems is far simpler using **geometrical optics** rather than a wave-optics approach.

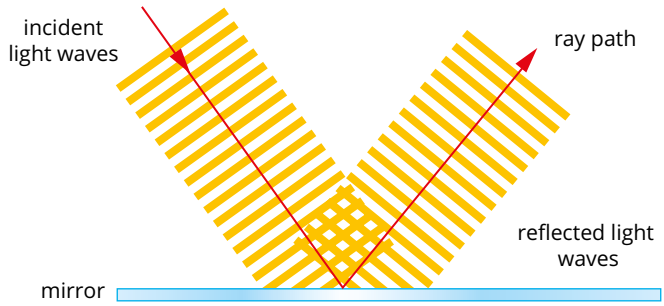


FIGURE 11.3.1 The path of light through many optical systems involving lenses and mirrors can be accurately represented using rays.

Consider the plane mirror drawn in Figure 11.3.2.

- A normal to the surface of the mirror is defined as the line perpendicular (at 90°) to the mirror's surface at the point where an incoming or incident ray strikes the surface of the mirror.
- The angle between an incident ray and the normal is the angle of incidence, denoted *i*.
- The ray strikes the mirror and reflects with an angle of reflection, *r*, which is the angle between the reflected ray and the normal.

Experiments show that whenever reflection occurs, the angle of incidence always equals the angle of reflection. In addition, the light reflects in such a way that the incident ray, the normal and the reflected ray all lie in the same plane. The law of reflection can then be re-stated using a ray model for light.

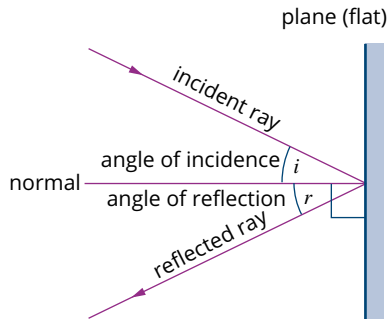


FIGURE 11.3.2 When light reflects from a plane mirror, the angle of incidence equals the angle of reflection: $i = r$.

The law of reflection states that the angle of incidence, *i*, is equal to the angle of reflection, *r* ($i = r$). The incident ray, the normal and the reflected ray will all lie in the same plane.

IMAGES IN PLANE MIRRORS

When considering the images formed in a mirror, it is helpful to distinguish between seeing an image directly and seeing an image of the object in the mirror.

When a person stands in front of a plane mirror, light from a point on their foot will travel to the mirror and be reflected. All rays obey the law of reflection, and a pair of slightly diverging rays can be traced as they leave the foot, reflect from the mirror and return to the observer's eyes. To form an image, the observer's eyes focus the diverging light rays and the brain interprets the rays as having come from a single point behind the mirror. This is where the image is seen in the mirror.

Figure 11.3.3 illustrates geometrically how the eye and brain subconsciously extrapolate diverging rays of light until they meet and are interpreted as an image.

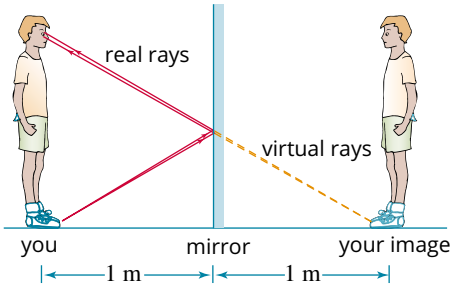


FIGURE 11.3.3 Diverging reflected rays are focused by the eye and the brain interprets the rays as having come from a single point behind a mirror.

It is important to note that the rays behind the mirror are not actually there. They are virtual rays, and by convention they are shown as dashed lines. When an image forms behind an optical element such as a mirror, it is classified as a **virtual image**. Other optical systems form a real image where the rays converge to meet in reality. A **real image** can be shown on a screen, like an image from a slide projector. Virtual images cannot be projected on to a screen.

The ray-tracing exercise shown in Figure 11.3.3 can be repeated for all parts of the body to locate the complete image of the whole person. A corresponding image point matches every point on the object. Each image point is the same distance behind the mirror surface as the object is in front. The object and the image are exactly the same size. All images formed by plane mirrors have the following characteristics:

- The image is always upright.
- The image is the same distance behind the mirror as the object is in front.
- The image is the same size as the object.

Lateral inversion

The image that you see in a mirror is not exactly what you look like. The geometry of reflection means that images are reversed from left to right, in a process known as lateral inversion. If you stand in front of a mirror and hold up your right hand, it will appear as if your image is holding up its left hand, as shown in Figure 11.3.4.

FIGURE 11.3.4 Although the woman is applying makeup with her right hand, in her image she appears to be applying it with her left hand.

Unlike a mirror image, a photo of your face is not laterally inverted, so it will look slightly different from the face that you are used to seeing in the mirror. However, the differences may not be so great that you consciously notice them. Instead, you might just feel like something is 'wrong' with the photo.

CURVED MIRRORS

The applications of plane mirrors in everyday life are limited by the features of the image that can be produced. For example, the image in a plane mirror is always the same size as the reflected object, so a plane mirror will not produce a **magnification**. Curved mirrors provide a greater variety of options, depending on the extent and sense of the curvature of the mirror and the placement of the object, as shown in Figure 11.3.5. Shop-security mirrors, shaving and make-up mirrors and dentist's mirrors all use a curved mirror to produce an image that is appropriate for the situation in which it is used.

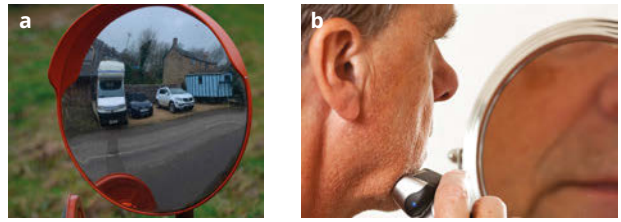


FIGURE 11.3.5 (a) In one mirror the image is upright and significantly reduced in size. (b) The image in the other mirror has been magnified many times. Both are examples of the application of curved mirrors.

All curved mirrors are either **concave** or **convex**. The **focal length** of a mirror is the distance from the mirror at which a parallel beam of light is brought to a focus.

- A concave mirror is curved like the inside of a spoon and is converging. When parallel rays of light are reflected at the surface of the mirror, the rays focus to a point in front of the mirror. Concave mirrors have a real focal point in front of the mirror, as shown in Figure 11.3.6a.
- A convex mirror is shaped like the back of a spoon and is diverging. When parallel rays of light are reflected at the surface of the mirror, the rays spread out in front of the mirror. Convex mirrors have a virtual or imaginary focal point behind the mirror, as shown in Figure 11.3.6b.

To understand how a curved mirror produces an image, consider it to be made up of a number of tiny plane mirrors. A two-dimensional representation of this is shown in Figure 11.3.6. If parallel rays of light shine directly onto the surface of each mirror, the rays reflect and the angle of incidence equals the angle of reflection, therefore obeying the law of reflection for the position of the (plane) mirror it strikes.

Curved mirrors are usually spherical in shape as if the mirror has been made from a portion of a sphere. They are cheap and easy to manufacture but are only capable of bringing parallel light rays to an approximate focus. The reflected rays do not intersect at precisely the one single point, as shown in Figure 11.3.7a. This causes blurring of an image near the edges of the mirror. This distortion is called spherical **aberration**, and is particularly noticeable if the mirror is large compared to its **radius of curvature**. If an undistorted image, free of spherical aberration, is required, a parabolic mirror is used. A parallel beam of light will reflect from a parabolic mirror to a sharp focus, as shown in Figure 11.3.7b.

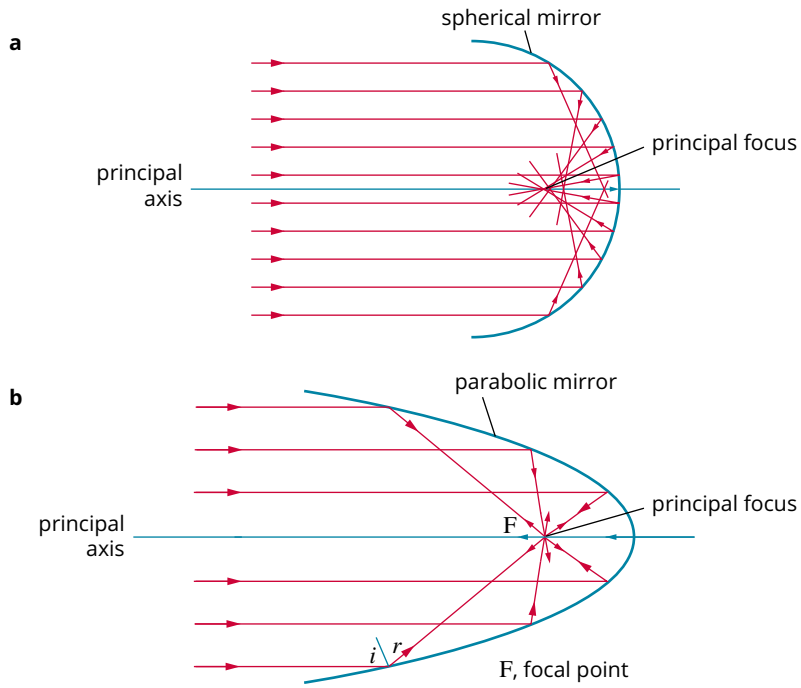


FIGURE 11.3.7 (a) Spherical mirrors do not have a precisely defined principal focus, and the further a ray of light is from the principal axis of the mirror, the greater the inaccuracy. The effect is most noticeable if the mirror is large compared to its radius of curvature. (b) A parabolic concave mirror will bring parallel rays to a perfect focus.

Spherical mirrors are often used in inexpensive torches and in security and dental mirrors, where the accuracy of the focal point is not a great concern. Parabolic mirrors are more difficult to produce and therefore are more expensive. Parabolic mirrors are usually reserved for situations in which a precise focus and undistorted images are required, such as in reflecting telescopes.

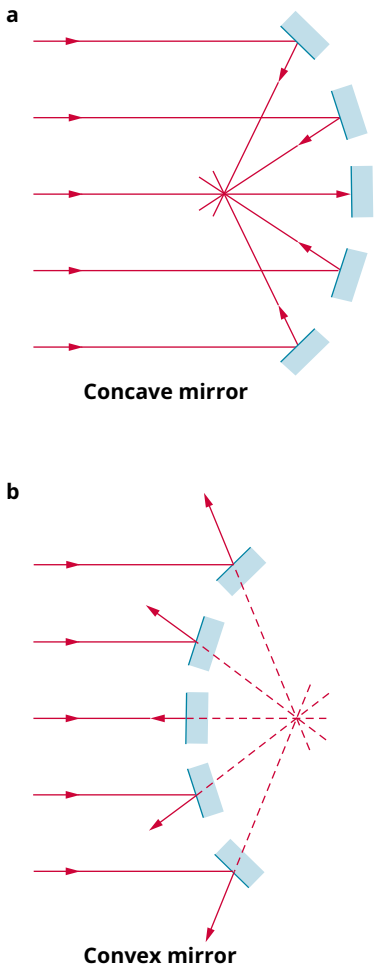


FIGURE 11.3.6 Each ray obeys the law of reflection, resulting in (a) converging rays or (b) diverging rays. In each case, a focal point can be defined. A concave mirror has a real focus, and the focal length is positive. The focus for the convex mirror is virtual because its position is determined by extrapolating the reflected rays behind the mirror.

DRAWING RAY DIAGRAMS

The image in a spherical mirror or a lens can be found using a ray diagram. Before explaining how an image is found, some standard terms used to describe a spherical mirror, as shown in Figure 11.3.8, need to be defined.

- A vertical line called the optical axis represents the reflecting surface (the back of the mirror). Although the mirror surface is curved, the optical axis is a straight vertical line. A ray diagram tends to use a much larger vertical scale than horizontal scale, allowing the mirror to be represented by a straight line with little loss of accuracy.
- The optical axis is perpendicular to the **principal axis**, and the pole, P, the centre of the mirror, is placed at the intersection of the optical axis and the principal axis. A small curved mirror symbol is placed here to indicate the type of mirror being used.
- The **principal focus** of the mirror, F, and its centre of curvature, C, are located on the principal axis to scale. The **centre of curvature** of the mirror is the point at the centre of the sphere of which the mirror forms a part.
- R is the radius of the sphere from which the mirror is assumed to have been made. This is the radius of curvature of the mirror.
- f is the distance between the pole and the principal focus. This is the focal length of the mirror. The focal length is half the radius of curvature: $f = \frac{R}{2}$.
- Traditionally, the object is on the left of the optical axis, along with the eye that will view the image. The object is usually represented as a small vertical arrow.

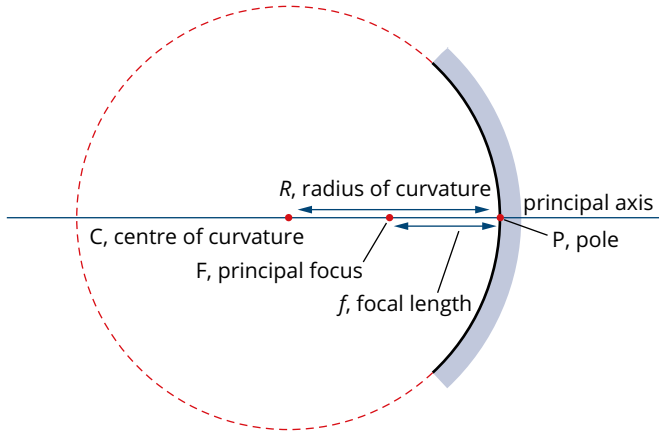


FIGURE 11.3.8 Terminology used to describe spherical mirrors.

Use these conventions to draw a ray diagram and find an image in a mirror (Figure 11.3.9).

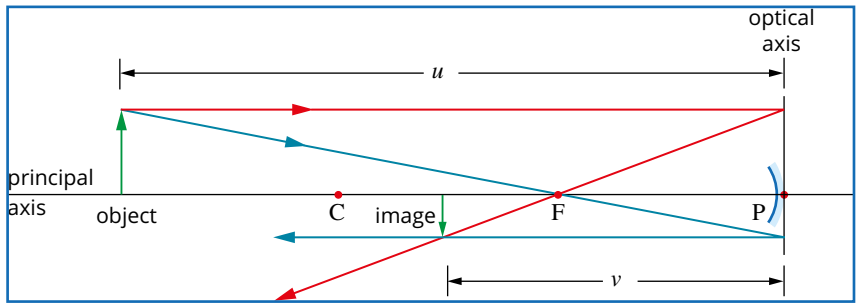


FIGURE 11.3.9 Layout for a ray diagram to find the image of an object in a concave mirror.

When constructing a ray diagram, the vertical scale for the diagram does not have to be the same as the horizontal scale. This is particularly useful if a tiny object such as a small whisker is to be viewed in a mirror with a focal length of 20 cm. The distance from the object to the mirror (or optical axis) is called the object distance, u, and the distance from the optical axis to the image is the image distance, v. At least two rays from the top of the object must be drawn to locate the position of the image. It is a good idea to use a third ray to check the final image. All three rays should meet at a single image point.

IMAGE FORMATION IN A CONCAVE MIRROR

To determine the image of an object in a concave mirror, the object is positioned on the principal axis to the left of the mirror. Between two and four rays are traced from the top of the object; the top of the image is found at the intersection of these rays. The rest of the image fills in the space from this point to the principal axis, and is perpendicular to the principal axis. The four rays are described below and shown in Figure 11.3.10.

- Ray 1: A ray of light that travels parallel to the principal axis will be reflected through the principal focus of the mirror, as shown in Figure 11.3.10a.
- Ray 2: A ray of light emanating from the object and travelling through the centre of curvature of the mirror will strike the surface at an angle of 90°, along a normal. This ray will therefore be reflected back along the path from which it came, as shown in Figure 11.3.10b.
- Ray 3: The ray that strikes the pole of the mirror will reflect at an angle equal to the angle of incidence. At the pole, the mirror acts like a plane mirror and the principal axis becomes a normal, as shown in Figure 11.3.10c.
- Ray 4: The ray emanating from the object and travelling through the principal focus before striking the mirror will be reflected from the mirror parallel to the principal axis, as shown in Figure 11.3.10d.

If any two of these four rays are traced, the point at which they intersect determines the location of the image, as shown in Figure 11.3.10e. When the position of the image is found, you know that any ray emanating from the top of the object and striking the mirror must reflect through this point, and a clear image is produced.

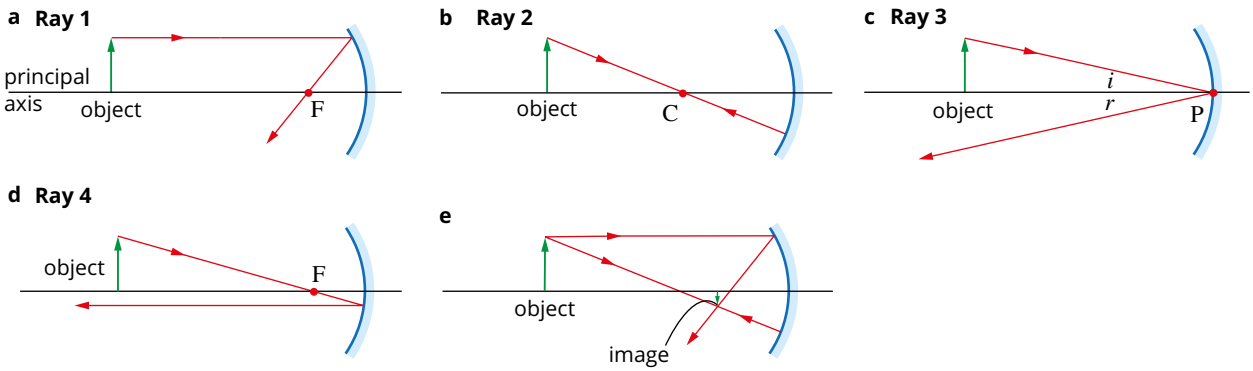


FIGURE 11.3.10 The path of four rays leaving the top of an object reflect from the mirror to produce an image. (a) This ray travels parallel to the principal axis and reflects through F. (b) Ray 2 passes through C and is reflected back along its incident path. (c) The ray striking the pole (P) will reflect as if it has struck a small plane mirror, $i = r$. (d) The ray passing through F reflects parallel to the principal axis. (e) Intersecting rays locate the image.

In practice, the quickest method to measure the focal length of a concave mirror is to stand near a window, holding the mirror so that an image of a distant object forms on a small white card or screen that you hold in your other hand. Light rays from a distant source are considered to be parallel to one another, so you are effectively focusing parallel rays of light. The distance from the mirror to the screen approximates the focal length of the mirror. Figure 11.3.11 shows the images produced when the same object is placed at various distances from a concave spherical mirror.

- Figure 11.3.11a shows that when an object is placed at a relatively large distance ($u > R$) from a concave mirror, the image formed is real, diminished and inverted.
- Figure 11.3.11b shows that when the object is placed at the centre of curvature of the mirror ($u = R$), the image formed is also real and inverted, but it is exactly the same size and distance from the mirror as the object.
- Figure 11.3.11c shows that when the object is placed between the centre of curvature and the focal point ($f < u < R$), the image is again real and inverted, but now it is magnified.
- Figure 11.3.11d shows that when an object is placed at the principal focus of a concave mirror ($u = f$) the reflected rays will emerge parallel to one another. This is the arrangement used in car headlamps, torches and similar objects, in which a globe is placed at the focal point of a concave mirror. The rays leaving the top of the object strike the mirror and emerge parallel to one another so the image can be considered to be at infinity.

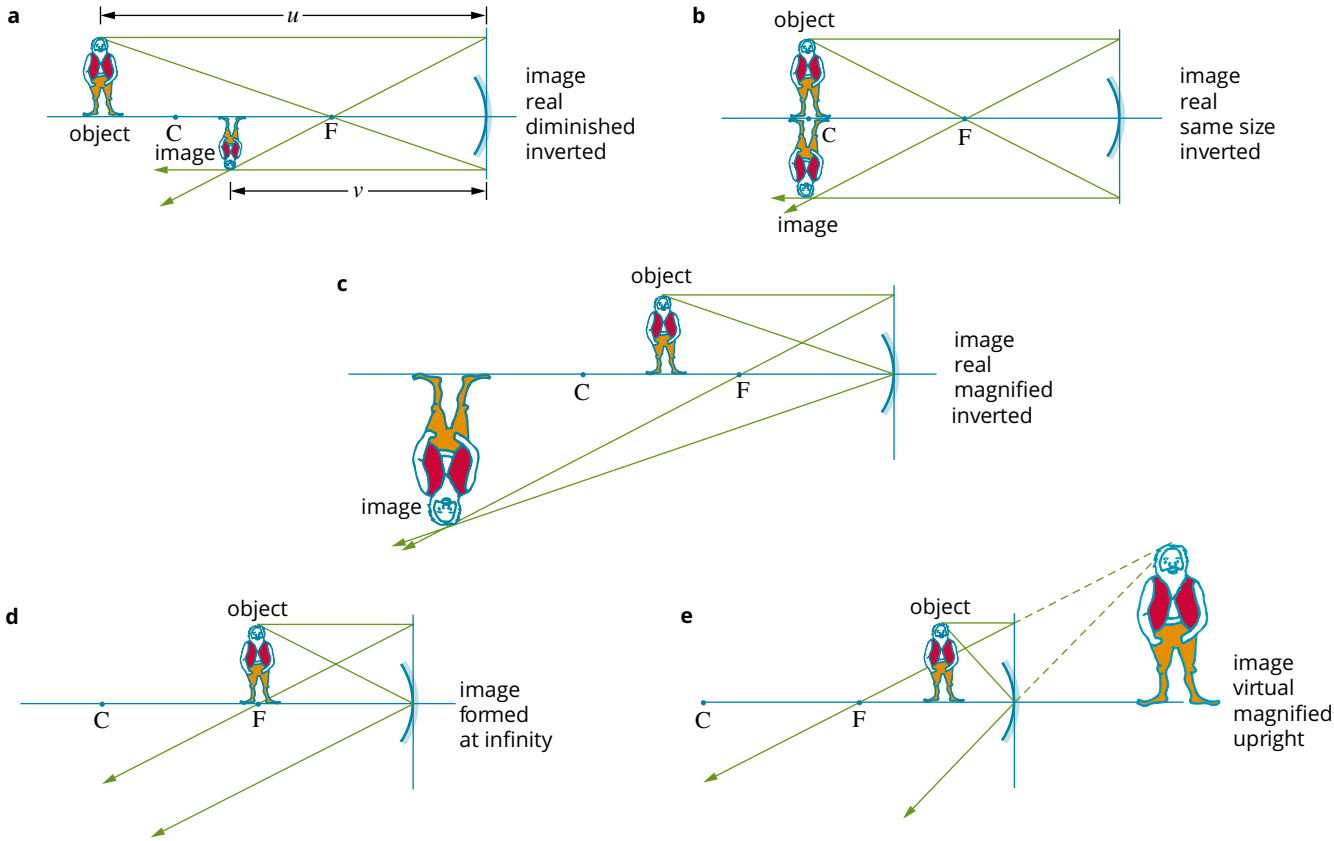


FIGURE 11.3.11 (a)–(c) A concave mirror will produce a real image when the object is placed farther than the focal point, F, and (d), (e) a virtual image when at or closer than the focal length.

- Figure 11.3.11e shows that when an object is placed inside the focal length of the mirror ($u < f$), the reflected rays diverge like those from a plane mirror. This means that the rays cannot intersect to create a real image and our eyes interpret the diverging rays as coming from an image behind the mirror and a virtual, upright and magnified image results. The location of the image is found by extrapolating the rays back to their point of intersection, as shown. It is a virtual image, so it cannot be projected onto a screen.

The complete description of an image requires its nature (real or virtual), orientation (upright or inverted), position and magnification to be stated. Magnification refers to the size of an image relative to the object. If the image is larger than the object, it can be described as being enlarged or magnified. A smaller image is described as diminished or reduced. Sometimes the actual height of an image has to be found, so a carefully drawn scale diagram is essential.

The magnification, M, of an image is the factor by which the size of the object has been multiplied. This is the ratio of the height of the image to the height of the object. By convention, the height of an inverted image is assigned a negative value. A positive magnification value indicates that the image is upright relative to the object. A negative magnification value indicates that the image is inverted relative to the object.

- A magnified image has a magnification factor of greater than one, $|M| > 1$.
- A diminished image has a magnification factor of less than one, $|M| < 1$.
- If $|M| = 1$, the image and object are the same size.

A mirror producing a magnification of −1.2, for example, means that the image is inverted and 20% larger than the object.

Note that $|M|$ is the absolute value of M, which is the magnitude of the value regardless of the sign (positive or negative).

The magnification of an image in a mirror can also be found by the ratio of the image distance to the object distance. The ratio of the heights of the image and object is exactly the same as the ratio of the distances of the image and the object from the mirror or lens.

The magnification factor in optics is the ratio of the image height to the object height, and can be found by direct measurement of a scaled ray diagram or by the ratio of the image distance to the object distance.

A summary of the images formed by concave spherical mirrors is provided in Table 11.3.1.

TABLE 11.3.1 Summary of images formed by concave spherical mirrors

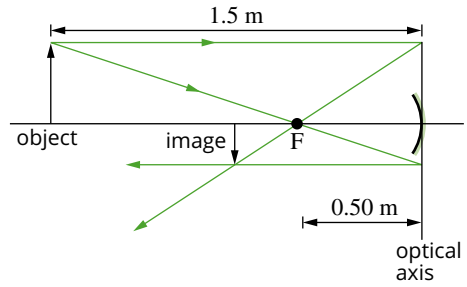
Position of object	Position of image	Description of image		
		Real or virtual	Upright or inverted	Enlarged or diminished
beyond C	between C and F	real	inverted	diminished
at C	at C	real	inverted	same size
between C and F	beyond C	real	Inverted	enlarged
at F	image at infinity	—	—	—
between F and P	behind mirror	virtual	upright	enlarged

Worked example 11.3.1

IMAGE FORMATION IN CONCAVE MIRRORS

An object is placed 1.5 m in front of a concave mirror with a focal length of 50.0 cm.

a Construct a ray diagram of this situation to describe the type of image formed.

Thinking	Working
Construct a ray diagram (only two rays are needed).	

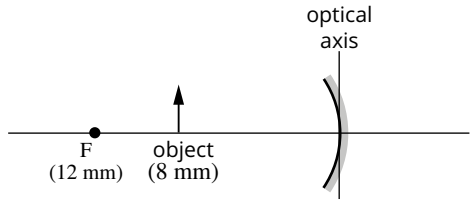
b Interpret the ray diagram.

Thinking	Working
Interpret the diagram. The image is in front of the mirror so it is real.	The image will be real, inverted and diminished.

➤ Try yourself 11.3.1

IMAGE FORMATION IN CONCAVE MIRRORS

A dentist holds a concave mirror of focal length 12 mm at a distance of 8 mm from the tooth that needs a filling.



a Construct a ray diagram of this situation to describe the type of image formed.

b Interpret the ray diagram.

FIGURE 11.3.12 Convex mirrors are used on the road to help drivers view traffic around sharp corners.

IMAGE FORMATION IN CONVEX MIRRORS

Convex mirrors are very common in everyday life, often seen as large mirrors used for security in the ceiling corners of shops or for traffic safety at blind corners, as shown in Figure 11.3.12, and as rear-view mirrors for particularly long vehicles. Convex mirrors can be spherical, parabolic, ellipsoidal or hyperbolic in shape, the last three only being used in telescopes and other specialised equipment.

The reflecting surface of a spherical convex mirror is again a portion of a sphere, but in this case the reflective surface is on the outside of the sphere. Incident light rays parallel to the principal axis of a convex mirror will diverge on reflection. If the rays are drawn back behind the mirror, they appear to come from one single point. The virtual principal focus of the mirror is shown in Figure 11.3.13. The distance from the pole of the mirror to this point is the focal length of the mirror (f) and, as with a concave mirror, the focal length is half the radius of curvature:

$$f = \frac{R}{2}$$

Convex mirrors (like plane mirrors) can only produce a virtual image. A convex mirror always provides a wide field of view and an image that is always upright, as shown in Figure 11.3.13.

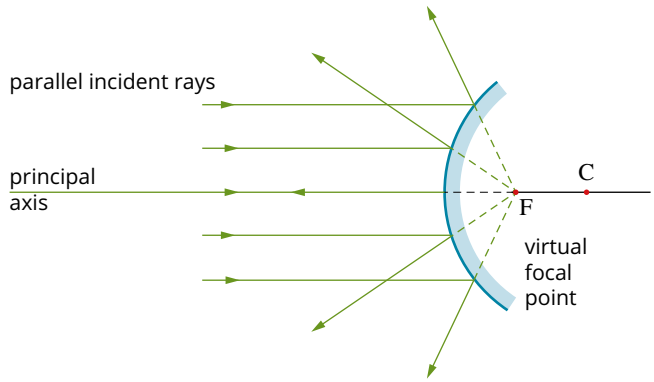


FIGURE 11.3.13 The parallel rays reflected from a convex mirror will diverge in such a way that they appear to come from a single point at a virtual focus. The reflecting surface is on the outside of the sphere indicated by the blue line.

When constructing a ray diagram for a convex mirror, the same conventions apply as for concave mirrors. A vertical line, the optical axis, representing the reflecting surface, is drawn perpendicular to the principal axis for the mirror. A small convex mirror symbol, whose pole lies at the origin for the axes, indicates the type of mirror used. The object is always placed to the left of the mirror and the principal focal point will lie to the right of the mirror (i.e. behind it). The horizontal and vertical scales need not be the same, so choose scales that accurately represent the height of the image.

Figure 11.3.14 shows the effect of placing the same object at various distances from a convex mirror. All the images lie behind the mirror between the pole and the focal point, and all are upright and diminished. Each image, however, has a different magnification that depends on the position of the object from the mirror. As the object is moved closer to the mirror, the image size increases. Because of the curvature of the mirror the image can never be quite as large as the object, so the magnification is always less than 1 ($|M| < 1$).

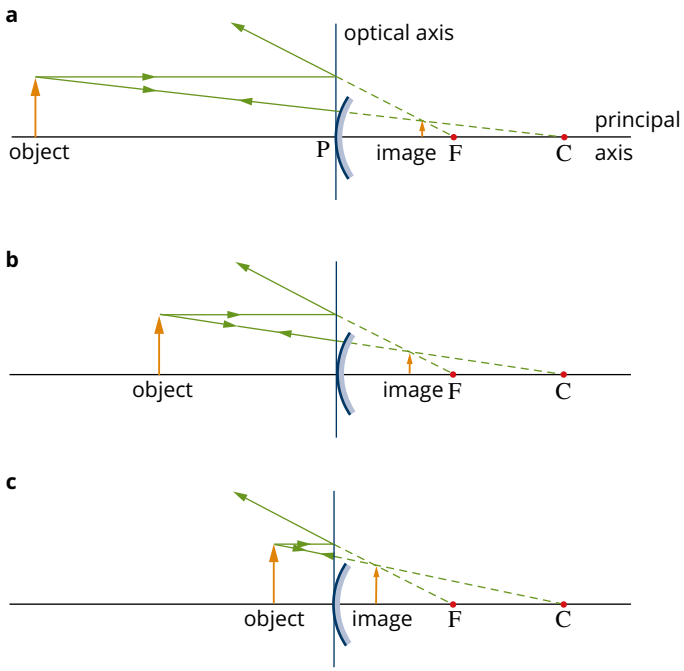


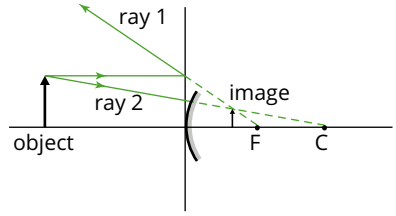
FIGURE 11.3.14 Ray tracing for a convex mirror. All images are upright, virtual and diminished. As the object is brought closer to the mirror, the image increases in size, but it will never be the same size as the object.

Worked example 11.3.2

IMAGE FORMATION IN CONVEX MIRRORS

A shop uses a convex mirror of focal length 2.0 m for security purposes. A 1.5 m tall person is standing 4.0 m from the mirror.

Construct a ray diagram of this situation and describe the type of image formed.

Thinking	Working
Construct the ray diagram. (Only two rays are needed.)	
Interpret the ray diagram.	The image will be virtual, upright and diminished.

➤ Try yourself 11.3.2

IMAGE FORMATION IN CONVEX MIRRORS

An object is placed 30 cm in front of a convex mirror of focal length 15 cm.
Construct a ray diagram of this situation and describe the type of image formed.

11.3 Review

SUMMARY

- Ray-tracing can be used to determine the image formed by a mirror or lens. An image of a point exists when rays from the point converge (or appear to converge) at another point.
- There are four rays, incident on a curved mirror, whose paths can be predicted to determine the position, nature, orientation, size and magnification of the image. At least two rays must be traced to locate an image when using a ray diagram.
- The complete description of an image requires that the position, nature, orientation and size of the image be stated.
- Diverging rays of light entering our eyes are interpreted as having come from a single point behind a plane mirror, where a virtual image is seen.
- The nature of an image is either 'real' or 'virtual'. A real image is formed in front of the mirror and a virtual image is formed behind. The orientation of an image is either 'upright' or 'inverted' relative to the object.
- A plane mirror produces an image that is always virtual, upright and the same size.
- A concave mirror is curved like the inside of the bowl of a spoon. A convex mirror is curved like the back of a spoon.
- A curved mirror is usually spherical or parabolic in shape. Parabolic mirrors create more precise images but are more difficult and costly to produce.
- A concave mirror can produce real images that are inverted and virtual images that are upright, depending on the position of the object relative to the focal length.
- Rays parallel to the principal axis will diverge on reflection from a convex mirror. They reflect as if they come from a single point behind the mirror, the principal focus.
- A convex mirror is useful because it has a wide field of view and always produces upright images.
- The focal length of spherical concave and convex mirrors is half its radius of curvature: $f = \frac{R}{2}$
- Convex mirrors always produce images that are virtual, upright and diminished. The size of the image depends on how close the object is to the mirror, but the magnification is always less than 1.

KEY QUESTIONS

Retrieval

1 Describe the image that is formed by a plane mirror.

2 Explain the term 'radius of curvature' for a spherical mirror.

3 Draw a labelled diagram for the following on a spherical concave mirror: centre of curvature, principal axis, principal focus, pole.

Comprehension

4 There are some applications where a convex mirror will be used in preference to a plane mirror. Describe such an application. Explain the similarities and differences between the images produced.

5 Explain why a convex mirror can never produce a real image.

6 List the four characteristics that must be described for an image formed in a mirror. Show the options for each characteristic.

Analysis

7 Compare and contrast concave and convex mirrors. Name one application of each.

8 A cavity in a tooth is 2 mm long. A dentist uses a concave mirror of focal length 15 mm to view the tooth. The mirror is held 8 mm from the tooth. The length of the image is 17 mm.

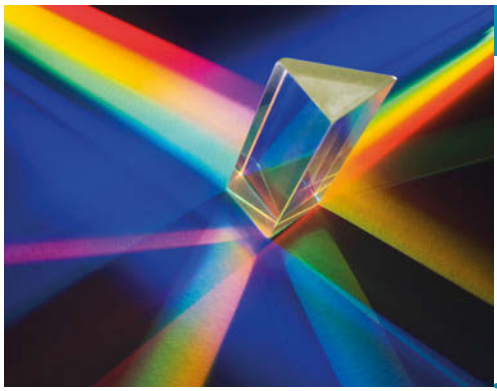
Describe the nature of the image formed.

9 A convex mirror of focal length 3 m is placed at a 'blind corner'. A person looking at the mirror sees a truck coming when the truck is 30 m from the mirror.

a Describe the nature of the image.

b Consider how the image of the truck will appear when it is 15 m from the mirror.

11.4 Refraction of light and image formation with lenses



BY THE END OF THIS MODULE, YOU SHOULD BE ABLE TO:

- use ray diagrams to demonstrate the refraction of light
- define Snell's law
- recall that a wave model of light can explain refraction, total internal reflection and dispersion
- solve problems involving the refraction of light at the boundary between two mediums
- use ray diagrams to determine image formation in single concave and convex lenses.

You will recall from Module 9.4 that light travels in a straight path through a uniform medium, but when entering a medium with a different optical density its path may be bent. Evidence of the bending of light is shown in Figure 11.4.1 in which a person's face can be seen through a glass of water. Some of the person's face can be seen directly. Light must be travelling along a straight path from the person's face to the observer's eyes. However, notice that parts of the person's face can also be seen through the glass of water. The light rays from the person's face passing through the glass of water have been re-directed or bent by the water towards the observer's eyes. The bending or change of direction of light as it passes from one medium to another is called refraction.

i Refraction is the bending of the path of light due to a change in speed as it enters a medium of different optical density.

A number of common phenomena are caused by refraction, including the bend that appears in a straw that is standing in a glass of water, as shown in Figure 11.4.2.

FIGURE 11.4.1 Refraction occurs because the light changes speed as it enters a medium of different optical density. In this case, the light reflected from the person's face is bent as it enters and leaves the glass of water. As a result the face is seen 'inside' the glass of water.

FIGURE 11.4.2 The refraction of light makes the straw appear to have a bend in it.

To fully understand these phenomena, the refraction of light can be investigated by using a block of glass and a narrow beam of light. Figure 11.4.3 shows a light beam travelling through air and entering a semicircular glass block. When light strikes the surface of a material, some of the incident light is reflected, some is transmitted and some is absorbed by the material. The transmitted ray deviates from its original direction of travel. This change in direction occurs at the boundary between the air and the glass; the ray has been refracted. Refraction occurs because the light changes speed as it enters a medium of different optical density.

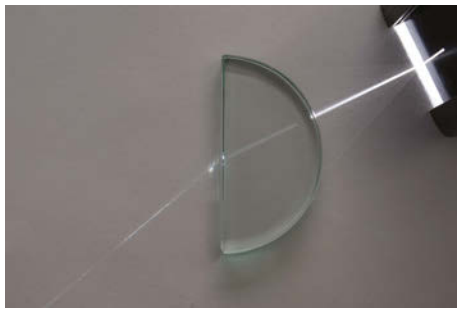


FIGURE 11.4.3 A light ray strikes the surface of a glass prism at an angle of incidence of 90° and is transmitted through the prism. The transmitted ray is refracted as it leaves the prism because of a change in the speed of the light. The bending occurs at the boundary of the two media.

REFRACTION BY RAYS

The refraction of light can be represented using a ray approach. The ray of light that strikes the boundary between two media is called the incident ray. A normal to the boundary is drawn at 90° to the boundary at the point where the incident ray strikes. The angle between the normal and the incident ray is called the angle of incidence, i. The angle between the normal and the transmitted or refracted ray is called the angle of refraction, r. The incident ray, the normal and the refracted ray all lie in the same plane, as shown in Figure 11.4.4.

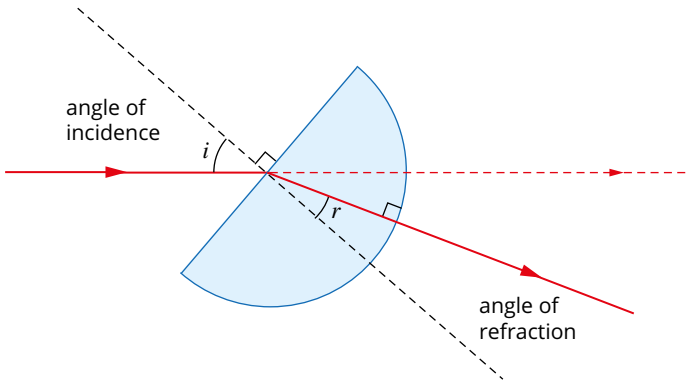


FIGURE 11.4.4 The angles of incidence and refraction are defined as shown. An example of refraction can be seen as light enters the glass prism.

Refraction is only noticeable if the angle of incidence is larger than 0°. If the incident ray is perpendicular to the boundary, i.e. $i = 0$, the direction of travel of the transmitted ray will not deviate even though the speed of light has altered. This can be seen in Figure 11.4.4 as the ray leaves the prism and continues in a straight path.

When light travelling through air enters a more optically dense medium such as glass (where it travels more slowly), it will be refracted so that the angle of refraction is smaller than the angle of incidence. We say that the path of light has been deviated 'towards the normal'. When light passes from glass to air it speeds up, as it has entered a less optically dense medium. The angle of refraction will be larger than the angle of incidence. The path of light is described as being refracted 'away from the normal'.

The behaviour of light undergoing refraction can be summarised by two statements:

- **When a light ray passes into a medium in which it travels more slowly (a more optically dense medium), it is refracted towards the normal.**
- **When a light ray passes into a medium in which it travels faster (a less optically dense medium), it is refracted away from the normal.**

REFRACTION BY WAVES

Although the way in which light is reflected is modelled equally effectively using either a particle or wave approach, this is not the case for refraction. The wave model is better able to explain the change in direction that is observed as light enters a medium in which its speed is altered.

Consider a light wave travelling at an angle towards a boundary between two media of differing optical density; for example, air to water, as shown in Figure 11.4.5a. As soon as the light wave enters the water it will slow down. At the moment shown in the diagram, the section of wavefront, AB, that first enters the water will be travelling at a slower speed than the section of the same wavefront, BC, that has not yet entered the water. This first section of the wavefront then effectively lags behind the position that it would have held had it continued at its initial faster speed. The overall result of this delay is that the direction of travel of the overall wavefront is altered. Figure 11.4.5b shows that, once a number of wavefronts have passed into the second medium, the direction of travel of the overall wave is deviated from its original course. A similar arrangement can be constructed for the refraction of light as it speeds up.

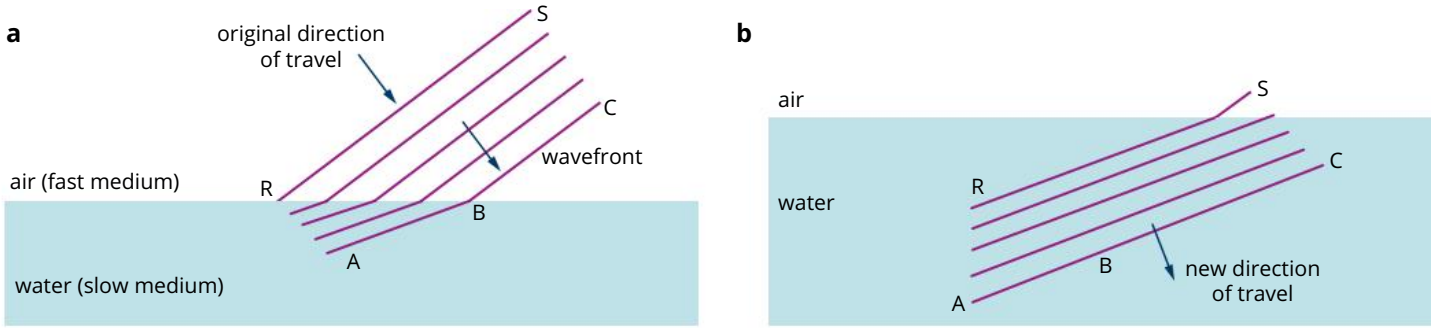


FIGURE 11.4.5 The change in the direction of light that is associated with a change of speed is called refraction. Refraction can be modelled by treating light as a wave.

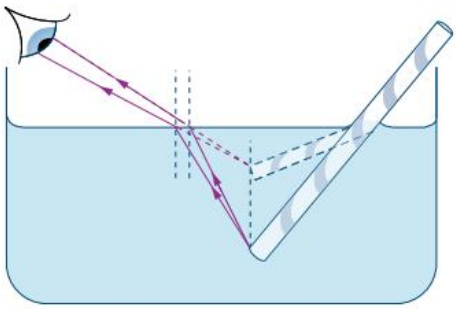


FIGURE 11.4.6 The immersed portion of the straw is apparently shifted upwards due to refraction. This is because the rays appear to have come from a raised position in the glass of water.

Objects partially immersed in water will be distorted because of refraction and will appear to have a kink. This is shown clearly in the photograph of the 'bent' straw (Figure 11.4.2, page 444). The path of the rays that produce this illusion can be drawn using a ray diagram, as shown in Figure 11.4.6. As each ray of light emitted from the base of the straw encounters the water–air boundary, it is refracted away from the normal, because the ray enters a less optically dense medium. The observer perceives these rays from the base of the straw to have come from a position higher up in the glass of water. **Ray tracing** can be carried out for each point along the straw, resulting in the image shown. The straw appears to have a bend in it because the part of the straw that is submerged appears closer to the air–water boundary.

Note that although ray diagrams are commonly used to represent the refraction of light and the formation of images in mirrors and lenses, these describe only the direction of travel of the refracted light and do not tell the whole story. Wave diagrams are more complicated, but show the reasons for the change in direction of travel of the light.

THE LAW OF REFRACTION: SNELL'S LAW

In about 1621 Willebrord Snell, a Dutch scientist, found that for a given pair of media the sine of the angle of incidence was directly proportional to the sine of the angle of refraction. This relationship is now known as Snell's law.

$$\sin i \propto \sin r$$

$$\frac{\sin i}{\sin r} = \text{constant}$$

Each combination of a pair of materials has a different constant. For example, the constant for the air–water interface is different from that for the glass–water interface. The constant is called the **relative refractive index**, denoted $n^{\star}$.

More usefully, the index of refraction for a particular material can be found.

Different transparent media allow light to travel at different speeds. Light travels fastest in a vacuum, more slowly in water and even more slowly in glass, which is more optically dense than water.

Table 11.4.1 shows the speed of light in various media. The amount of refraction occurring at any boundary depends upon the extent to which the speed of light changes between the media.

TABLE 11.4.1 The speed of light in different media for yellow light ($\lambda = 589\,\text{nm}$)

Material	Speed of light ($\times 10^8\,\text{m s}^{-1}$)
vacuum	3.00
air	3.00
ice	2.29
water	2.25
quartz	2.05
crown glass	1.97
flint glass	1.85
diamond	1.24

Snell's law can be expressed in terms of the ratio of the two speeds of light in the two different media, v_1 and v_2, as shown in Figure 11.4.7.

$$\frac{\sin i}{\sin r} = \frac{v_1}{v_2}$$

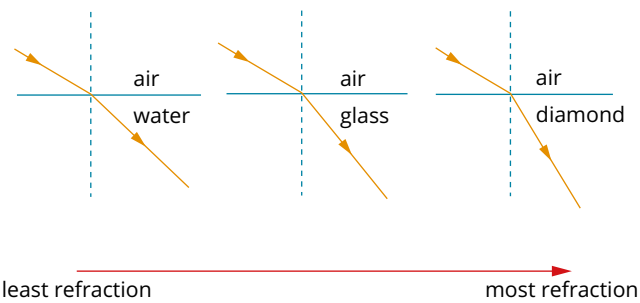


FIGURE 11.4.7 In each case, light is entering a medium of greater optical density. The bending of the path of the light depends on the ratio of the speeds in the two different media. The path of light deviates most when the change in speed is greatest.

The greater the change in the speed of a light ray passing through the boundary of different media, the greater the deviation of the beam.

THE INDEX OF REFRACTION

The degree of refraction is determined by comparing the speeds of light in the two different media. The **absolute refractive index**, n, of a medium is the ratio of the speed of light in the medium, v_{medium}, to the speed of light in a vacuum, c.

$$n = \frac{c}{v_{\text{medium}}}$$

By definition the refractive index of a vacuum would be exactly 1. Light travels only marginally more slowly in air and so the refractive index of air is 1.0003, but in most cases a value of 1.00 is sufficiently accurate. Materials in which light travels slowest will have the highest indices of refraction. For example, if a particular medium allowed light to travel at half the speed it does in a vacuum, then the refractive index of the medium would be 2.

The refractive index can therefore be considered an indication of the 'bending power' of a material. Table 11.4.2 lists the absolute refractive indices for various media.

TABLE 11.4.2 The refractive index of light in different media for yellow light ($\lambda = 589\,\text{nm}$)

Material	Refractive index, n
vacuum	1.00
air	1.00
ice	1.31
water	1.33
quartz	1.46
crown glass	1.52
flint glass	1.62
diamond	2.42

Snell's law can then be expressed in terms of the ratios of the speed of light in each medium, the wavelengths in each medium and the absolute refractive indices of the respective mediums.

Snell's law:

$$\frac{\sin i}{\sin r} = \frac{v_1}{v_2} = \frac{\lambda_1}{\lambda_2} = \frac{n_2}{n_1} = n^*$$

where

n^* is a constant called the relative refractive index for medium 1 and medium 2

n_1 is the refractive index of medium 1

n_2 is the refractive index of medium 2

v_1 is the speed of light in medium 1

v_2 is the speed of light in medium 2

λ_1 is the wavelength of the light in medium 1

λ_2 is the wavelength of the light in medium 2.

Note that the wavelength of the light will vary with the change in velocity, but the frequency and therefore the colour remain unchanged.

Worked example 11.4.1

CALCULATING REFRACTIVE INDEX

The speed of light in water is $2.25 \times 10^8\,\text{m s}^{-1}$. Calculate the refractive index of water given that the speed of light in a vacuum is $3.00 \times 10^8\,\text{m s}^{-1}$.

Thinking	Working
Recall the definition for refractive index.	$n = \frac{c}{v_{\text{medium}}}$
Substitute the appropriate values into the formula and solve.	$n = \frac{3.00 \times 10^8}{2.25 \times 10^8} = \frac{3.00}{2.25} = 1.33$ The refractive index of water is 1.33.

➤ Try yourself 11.4.1

CALCULATING REFRACTIVE INDEX

The speed of light in crown glass (a type of glass used in optics) is $1.97 \times 10^8\,\text{m s}^{-1}$. Calculate the refractive index of crown glass given that the speed of light in a vacuum is $3.00 \times 10^8\,\text{m s}^{-1}$.

Worked example 11.4.2

SPEED OF LIGHT CHANGES

A ray of light travels from crown glass ($n = 1.52$), where it has a speed of $1.97 \times 10^8\,\text{m s}^{-1}$ into water ($n = 1.33$). Calculate the speed of light in water.	
Thinking	**Working**
Recall the relevant part of Snell's law.	$\frac{v_1}{v_2} = \frac{n_2}{n_1}$
Substitute the appropriate values into the formula and solve.	$\frac{1.97 \times 10^8}{v_2} = \frac{1.33}{1.52}$ $1.33 \times v_2 = 1.52 \times 1.97 \times 10^8$ $v_2 = \frac{1.52 \times 1.97 \times 10^8}{1.33}$ $= 2.25 \times 10^8\,\text{m s}^{-1}$

➤ Try yourself 11.4.2

SPEED OF LIGHT CHANGES

A ray of light travels from water ($n = 1.33$), where it has a speed of $2.25 \times 10^8\,\text{m s}^{-1}$, into glass ($n = 1.85$). Calculate the speed of light in glass.

Worked example 11.4.3

USING SNELL'S LAW

A ray of light in air strikes the surface of a pool of water ($n = 1.33$) at angle of 30.0° to the normal. Calculate the angle of refraction of the light in water.	
Thinking	**Working**
Recall the relevant part of Snell's law.	$\frac{\sin i}{\sin r} = \frac{n_2}{n_1}$
Recall the refractive index of air.	$n_1 = 1.00$
Substitute the appropriate values into the formula to find a value for $\sin r$.	$\frac{\sin 30°}{\sin r} = \frac{1.33}{1.00}$ $1.00 \times \sin 30° = 1.33 \times \sin r$ $\sin r = \frac{1.00 \times \sin 30°}{1.33}$ $= 0.3759$
Calculate the angle of refraction.	$r = \sin^{-1}(0.3759) = 22.1°$

➤ Try yourself 11.4.3

USING SNELL'S LAW

A ray of light in air strikes a piece of flint glass ($n = 1.62$) at an angle of incidence of 50.0° to the normal. Calculate the angle of refraction of the light in the glass.

TOTAL INTERNAL REFLECTION AND CRITICAL ANGLE

When light is incident upon the boundary between two media, it may undergo reflection, transmission or absorption. As the angle of incidence increases, the **intensity** of the reflected beam increases and less light is transmitted. When light travels from water into air, the transmitted light enters a less optically dense medium, so it travels faster and is refracted away from the normal. The series of diagrams in Figure 11.4.8 show the effects of increasing the angle of incidence on transmitted light.

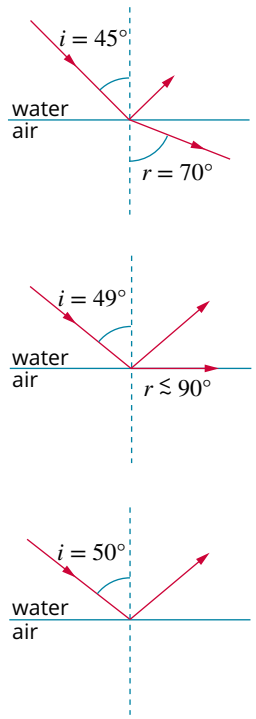


FIGURE 11.4.8 The critical angle for light travelling from water into air is approximately 49°. If the incident angle is greater than 49° total internal reflection occurs.

- As the angle of incidence is increased, the angle of refraction also increases.
- If the angle of incidence is the critical angle, i_c, then the angle of refraction will be to 90° and the light will be transmitted along the surface of the incident medium.
- If the angle of incidence is greater than the critical angle, then the angle of refraction will be greater than 90° and all of the light will be reflected and none will be transmitted.

As the angle of incidence is increased, the angle of refraction also increases. This continues until, at a certain angle of incidence called the **critical angle**, i_c, the angle of refraction will be 90° and the transmitted ray travels just along the surface of the water. The angle of refraction can increase no further. If the angle of incidence is then increased beyond the critical angle, then no ray is transmitted and **total internal reflection** will occur. The critical angle is appropriately named, because none of the incident light energy can be transmitted into the next medium. In effect, as the angle of incidence increases, the intensity of the reflected beam gradually becomes stronger, until at an angle of refraction of more than 90° all of the light is reflected and no light is transmitted at all.

The critical angle can be found for any boundary between two media by using Snell's law. If the refractive indices of the two media are known, assuming that the angle of refraction is 90°, then the critical (incident) angle can be calculated:

$$\frac{\sin i_c}{\sin 90^\circ} = \frac{n_2}{n_1}$$
$$\frac{\sin i_c}{1} = \frac{n_2}{n_1} \quad (\sin 90^\circ = 1)$$
$$\sin i_c = \frac{n_2}{n_1}$$

The critical angle for any boundary between two media:

$$\sin i_c = \frac{n_2}{n_1}$$

where

i_c is the critical angle as light is transmitted into a medium n_2

n_1 is the refractive index of medium 1

n_2 is the refractive index of medium 2

light has a greater speed in medium n_2 than the medium n_1.

Worked example 11.4.4

CALCULATING CRITICAL ANGLE

Calculate the critical angle for light passing from water into air.	
Thinking	**Working**
Recall the equation for critical angle.	$\sin i_c = \frac{n_2}{n_1}$
Substitute the refractive indices of water and air into the formula. (Unless otherwise stated, assume that the second medium is air with $n_2 = 1$.)	$\sin i_c = \frac{1.00}{1.33} = 0.7519$
Solve for i_c.	$i_c = \sin^{-1}(0.7519) = 48.8^\circ$

➤ Try yourself 11.4.4

CALCULATING CRITICAL ANGLE

Calculate the critical angle for light passing from diamond into air.

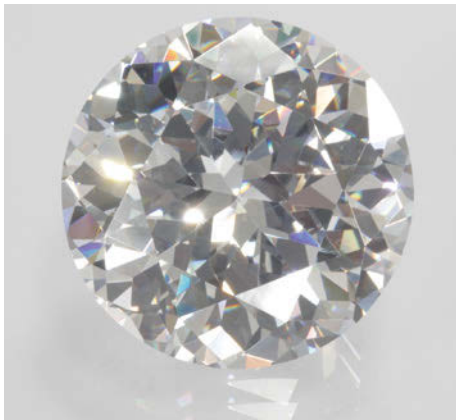


FIGURE 11.4.9 The refractive properties of diamonds mean they appear to sparkle.

The refractive index of any given medium depends on the colour (wavelength or frequency) of the light travelling through the medium, so each colour of light will have a slightly different critical angle. For example, if the critical angle for red light travelling from glass to air is 40.5°, then yellow light would have a slightly smaller critical angle of 40.2°. Violet light would have an even smaller critical angle of 39.6°. Although these values are very similar, they are sufficiently different to cause the dispersion of white light into its component colours; the colours of the rainbow!

A special case: The refractive index of diamonds

Diamond has a very high refractive index, so it has a small critical angle. This means that a light ray that enters a diamond will often bounce around inside the diamond many times before leaving the diamond. This causes the diamond to 'sparkle' as it appears to reflect more light than is falling on it. A jeweller can cut a diamond to take advantage of this property, as shown in Figure 11.4.9.

REFRACTION AND LENSES

In the preceding sections you have seen how ray tracing can be used to demonstrate the formation of images by plane and curved mirrors, and in tracing the path of refracted light. A similar approach can be taken regarding image formation by lenses.

A lens is a piece of transparent material that has been shaped so that the light passing through it will bend in a particular way. Lenses can take on a variety of shapes, depending on their function and the exact optical properties required of them. Most common lenses have spherical curvature. This means that each face is part of a sphere. Other shapes are possible but are much more difficult to achieve.

The function of a lens can be demonstrated by examining the refraction of light rays as they change speed on entering and exiting a lens. Refraction must occur as the light both enters and exits the lens, so the curvature of both surfaces of the lens must be chosen specifically for a particular application. The curvature of the surface of most lenses is spherical and the surface of the lens is actually a portion of a sphere. Spherical lenses do have some problems related to accurate image formation but are very commonly used. Spherical lenses are much easier and cheaper to produce than other shapes, so non-spherical lenses are generally only used in high precision optical equipment.

This section covers bi-concave or bi-convex lenses, which are by far the most common types of spherical lenses. Scientists often just call these 'concave' and 'convex' lenses respectively.

- Convex lenses have one or both sides curved outwardly, like the back of a spoon. These are called plano-convex and bi-convex respectively, as shown in Figure 11.4.10a.
- Concave lenses have one or both surfaces curved inwardly like the bowl of a spoon. These are called plano-concave and bi-concave respectively, as shown in Figure 11.4.10b.

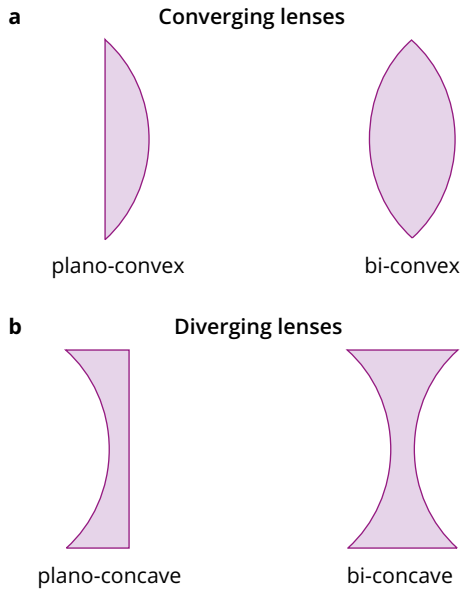


FIGURE 11.4.10 (a) Converging lenses are convex lenses, which are thicker in the middle. (b) Diverging lenses are concave lenses, which are thinner in the middle. In both types of spherical lenses, the curved surfaces form part of the surface of a sphere.

Figure 11.4.11 demonstrates the effects that convex and concave lenses have on a beam of light. The path of light is bent at the front and back surfaces of the prism, according to the law of refraction. The shapes of these lenses have been chosen so that the separate light rays converge to a single point.

- Figure 11.4.11a shows a convex lens. Rays parallel to the principal axis enter a convex lens and converge to the principal focal point, F, of the lens.
- Figure 11.4.11b shows a concave lens. The curvature of the faces means that parallel rays diverge after passing through the lens. The diverging rays can be traced back through the lens to a point behind the lens. This is the principal focus for a concave lens. It is sometimes known as a virtual focus because the rays only meet at this point in our imagination. A virtual image formed by a lens can only be seen when looking directly through the lens.

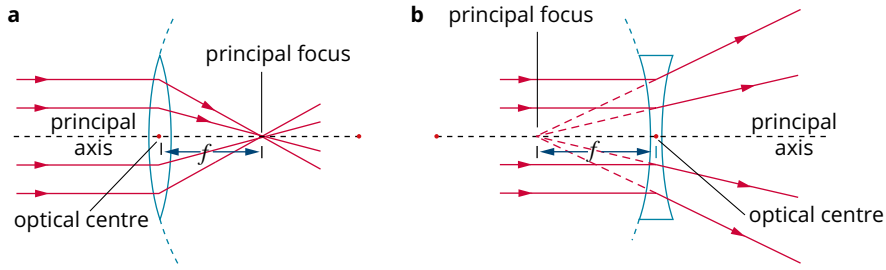


FIGURE 11.4.11 (a) For a convex lens, rays parallel to the principal axis converge to the principal focal point. (b) For a concave lens, rays parallel to the principal axis diverge as if they came from a single principal focal point called the virtual focus.

Each lens is considered to have two focal points (or foci), one either side of the lens. Each lens also has a special point known as the optical centre of the lens. A light ray that passes through the optical centre of the lens experiences no refraction; it passes straight through the lens undeviated. The distance between the optical centre and the focal point is known as the focal length of the lens. As with mirrors, it is helpful to imagine the principal axis of the lens as a line that passes through the two focal points and the optical centre.

RAY PATHS THROUGH SPHERICAL LENSES

The nature of the image formed by either a concave or a convex spherical lens can be determined using the ray-tracing techniques shown previously in Module 11.3. For spherical lenses there are three particular rays whose path can be predicted, and any two of these rays can be used to locate the image, as shown in Figure 11.4.12.

- Figure 11.4.12a shows that a ray passing through the optical centre of a spherical lens will be undeviated.
- Figure 11.4.12b shows that a ray travelling parallel to the principal axis will be deviated through the principal focus of a convex lens, or deviated so that it appears to have come from the principal focus of a concave lens.
- Figure 11.4.12c shows that a ray passing through the principal focus of a convex lens (or directed towards the principal focus of a concave lens) will be deviated so that it emerges parallel to the principal axis.

Graphical ray tracing can also be used to locate the image formed by a spherical lens. A horizontal line represents the principal axis for the lens. A vertical line called the optical axis or vertex represents the lens. To indicate the type of lens in use, a small symbol is drawn at the intersection of the principal and optical axes. The principal foci of the lens should be labelled. All refraction is shown as occurring at the optical axis.

Recall from the earlier work on mirrors that there are four aspects of an image that may be determined:

- nature: whether the image is real or virtual
- orientation: whether the image is up right or inverted
- position: the distance of the image from the optical axis
- size: the image is described as enlarged, reduced or the same size as the object. This is often described in terms of magnification.

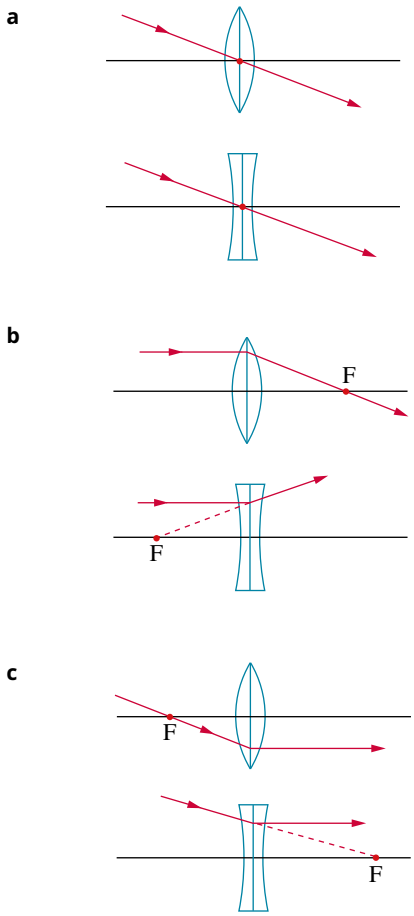


FIGURE 11.4.12 (a) A ray passing through the optical centre is undeviated. (b) A ray parallel to the principal axis passes (or appears to pass) through the principal focal point, F. (c) A ray that passes through (or travels towards) the focal point emerges parallel to the principal axis.

Figures 11.4.13 and 11.4.14 demonstrate how ray diagrams can be used to locate the images of objects at various distances from convex and concave lenses respectively. Figure 11.4.15 shows how a concave lens always shows a reduced, upright image.

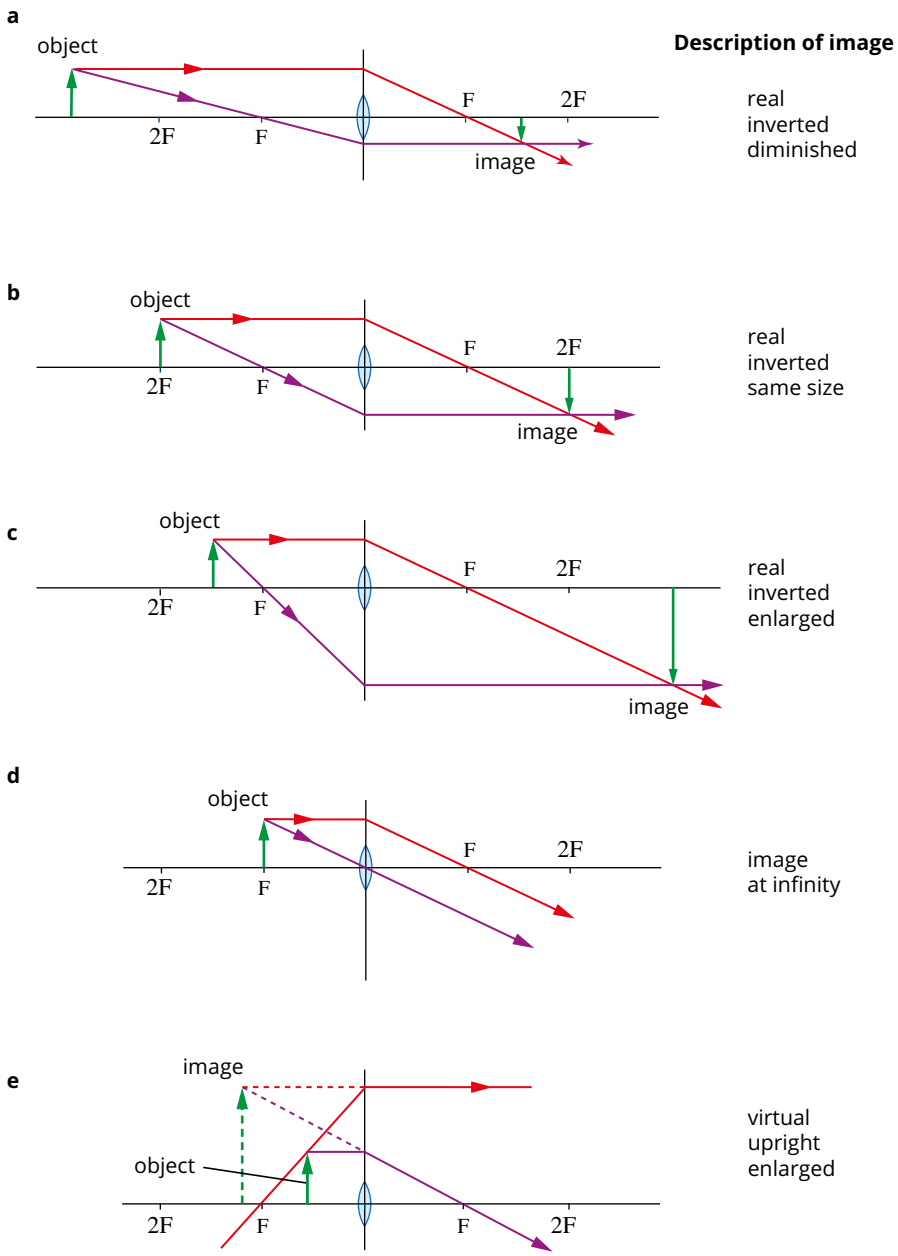


FIGURE 11.4.13 (a)–(c) When the object is placed beyond the focal point of a convex lens, a real image is formed. As the object is brought closer, the size of the image increases. (d) The image of an object at the focal point of a convex lens is considered to be at infinity. (e) A convex lens forms an upright, virtual image of an object placed inside the focal point.

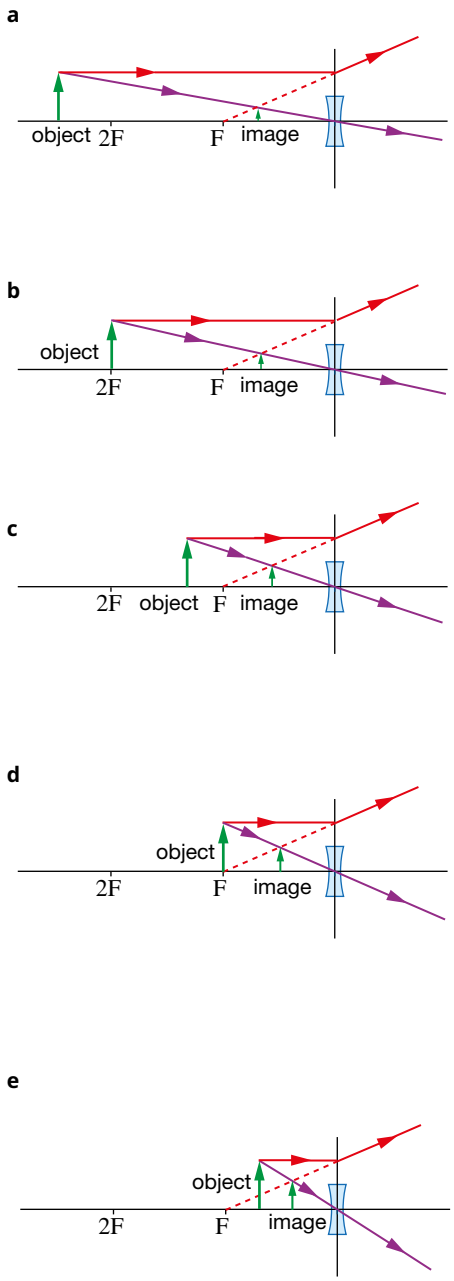


FIGURE 11.4.14 A concave lens causes rays to diverge and so a virtual, reduced image is always formed regardless of where the object is in relation to the lens.

WS 2.2.5

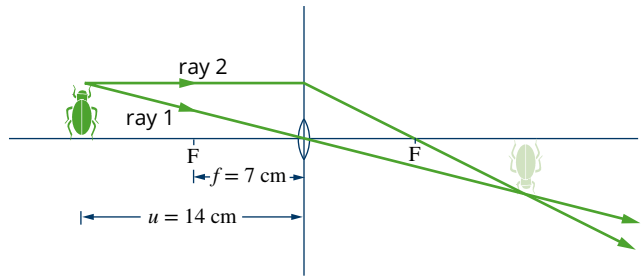
FIGURE 11.4.15 A concave lens always forms a reduced upright image.

Worked example 11.4.5

USING LENSES

A child examines a beetle by using a magnifying glass (i.e. a convex lens) of focal length 7 cm and holding the magnifying glass 14 cm from the beetle.

Construct a ray diagram to describe the image.

Thinking	Working
Construct the ray diagram (only two rays are needed).	
Interpret the ray diagram.	The image is virtual, inverted and the same size as the object.

➤ Try yourself 11.4.5

USING LENSES

An artist uses a concave lens of focal length 10 cm to reduce a sketch of a tree to see what it would look like in miniature. The sketch is of a 20 cm tall tree and the lens is held 15 cm above the page.

Construct a ray diagram to describe the image.

PA 2.2.3

PA 2.2.4

11.4 Review

SUMMARY

- Refraction is the bending of light due to a change in its speed as it enters a medium of different optical density. The greater the change in the speed of light the greater the bending.
- The angle between the normal and the incident ray is called the angle of incidence. The angle between the normal and the transmitted or refracted ray is called the angle of refraction.
- When a light ray passes into a medium in which it travels more slowly (a more optically dense medium) it is refracted towards the normal.
- When a light ray passes into a medium in which it travels faster (less optically dense) it is refracted away from the normal.
- A transparent medium has an absolute refractive index, n, determined by the speed at which light can travel in the medium compared with the speed of light in a vacuum, c:

$$n = \frac{c}{v_{medium}}$$

  where c is the speed of light in a vacuum and v_{medium} is the speed of light in the medium.
  Snell's law describes the relationship between the angle of incidence, i, and the angle of refraction, r, for a given pair of media:

$$\frac{\sin i}{\sin r} = \frac{v_1}{v_2} = \frac{\lambda_1}{\lambda_2} = \frac{n_2}{n_1} = n^*$$

- As the angle of incidence of light onto a transparent surface is increased, proportionally more light is reflected and less light is refracted.
- When light enters a less optically dense medium it is refracted away from the normal. At the critical incident angle, i_c, the angle of refraction is 90°.
- If the incident angle is greater than the critical angle, i_c, total internal reflection occurs.
- The critical angle is given by:

$$\sin i_c = \frac{n_2}{n_1}$$

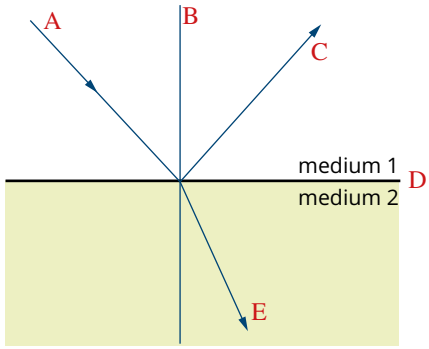
- The path of light is refracted as light both enters and exits a lens. A convex or converging lens brings parallel rays to a focus. A concave or diverging lens spreads parallel rays further apart.
- The focal length of a spherical lens is determined by its index of refraction and the radius of curvature. Thinner lenses, with less severe curvature, have longer focal lengths.
- For spherical convex and concave lenses there are three rays whose paths can be predicted easily, and any two of these rays can be used to locate an image.
  - Ray 1: A ray through the optical centre is undeviated.
  - Ray 2: A ray parallel to the principal axis passes (or appears to pass) through the principal focus.
  - Ray 3: A ray through (or travelling towards) the principal focus emerges parallel to the principal axis.
- Graphical ray tracing can be used to locate the image formed by a spherical convex lens. The nature, orientation, position and size of the image depends on the position of the object relative to the focal length of the lens.
- In general, convex lenses form real images of distant objects and virtual images of very close objects.
- Regardless of the position of the object, a concave lens always forms a virtual, upright and diminished image. The image is always on the same side of the lens as the object. When the object is brought closer to the lens the image becomes larger, but it can never equal the size of the object.

11.4 Review *continued*

KEY QUESTIONS

Retrieval

1 The figure below represents a situation involving the refraction of light. Complete the following table with the letter corresponding to each line on the diagram.



boundary between two media	
normal	
incident ray	
refracted ray	
reflected ray	

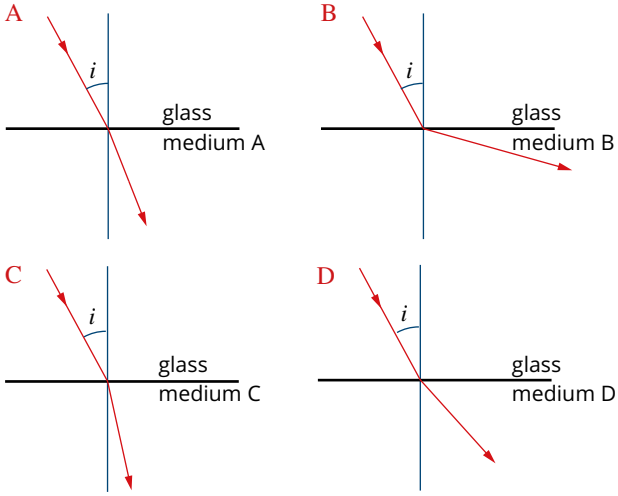
2 State the direction in which light bends when a light ray passes into a medium in which it travels more slowly (a more optically dense medium).

3 Describe what happens to the path of parallel rays of light passing through a convex lens.

4 Describe the path of a ray passing through the optical centre of a concave lens.

Comprehension

The following diagrams relate to questions **5**–**9**. The diagrams show light passing from glass into different media labelled A, B, C and D.



5 Determine which (one or more) media are more optically dense than glass.

6 Name the media that have a refractive index less than the refractive index of glass.

7 Select the medium that has the highest refractive index.

8 Select the medium with a refractive index very close to the refractive index of this sample of glass.

9 Explain what happens to the speed of light as it crosses the boundary between glass and medium D.

10 Explain why an upright, real image can never be formed by a single concave lens.

11 Two convex lenses are exactly the same size and shape but lens A is made of a glass with a higher refractive index than lens B.

a Identify the lens with the longer focal length.

b Identify the lens that would provide the largest magnification.

Analysis

12 The speed of light in a particular transparent plastic is $2.00 \times 10^8\,m\,s^{-1}$. Calculate the refractive index of the plastic. Use speed of light in a vacuum as $3.00 \times 10^8\,m\,s^{-1}$.

13 A jeweller is checking the brilliance (or refracting power) of a diamond by passing white light through water into the diamond, while it is submerged. Determine the refractive index of the diamond, if an incident angle of 30.0° produces an angle of refraction of 16°. Use $n_{water} = 1.33$.

14 Light travels from water ($n = 1.33$) into glass ($n = 1.60$). The incident angle is 44°. Calculate the angle of refraction.

15 Calculate the critical angle for light travelling from diamond ($n = 2.42$) into air ($n = 1.00$)

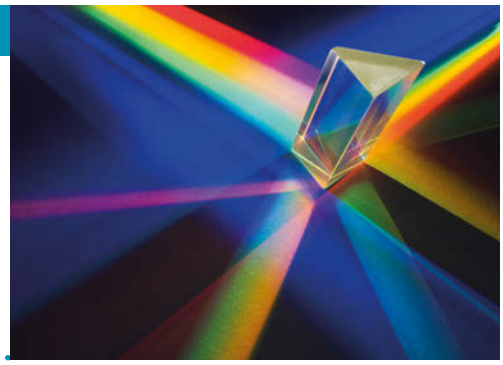
16 A concave lens of focal length 15 cm is held 30.0 cm above a page of writing. Apply graphical ray tracing to find the image. Describe the image.

17 A spherical convex lens has a focal length of 20.0 cm in air. The lens is immersed in water. Determine whether the focal length will increase or decrease.

11.5 Interference and diffraction of light

BY THE END OF THIS MODULE, YOU SHOULD BE ABLE TO:

- recall that a wave model of light can explain diffraction
- describe diffraction and the effects of the ratio $\frac{\lambda}{w}$ on the diffraction pattern
- recall that a wave model of light can explain interference
- describe Young's double slit experiment as evidence of the wave nature of light
- describe the qualitative effect of wavelength, distance from screen and slit separation on interference patterns.



Scientists continued to explore the nature of light through the 19th century. Two key observations provided crucial evidence supporting the wave nature of light, independent of measurement of the speed of light. The observations involved the diffraction and interference of light.

DIFFRACTION

If you have ever watched carefully as water waves lap gently against a partial barrier, such as a rocky outcrop or sand bar at the beach, you may have noticed their ability to bend around and enter the region behind the barrier. An example of this is shown in Figure 11.5.1. This phenomenon is known as diffraction. As it is an observed property of both water and other waves such as sound waves, it contributed to the acceptance of the wave nature of light.

FIGURE 11.5.1 Water waves will bend around an obstacle. Sound waves diffract as well, allowing us to hear around corners.

It is an observed property of waves that obstacles placed in their path will bend around and enter the area behind the barrier. This also applies when waves pass through an aperture, which can be thought of as a pair of barriers, as shown in Figure 11.5.2. In Figure 11.5.2a, the waves have bent into a large region behind the barrier in the ripple tank. In Figure 11.5.2b, a wider slit is used and the waves have not bent around as far behind the edge of each barrier. From the diffraction of waves in Module 9.5, the following relationship has been observed:

- Wavelengths much smaller than the diameter of the gap or obstacle produce a small degree of bending around the edges.
- Wavelengths comparable to or larger than the diameter of the obstacle or gap produce significant bending or diffraction.

The relationship can be expressed as the ratio:

$\frac{\lambda}{w} \geq 1$

where

λ is the wavelength of the EMR (m)

w is the width of the obstacle or gap.

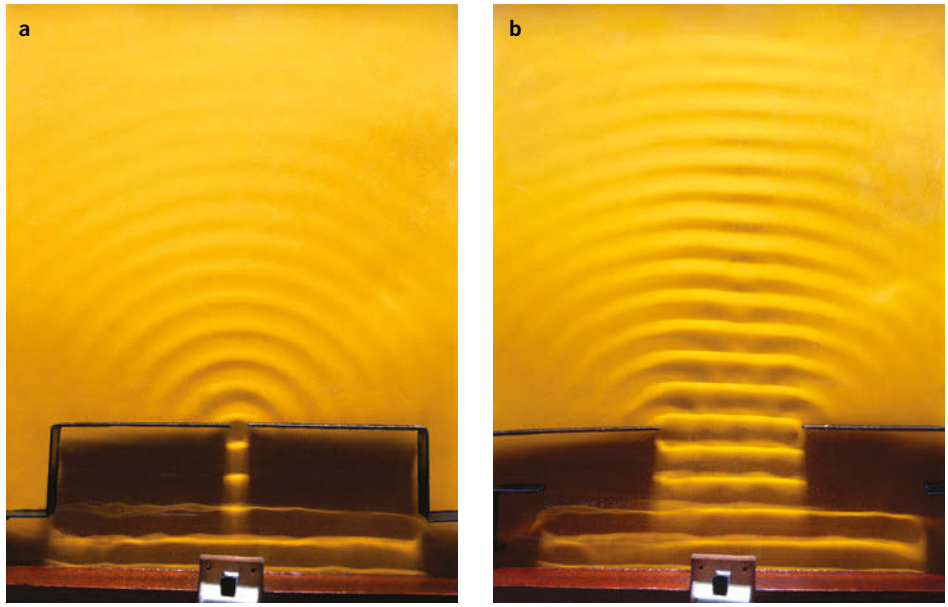


FIGURE 11.5.2 The diffraction of water waves in a ripple tank. (a) Significant diffraction occurs when the wavelength approximates the slit width, $\lambda \approx w$. (b) As the gap increases, diffraction becomes less obvious, because $\lambda < w$.

Diffraction effects caused by light are not as readily observed in everyday circumstances. The light and dark fringes around the shadows of objects caused by the diffraction of light require particular conditions to occur to be readily observed.

Practical observations of diffraction

You can observe a crude single-slit diffraction pattern by making a 3 cm cut perpendicular to the edge of a small piece of dark (opaque) paper. Hold the paper about 5 cm in front of one eye and look through the slit at a light source such as a computer screen. You should see 'fringes' of light and dark. Pull the paper so that the slit widens and observe the effect on the diffraction pattern.

An object or aperture is best illuminated by a point source of light, so the diffraction fringes created by each part of a large light source don't overlap and uniformly illuminate the area adjacent to the shadow. Similarly, monochromatic (a single wavelength) light works best. If white light is used, fewer or no fringes may be seen, as the different wavelengths produce fringes of different spacing and these too may overlap. The shadow of a razor blade shown in Figure 11.5.3a has been produced using a laser, meeting these conditions.

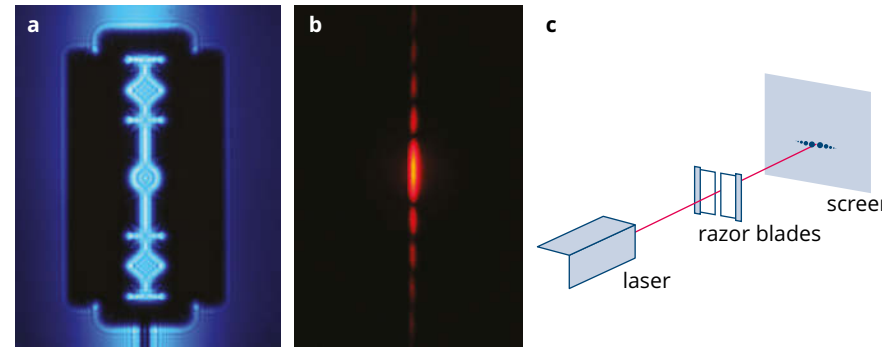


FIGURE 11.5.3 (a) Diffraction around a razor blade screen. (b) Diffraction occurs when light passes through a single slit. (c) The extent of the diffraction pattern changes as the distance between the blades changes. If the slit size decreases, the pattern will spread.

Note that the wavelengths of visible light are 400–700 nm and are far smaller than anyone originally imagined. Recall that diffraction effects are significant only if the aperture or obstacle is of a comparable size to the wavelength of the wave passing through and that waves diffract significantly when they interact with objects of a similar size. But even single cells are much larger than the wavelength of light. The wavelength of visible light is far smaller than the size of any everyday object, so diffraction is not readily seen. As a consequence, beams of light are observed to travel in straight lines and cast sharp shadows. This is why the behaviour of light is, in most circumstances, modelled successfully by the ray diagrams described in the earlier sections of this chapter.

To produce an observable example of single-slit diffraction, a single aperture can be created by scratching a fine line on a black-painted projector slide or by mounting the edges of two razor blades so there is only a tiny gap between them, as shown in Figure 11.5.3b. The observed diffraction pattern is a series of bright and dark fringes produced on the screen, which can be modelled by waves that are said to interfere constructively and destructively. The extent of the diffraction of the light waves depends on the relative sizes of the wavelength, λ, and the diameter or width of the gap, w (as it does for water waves), as shown in Figure 11.5.3c. It is useful to consider the amount of diffraction by referring to the ratio of wavelength to gap width $\frac{\lambda}{w}$.

This ratio determines the spacing of the individual fringes and the width of the overall diffraction pattern. The diffraction pattern will have a central fringe that is twice as wide as the other fringes.

- If the wavelength is constant and the aperture or gap is made smaller, then greater diffraction is seen.
- If different wavelengths enter the same gap, then those with a small wavelength will undergo less diffraction than those with longer wavelengths.

That means there will be greater diffraction of red light than blue light, as shown in Figure 11.5.4.

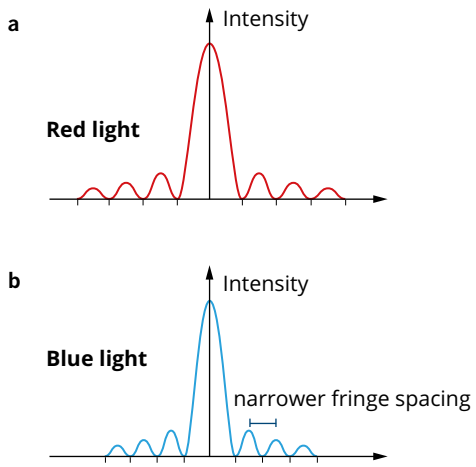


FIGURE 11.5.4 Small apertures are required in order to demonstrate the diffraction of light so (a) red light is diffracted to a greater extent than (b) blue light. Red light has a longer wavelength, which results in more widely spaced fringes and a wider overall pattern.

Diffraction in optical instruments

The diffraction created by the small apertures in microscopes and telescopes results in blurred images. A significant problem is that the light from two tiny objects being observed can be diffracted so much that the two objects appear as one blurred object. We say that the objects are unresolved. Essentially, the same ratio, $\frac{\lambda}{w}$, dictates how small an object can be clearly imaged by a particular microscope or telescope. A general rule is that optical instruments can only create images of objects of a size similar to the wavelength of the light they use; otherwise, diffraction effects are too significant for the images to be successfully viewed.

WS 2.2.6

Diffraction gratings

A diffraction grating is a flat piece of glass or plastic with as many as 10 000 lines per centimetre etched on it. Each line is a scratch that is opaque to light that is incident on the surface. The gaps between the scratches remain transparent. If white light is shone onto the surface, each wavelength produces a set of fringes at different angles to the incident beam. The result is the light will be separated into its component colours, and a coloured spectrum is produced, as shown in Figure 11.5.5. You may have observed this effect on the bottom of an old CD or DVD, if you still have any of these. In the science laboratory, diffraction gratings can be used to determine the wavelength of particular light by measuring the distance between fringes of the same colour.

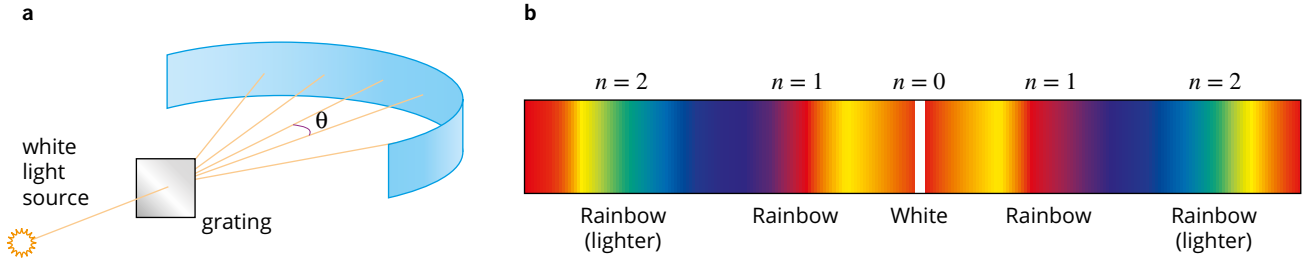


FIGURE 11.5.5 (a) The interference pattern from a diffraction grating for white light. The pattern extends through large angles. (b) The maxima are so sharp that the component wavelengths of white light will separate into a spectrum on the screen.

INTERFERENCE OF LIGHT

In 1801, an English physician and physicist, Thomas Young, conducted an experiment that showed that light definitely had a wave nature. In his experiment, Young projected a narrow beam of light through a pair of closely spaced holes in a darkened room. The light from the holes was viewed on a screen some distance away. If the light from the two holes produced a very bright region on the screen where they overlapped, then this would support Newton's hypothesis that light was particle-like in nature. However, what Young saw in the region where the two beams of light fell, was a series of alternating bright and dark fringes, as shown in Figure 11.5.6.

Young knew about the interference of water and sound waves, so he could only conclude that light too must have a wave nature. Young suggested that at each bright band, the light coming from each source was added, and that at each dark band it was being cancelled.

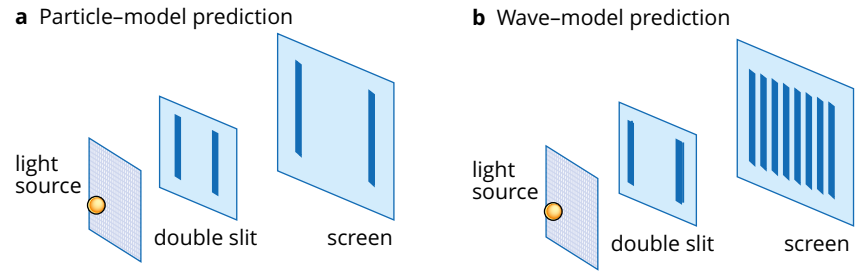


FIGURE 11.5.6 (a) In a reproduction of Young's experimental set-up a particle model for light would predict that two bright bands would appear on the screen. (b) However, the fringe pattern that is observed supports a wave model for light.

To see how this is possible, consider this modern version of Young's experiment. Monochromatic light (light consisting of only one wavelength) is directed at two narrow, parallel slits, S_1 and S_2, which are placed very close together. A screen is placed at some distance behind the slits. As the light passes through each slit, it diffracts, and two sets of circular wavefronts emerge and spread into the region beyond the slits, as shown in Figure 11.5.7.

The incident light consists of plane waves that come from the same source, so the light emerging from each slit will be **in phase**. This means that if there is a crest emerging from S_1, there will also be a crest emerging from S_2.

At every point on the screen, a wave train from one slit will meet a wave train from the other slit. The resulting intensity at each point is determined by the principle of superposition, in which constructive interference and destructive interference of waves produce antinodes where the waves add to form a bright line and nodes where the waves cancel each other out to form a dark line. This is an example of an **interference pattern**.

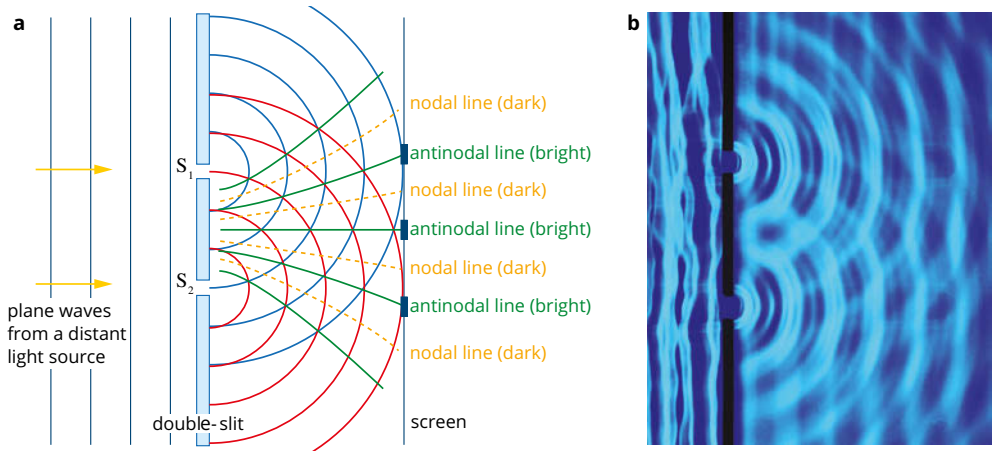


FIGURE 11.5.7 (a) Light from a monochromatic and distant source is incident on a pair of slits. Plane waves enter each slit at the same time, resulting in two sets of circular waves that overlap and spread into the region beyond the slits. The circular waves then interfere to produce a series of nodal (dark) lines and antinodal (bright) lines. (b) This interference pattern of alternating nodal and antinodal lines can also be seen in water waves when a pair of dippers oscillate in phase in a ripple tank.

FACTORS AFFECTING INTERFERENCE PATTERNS

Factors that affect the fringe spacing, which is the distance between adjacent bright bands on the screen, include the wavelength of light, the separation between the two slits and the distance to the screen. If the viewing screen is moved further from the two slits, the fringes will appear further apart. Alternatively, using light of a longer wavelength will also result in increased fringe spacing. However, if the screen position and wavelength of light are held constant, the fringe spacing can also be increased by reducing the separation of the slits, as shown in Figure 11.5.8.

When observing interference patterns created by two slits, the fringe spacing can be increased by:

- increasing the wavelength
- increasing the distance to the screen
- decreasing the distance between the slits.

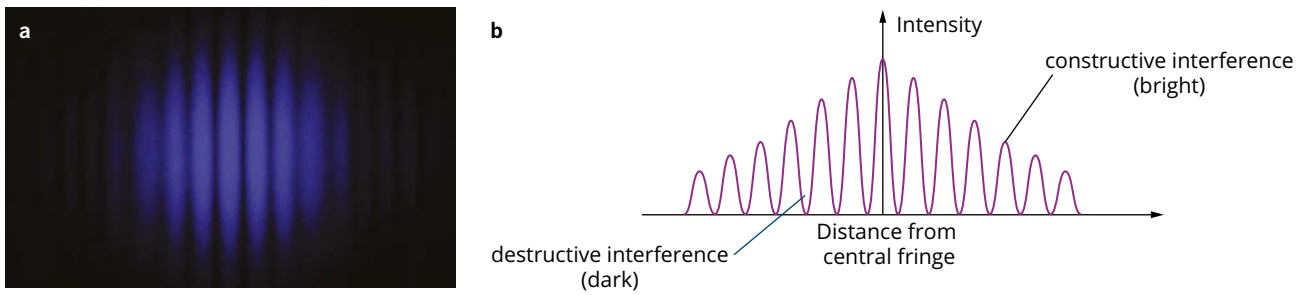


FIGURE 11.5.8 (a) The fringes produced by double-slit interference are evenly spaced. The central band is brightest and the adjacent fringes diminish in intensity. The overall width of the pattern is a diffraction effect. (b) The double-slit interference pattern can be considered in terms of an intensity distribution graph. The horizontal axis represents a line drawn across the screen. The centre of the distribution pattern corresponds to the centre of the brightest central fringe.

Different colours (wavelengths) of light produce different fringe spacing. Young was the first to determine approximate values for the various wavelengths of visible light by using his understanding of the interference of light from two sources. He showed that the physical property distinguishing the different colours of light from each other is their wavelength, a key property of a wave model of light.

11.5 Review

SUMMARY

- Waves diffract (bend) as they pass by an obstacle or through a gap. The extent of the diffraction is determined by the relative sizes of the wavelength, λ, and the obstacle or gap diameter, w. Significant diffraction occurs when $\lambda \geq w$.
- The interference pattern seen in a double-slit experiment consists of alternating bright and dark fringes resulting from constructive and destructive interference of monochromatic (single frequency) light. The small wavelength for light (400–700 nm) requires that the slits are very close to each other and the screen is a significant distance from the slits (about 1 m).
- The fringe spacing of an interference pattern can be increased by using light of a longer wavelength (lower frequency), placing the viewing screen or film further from the pair of slits, or by decreasing the separation of the slits.
- A wave model of light can explain interference.
- Young's double-slit experiment was the first time light was seen to behave as a wave.

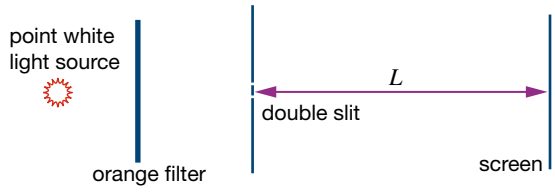
KEY QUESTIONS

Retrieval

1 When light is shone on the playing surface of a DVD or BluRay disc, rainbow patterns can be observed on the playing surface. State the key wave behaviour of light that leads to these rainbow patterns.

2 Young's experiment can be modelled using circular waves in a ripple tank. Describe the observation/s of the waves that would be representative of constructive interference.

The following information applies to questions **3**–**5**.
A double-slit interference experiment is set up to produce an interference pattern on a screen at a distance L from the slits. The arrangement is illustrated in the diagram below.



3 List the way/s in which increased fringe spacing could be produced on the screen.

4 Describe what happens to the spacing of the interference fringes when the slit separation is increased.

5 If the orange filter is removed and white light passes through the slits, coloured fringes are observed. State the phenomenon that is responsible for this observation. Justify your explanation.

Comprehension

6 The extent to which light diffracts is dependent on the ratio of gap or obstacle width, w, to the wavelength of the light, λ. Explain the relationship between width and wavelength that will lead to significant diffraction being observed.

7 Two students are trying to replicate Young's double-slit experiment. One uses torch light and the other uses light from a laser. Explain which student is more likely to obtain the expected diffraction pattern. Explain the reasoning behind your choice.

8 A green light is directed through a pair of thin slits. The slits are exactly 1 m from a viewing screen, on which an interference pattern is observed.

a Explain the effect that moving the screen closer has on the observed pattern.

b The green light is then replaced with a light of a different frequency. The fringe spacing is observed to increase. State whether the frequency of the light increased or decreased. Justify your answer.

Analysis

9 Yellow light is directed through a single thin gap. Yellow light has a wavelength of 580 nm. Determine the maximum width of the gap if a diffraction pattern is to be readily observable on a screen.

11.6 Intensity

BY THE END OF THIS MODULE, YOU SHOULD BE ABLE TO:

- define the concept of intensity of light
- use the relationship $I \propto \frac{1}{d^2}$ to solve problems involving the intensity of light at a distance from the source.

In mathematics, a ray continues on infinitely in one direction. In the real world, a light ray does not continue indefinitely due to the wave nature of light; it reduces in intensity due to its wave behaviour, the further it gets from its source. In physics, intensity is a measure of the rate at which energy passes through an area of space. This corresponds roughly to what we would call the 'brightness' of the light. In general, the intensity of the light, I, at a distance r from the source is inversely proportional to the square of the distance from the light source.

The unit of intensity is the $W\,m^{-2}$. Note that the human eye is more sensitive to some colours than to others. For example, our eyes are most sensitive to greenish-yellow light. There are also types of light in the light spectrum, such as infrared or ultraviolet light, that our eyes cannot see at all.

When discussing our perception of the brightness of a light source, a standard Wm^{-2} is used, as is one for sound levels, which compensates for the specific colour sensitivity of our eyes.

As light wavefronts radiate outwards from a point source as a sphere, as shown in Figure 11.6.1, the initial energy is spread over an increasingly larger area. Recall that if the scale factor for length is r, then the scale factor for area is r^2. So, the surface area will increase with the square of the radius.

Assume that light energy flowing through the shaded box at a distance, r, represents an intensity, I, of the light source.

- For r, the light energy flowing through an area is proportional to r^2.
- For $2r$, the light energy flowing through an area is proportional to $(2r)^2$, which is 4 times as large as at r. This means that the light at this point will be only one-quarter as bright as at r:

$$I_2 = \frac{1}{4} I_1$$

- For $3r$, the light energy flowing through an area is proportional to $(3r)^2$, which is 9 times as large as at r. This means that the light at this point will be only one-ninth as bright as at r:

$$I_3 = \frac{1}{9} I_1$$

The relationship between the intensity of light at any two points at different distances, r_1 and r_2, from a light source can be found by:

$$I_1 r_1^2 = I_2 r_2^2$$

That the intensity of light decreases with the square of the distance from the source provides further evidence of the wave nature of light and is referred to as an **inverse square law**.

In physics, there are a number of phenomena that decrease in strength or intensity as the square of distance increases. The intensity of sound waves varies according to an inverse-square relationship. Gravitational, electrostatic and magnetic effects all follow this same type of relationship, as will be seen in later studies.

$I \propto \frac{1}{r^2}$

where

I is the intensity of the light source ($W\,m^{-2}$)

r is the distance from the light source (m).

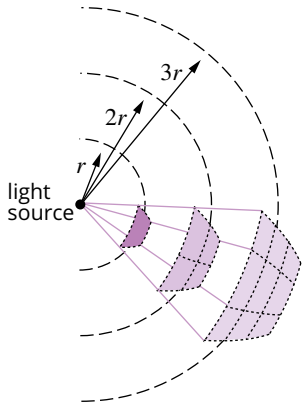


FIGURE 11.6.1 As light moves away from the source, it spreads out radially. As the radius increases, the same amount of energy passes through a larger area. The area increases with the square of the radius, so the intensity decreases by this same ratio.

$I_1 r_1^2 = I_2 r_2^2$

where

I_1 and I_2 are the intensities at points 1 and 2 respectively ($W\,m^{-2}$)

r_1 and r_2 are the distances of points 1 and 2 respectively from the light source (m).

Worked example 11.6.1

CALCULATING INTENSITY

The light from a 25 W compact fluorescent light bulb has an intensity of 11 W m^{-2} at a distance of 1.0 m from the bulb. Calculate the intensity of the light at a distance of 2.0 m from the bulb.

Thinking	Working
Recall the formula for intensity.	$I_1 r_1^2 = I_2 r_2^2$
Rearrange the formula to make I_2 the subject.	$I_2 = \frac{I_1 r_1^2}{r_2^2}$
Substitute the appropriate values into the formula and solve.	$= \frac{11 \times 1^2}{2^2}$ $= 2.8$ W m^{-2}

➤ Try yourself 11.6.1

CALCULATING INTENSITY

The intensity of the light 50.0 cm away from a light-emitting diode (LED) is 0.016 W m^{-2}. Calculate the intensity of the light at a distance of 10.0 cm from the LED.

SKILLBUILDER

Using proportional reasoning in physics

If the type of relationship between two variables is known (e.g. direct, quadratic, inverse, inverse-square), we can use our knowledge of proportion to determine how much one variable will change due to a change in the other variable.

Consider a situation where there is a direct relationship between two variables x and y ($x \propto y$). If we are told that the value of x will double, then we can predict that y will also double. This is an example of 'proportional reasoning'.

Similarly, if there is an inverse relationship between x and y ($x \propto \frac{1}{y}$), then we know if the value of x is doubled, the value of y will be halved.

There are many different strategies that can be used to solve problems involving proportional reasoning. One reliable method is outlined below.

1. Describe the relationship between variables as a statement of proportion (e.g. $x \propto \frac{1}{y}$).
2. Rewrite the proportionality as an equation by introducing a constant of proportionality (e.g. $x = \frac{k}{y}$).
3. Transpose the equation to make the constant the subject (e.g. $k = xy$).
4. As the constant of proportionality will not change, describe the relationship between an original set of values for the variables (e.g. x_1 and y_1) and the changed set of values (e.g. x_2 and y_2) to write an equation ($k = x_1 y_1 = x_2 y_2$).
5. Describe the change to one variable as an equation (e.g. if x_1 is doubled, then $x_2 = 2x_1$).
6. Substitute the equation from step 5 into the equation from step 4 (e.g. $x_1 y_1 = (2x_1) y_2$).
7. Simplify this new equation to describe the change in the other variable (e.g. cancelling x_1 from both sides: $y_1 = 2y_2$, therefore $y_2 = \frac{1}{2} y_1$).
8. Interpret the answer (e.g. y has been halved).

Note: This process is made much simpler when physical relationships are expressed in a way that means that the initial steps 1–4 have already been completed (e.g. $I_1 r_1^2 = I_2 r_2^2$).

Worked example 11.6.2

CALCULATING INTENSITY CHANGES USING PROPORTIONAL REASONING

The distance between a compact fluorescent light bulb and the observer is doubled. Determine by what ratio the intensity of the light from the bulb will change.	
Thinking	**Working**
Recall the formula for intensity.	$I_1 r_1^2 = I_2 r_2^2$
Describe the change to the radius as an equation.	$r_2 = 2r_1$
Substitute this relationship into the formula for intensity.	$I_1 r_1^2 = I_2 (2r_1)^2$
Simplify this equation to describe the change in intensity.	$I_1 r_1^2 = I_2 \times 4r_1^2$ $\therefore I_1 = I_2 \times 4$ $\therefore I_2 = \frac{1}{4} I_1$
Interpret the answer.	The intensity has reduced by a quarter.

➤ Try yourself 11.6.2

CALCULATING INTENSITY CHANGES USING PROPORTIONAL REASONING

A light-emitting diode (LED) is brought five times closer to a light meter. Determine by what ratio the measured intensity of the LED will change.

The inverse square law for intensity of a light source at a distance, r, from an observer can be applied to light sources as close as a light in the same room to the intensity of a distant star or galaxy, as long as the medium in between is constant (Figure 11.6.2). Where light is dispersed, reflected or absorbed by changes in the medium, then these other factors mean that the intensity may be greater or less than expected.

PA 2.2.5

FIGURE 11.6.2 The distance to distant galaxies, such as the Klemola galaxy cluster pictured here, or the relative intensity can be calculated using the relationship between intensity and distance from the source, provided that the medium between source and observer is constant.

11.6 Review

SUMMARY

- Intensity is a measure of brightness or the rate at which light energy passes through an area of space. The unit for intensity is Wm^{-2}.
- The relationship between the intensity of light at two points at different distances from a light source is given by $I_1r_1^2 = I_2r_2^2$.
- The reduction in intensity with the square of the distance from the source provides further evidence of the wave nature of light.
- Proportional reasoning can be used to simplify calculations where there is a standard relationship between two variables.
- The inverse square law for the intensity of light from a source at a distance r, only applies when the medium between source and observer is constant.

KEY QUESTIONS

Retrieval

1 State the unit for intensity.

Comprehension

2 The change in intensity, I, of a light source with distance is further confirmation of the wave nature of light. Explain why this is the case.

Analysis

3 A light source is 5.0 m from an observer. Calculate the intensity relative to the intensity at the source.

4 An observer moves to a position I_1, which is 10.0 m from a candle (the point source of light). Calculate the intensity of the candle at the observer's new position relative to its intensity at the source, I_0.

5 Two observers, A and B, are 1.0 m and 3.0 m respectively away from a point light source. Calculate the relative intensity of the light source seen by observer A compared with that seen by observer B.

6 If the distance between a light source and an observer is increased by a factor of 2.5. Calculate the factor by which the intensity of the light will increase or reduce.

11.7 Polarisation

BY THE END OF THIS MODULE, YOU SHOULD BE ABLE TO:

- describe polarisation using a transverse wave model of light
- explain plane polarisation of light using a transverse wave model of light
- describe applications of polarisation.

Further evidence for the wave nature of light is the finding that light can be polarised. Consider that light is an electromagnetic wave with associated electric and magnetic fields that vary as the light is propagated from the source. Each of these fields varies at a right angle to the direction in which the wave travels. For this discussion, think about the varying electric field, as it is this that largely determines how light interacts with materials. You can therefore represent light as a simple transverse wave in one plane.

An LED inside a torch produces light that is emitted from many different atoms and many light waves may be sent in a particular direction as a beam of light. However, the electric fields of these light waves will not be aligned, so the light is unpolarised. Most light sources, including our Sun, produce unpolarised light.

- In Figure 11.7.1a, the electric fields of the light waves are not aligned. This is **unpolarised light**.
- In Figure 11.7.1b, the electric fields of the light waves are aligned. This is **polarised light**.

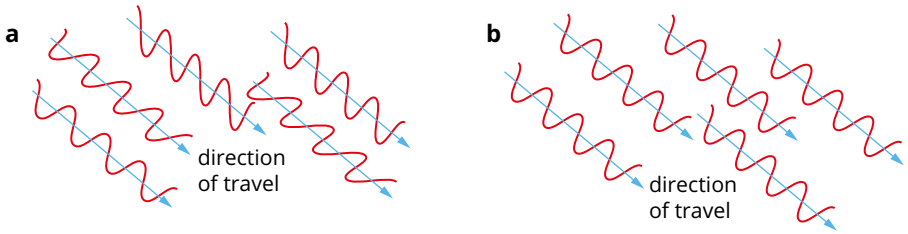


FIGURE 11.7.1 (a) Unpolarised light, such as that emitted by the Sun or a globe, has electric field variations that are not in alignment with one another. (b) Polarised light waves, such as those from a laser, have electric fields that vary in the same plane as one another.

A polariser demonstration set is shown in Figure 11.7.2. The fact that unpolarised light can be converted into polarised light provides strong evidence that light is a wave. Also, the fact that light can be polarised indicates that it's a transverse wave because longitudinal waves cannot be polarised.

POLARISING UNPOLARISED LIGHT

The best known way in which unpolarised (non-aligned) light can be converted to polarised (aligned) light is by using **polarising filters**. These filters have molecules that will block all wave components of the electric field except those in the plane that is aligned in a particular direction. Figure 11.7.3 demonstrates this process using a 'slit' to represent the filter. Keep in mind that filters are actually solid materials, usually specially treated plastics.

FIGURE 11.7.2 A polariser demonstration set usually consists of a pair of thin treated plastic discs or sheets that allow investigation of polarised and unpolarised light.

- If a light wave has its electric field in a plane aligned with the filter, then it will pass straight through the filter and maintain its original amplitude. All of the light energy aligned in this way will pass through. A vertically orientated filter will only allow light with a vertically orientated electric-field variation to pass through, as shown in Figure 11.7.3a.
- If a light wave has its electric field in a plane completely out of alignment with the filter, then it will be blocked. The filter will absorb the light, as shown in Figure 11.7.3b.
- If a light wave has only a component of its electric-field plane in alignment with the filter, then only this component of the wave will be transmitted. The emerging wave will have a significantly reduced amplitude. A portion of the light energy won't pass through the filter, as shown in Figure 11.7.3c. The emerging light is described as 'vertically polarised'.

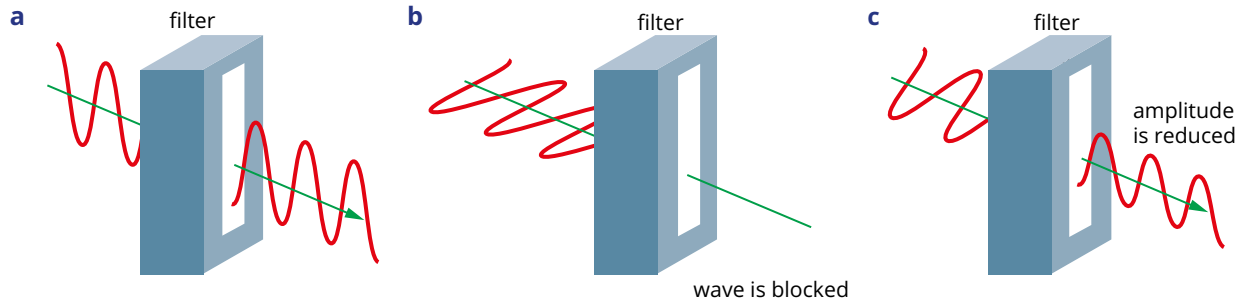


FIGURE 11.7.3 (a) The first filter allows vertically polarised light to pass through, matching the orientation of the slits. (b) All horizontally polarised light is blocked. (c) The horizontal component of the light is suppressed matching the slit width, resulting in vertically polarised light of reduced amplitude. The emerging light will be less bright than the incident light.

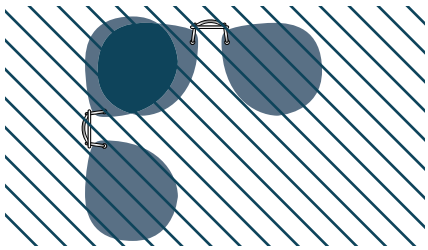


FIGURE 11.7.4 Polarising materials crossing over at right angles to one another will prevent any light from passing through.

If unpolarised light is incident on the filter (at 90°), then only vertically polarised light would emerge. A pair of polarising filters with a very fine slit width placed at right angles would prevent all light from passing through. One filter would block all of the horizontal electric-field components and the other filter would block the vertical components, as shown with the polarising sunglasses in Figure 11.7.4. In practice, the physical width of the polarising 'slit', while very small, will allow small amounts of very short wavelengths through. This light will be in the violet end of the spectrum. As a result, typically, when looking through a pair of crossed polaroids, low intensity violet light can be seen.

PLANE POLARISATION OF REFLECTED LIGHT

When outdoors on a bright, sunny day, the smooth, highly reflective, horizontal surfaces around you are a significant contributor to the amount of light entering your eyes. Bring to mind the glare that can occur from the surface of the ocean on a sunny day, or that from snow.

Fortunately light that is reflected from smooth, horizontal surfaces tends to be polarised (aligned) in a horizontal direction. This is termed the **plane polarisation** of reflected light. An appropriately orientated polarising filter can be used. Lenses in a pair of polarised sunglasses are polarising filters orientated to block the horizontal wave components of reflected light, allowing only the vertical components through. Therefore the intensity of light, or glare, is markedly reduced.

OTHER APPLICATIONS OF POLARISATION

If you have ever used polarised sunglasses, you may have noticed one of the other affects of polaroids, particularly when driving. The amount of glare off the windscreens of other cars is substantially reduced, but in its place can be seen what appear to be rainbows within the glass. This is particularly true of modern laminated glass windscreens that are part of the car structure and therefore come under some stress.

You can try this yourself. Place a clear piece of thick plastic, or similar, between two polaroids. Shine a light source through the polaroids then flex or twist the piece of plastic and note any changes in the appearance of the plastic. Initially, the plastic will look quite flat. If the polaroids are twisted at right angles to each other, the plastic may be seen as a lighter area, suggesting that the plane of the light that travelled through the first polaroid is being partially rotated by the passage through the plastic. When the plastic is twisted, rainbows appear across the surface of the plastic. The more stress that is applied, the tighter the pattern of the rainbows. The patterns are indicating where the stress in the plastic is greatest and hence where it is most likely to break.

This application of polarisation is referred to as photoelasticity and was originally explained by Scottish physicist David Brewster, before its widespread use in the early part of the 20th century. This method determines stress distribution in a material experimentally, and gives a fairly accurate picture of stress distribution around likely breaking points in materials. With the advent of computer monitoring, the method became less common but it is still used for determining stress concentration in irregular geometries or where mathematical models are too cumbersome or slow to develop. The digital 'polarisope' using LEDs allows continuous monitoring of structures under loads, contributing to the study of causes of fracturing of materials, as shown in Figure 11.7.5.

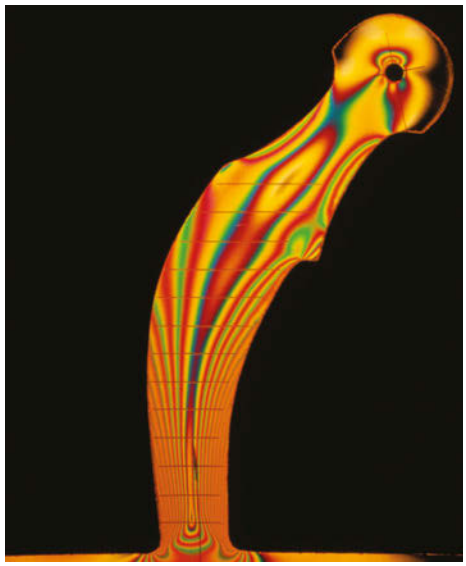


FIGURE 11.7.5 Stress patterns in a plastic model of a proposed human hip joint replacement. The model has been photographed between two polaroids. Points of discontinuity in the patterns indicate where the model is likely to break and changes can be made before being produced out of the final metal material.

Similar patterns can be observed in some solutions, termed chiral solutions. Since 1812, it has been know that certain molecules are optically active and can rotate plane-polarised light. For example, table sugar is an optically active substance. Table sugar has a tetrahedral carbon atom that has four different groups attached to it. This carbon is known as a chiral centre. The geometry of the chiral centre allows the formation of mirror image molecular forms under the right conditions. One of the molecular forms is able to rotate plane-polarised light to the right and the other mirror image molecular form is able to rotate plane-polarised light to the left by the same angle.

Experimentation is the only way to determine which form of molecule is which. The procedure consists of preparing a solution of known concentration and placing it between two polarising filters. A polarimeter, essentially two polaroids with a scale to measure the difference in angle of polarisation between them, measures the amount and direction of rotation of the plane-polarised light (Figure 11.7.6). The specific angle is a fundamental property of the chiral solution, and polarimetry makes it possible to determine the purity of solutions of known compounds and identify unknown substances from a short list.

FIGURE 11.7.6 A sample bottle of sugar solutions placed between two polaroids will rotate the polarised light from the first polaroid by an amount that is a property of the type of solution, the concentration and temperature. The second polaroid can be used to determine the amount of rotation.

11.7 Review

SUMMARY

- Unpolarised light waves have electric-field variations that are not in alignment with one another. Polarised light waves have electric fields that vary in the same plane as one another.
- Polarising filters are able to convert unpolarised light into polarised light, providing strong evidence that light is a transverse wave.
- Light reflected off a horizontal surface is said to be partially plane polarised.
- Polarisation can be used to determine the likely stress and breaking points in manufactured equipment during design. This application is referred to as photoelasticity.
- A polarimeter can be used to determine the concentration, substance and temperature of optically active solutions, termed chiral solutions. Sugar solutions are an example of a chiral solution.

KEY QUESTIONS

Retrieval

1 State the factor by which the intensity of any unpolarised light shining through a single polaroid will be reduced.

2 A second polaroid is rotated at an angle of 90.0° to the first. State the percentage by which the intensity of light would be reduced if the light travels through the single polaroid first.

3 A second polaroid is rotated at an angle of 180.0° to the first. Describe the factor by which the intensity of light would be reduced if the light travels through the single polaroid first.

4 Light reflecting off a horizontal surface is said to be plane polarised. Define 'plane polarised'.

Comprehension

5 Explain the effect that a polarising filter has on unpolarised light.

6 Explain how polarisation supports a wave model of light model.

Analysis

7 A polarising filter is positioned so that it produces vertically polarised light. If another filter is orientated at an angle of 30.0° to this filter, describe what happens to the intensity of the light.

8 In some instances, dim violet light can still be seen after light has travelled through two polaroids at right angles to each other. Explain why this can occur.

MP 6

Determining the refractive index of a transparent substance

Research and planning

Aim

- To determine the relative refractive index of various materials with air.

Rationale

When light passes from one transparent medium to another, the rays bend or refract. The law of refraction (Snell's law) states that:

$$n_1 \sin i = n_2 \sin r$$

where

n_1 is the index of refraction for the incident ray

i is the angle of incidence relative to the normal

n_2 is the index of refraction for the refracted ray

r is the angle of refraction relative to the normal.

The relative refractive index is the ratio $\frac{n_2}{n_1}$.

Timing

45 min

Materials

- light box
- rectangular prisms of clear glass and/or perspex
- semicircular prisms of clear glass and/or perspex
- plain paper
- ruler and protractor

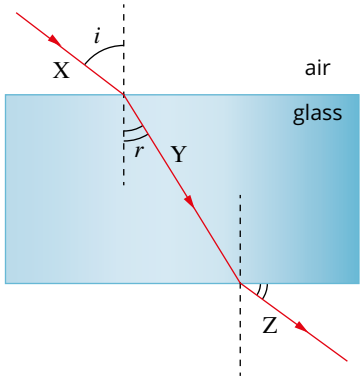
Method

Risk assessment

Before you commence this practical activity, you must conduct a risk assessment. Complete the template in your Skills and Assessment Book or download it from your eBook.

A Rectangular prism

1 Place a glass block on a piece of plane paper and draw around its outline with a sharp pencil. Turn on the light box and adjust it to produce a single, thin beam of light incident to the glass block, as shown in the diagram.



2 Mark a point along the incident beam, X, the point where it intersects the glass block, Y, and the point where it leaves the glass block and re-enters the air, Z.

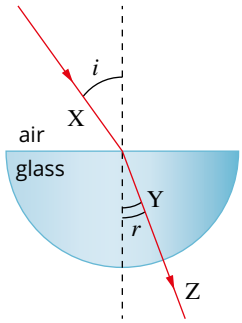
3 Join the points X to Y and Y to Z. Use a protractor to draw the normal to the block at point Y. Record both the incident angle (i) and refracted angle (r).

4 Repeat steps 1–3 for at least three other values of i.

5 Repeat the procedure for other materials. For example, perspex, and different types of glass.

B Semicircular prism

1 Place a semicircular glass block on a clean piece of plane paper. Turn on the light box and adjust it to produce a single, thin beam of light incident on the centre of the straight edge of the prism. Trace the outline of the glass block with a sharp pencil, as shown in the diagram.



2 Mark positions X, Y and Z as shown in the diagram above. Join the points X to Y and Y to Z. Use a protractor to mark the normal and measure the incident angle i and the refracted angle r.

3 Repeat for different values of i and for different materials (if available).

Variables

i Independent: incident angle

ii Dependent: angle of refraction

iii Controlled: prism material

Analysing

Raw and processed data

1 Record your results in the following tables.

A Rectangular prism

i	r	$\sin i$	$\sin r$	Uncertainty in i	Uncertainty in r	Uncertainty in $\sin i$	Uncertainty in $\sin r$

B Semicircular prism

i	r	$\sin i$	$\sin r$	Uncertainty in i	Uncertainty in r	Uncertainty in $\sin i$	Uncertainty in $\sin r$

2 Note that the uncertainty in $\sin x$ is given by $\cos x$ multiplied by the uncertainty in x (in radians).

3 Plot your your results, including error bars, on a graph, with $\sin i$ on the horizontal axis and $\sin r$ on the vertical axis. Label the axes, include units and add a title for your graph.

4 Draw a line of best fit, and find its gradient. Use your error bars to draw a minimum and a maximum line.

5 Calculate the uncertainty in the gradient to find the uncertainty of the index of refraction, n.

6 Are there any points on your graph that do not fit the trend? Explain why this may have been the case.

7 What factors contribute the most to the uncertainty in n and how they can be reduced?

Processed data

➤ Reflect and check that your data analysis demonstrates these characteristics

- ❑ Effective investigation of phenomena is demonstrated by the collection of sufficient and relevant raw data.
- ❑ Accurate application of algorithms, visual and graphical representations of data is demonstrated by appropriate processing and presentation of data to aid the analysis and interpretation of data.

Analysis

➤ Reflect and check that your analysis demonstrates these characteristics

- ❑ Systematic and effective analysis of evidence is demonstrated by a thorough and appropriate error analysis.
- ❑ Systematic and effective analysis of evidence is demonstrated by a thorough identification of relevant trends, patterns and relationships.
- ❑ Insightful and valid interpretation of evidence is demonstrated by drawing a valid and defensible conclusion based on the analysis.

Interpreting and communicating

Conclusion

1 Summarise your values for the relative refractive index of each prism and material you have used. Compare your results and comment on the reliability of each method.

Evaluation

2 The incident ray is in the same plane as the drawing paper. Determine whether or not the refracted ray is in the same plane.

3 Identify the advantages of using a semicircular prism.

4 Determine whether the relative refractive indices of air–glass and air–perspex are the same.

Improvements

5 Assuming the opportunity arose to repeat the experiment, identify the steps or processes you would do differently.
Include in your answer:
- the new methodology and contrast the results from this approach with the initial experiment
- the skills you used to perform the tasks and explain improvements that could be achieved
- methods by which the collection of data could be made more reliable and the uncertainty reduced.

Extension

6 Investigate refraction in a practical context, such as droplets of water, fibre optics.

➤ Reflect and check that your evaluation demonstrates these characteristics

- ❑ Critical evaluation of processes is demonstrated by a discussion of the reliability and validity of the experimental process supported by evidence such as the quality of the data (as quantified in the error analysis).
- ❑ Critical evaluation of the conclusion is demonstrated by a discussion of the veracity of the conclusions with respect to the error analysis and limitations or sufficiency of the data.
- ❑ Insightful evaluation of processes and conclusions is demonstrated by a suggestion of improvements or extensions to the experiment which are logically derived from the analysis of the evidence.

References

Having completed your report make sure that you read it ALOUD and check that it demonstrates these characteristics

- ❑ Concise communication of understandings, findings, arguments and conclusions is demonstrated by the use of genre conventions.
- ❑ Accurate communication of understandings, findings, arguments and conclusions is demonstrated by the fluent and consistent use of scientific language, representations and conventions.
- ❑ Suitable communication of understandings, findings, arguments and conclusions is demonstrated by correct referencing of sources.

Chapter review

WS 2.2.7 WS 2.2.8 TR 2.2 S.A.T. IA2 Student Experiment

11

KEY TERMS

aberration
absolute refractive index
aether
centre of curvature
collinear
concave
convex
corpuscular
critical angle
electromagnetic radiation
electromagnetic spectrum
focal length
geometrical optics
in phase
intensity (of a wave)
interference pattern
inverse square law
magnification
optical density
plane polarised
polarised light
polarising filters
principal axis
principal focus
radius of curvature
ray tracing
real image
rectilinear propagation
relative refractive index
spectrum
spherical mirror
total internal reflection
unpolarised light
virtual image
visible light

KEY QUESTIONS

Retrieval

1 As light travels from quartz to water it will:
- **A** speed up
- **B** slow down
- **C** stay the same speed
- **D** be stopped all together

2 List the following forms of electromagnetic radiation in order of increasing frequency:
X-rays, microwaves, visible light, radio waves.

3 Identify which of the following statements, A–D, regarding a virtual image is correct:
- **A** A virtual image can be projected onto a screen.
- **B** A virtual image really exists.
- **C** A virtual image is produced by intersecting rays.
- **D** A virtual image is located at a point from which rays of light seem to diverge.

4 Indicate which of the following boundaries between two media will result in the greatest refraction of any light ray that crosses the boundary.
- **A** water to air
- **B** water to diamond
- **C** air to diamond
- **D** glass to air

5 State the term for the point at which parallel rays of light through a convex lens converge.

6 List which one or more models of light (ray model, waves, electromagnetic waves) can be used to explain the following behaviours of light.
- **a** reflection
- **b** total internal reflection
- **c** interference
- **d** polarisation

Comprehension

7 If the distance between a light source and an observer is halved, determine how much will the intensity of the light will change.

8 You stand 3 m in front of a plane mirror. Determine how far from you your image appears to be.

9 Explain how the spectrum of colours reflected from a black object is different from the spectrum of light reflected by a grey object.

10 A key finding by Michelson and Morley was that light was not a mechanical wave. Describe how their investigation of interference establish that this was the case.

11 At the boundary between two media, medium 1 and medium 2, the angle of refraction is smaller than the angle of incidence. Explain in which medium light will travel faster. Justify your answer.

12 Explain how it is possible to see a star, even when it is actually positioned below the horizon. Use diagrams where appropriate.

13 A shop owner installs a large convex mirror for security purposes. Describe the nature of the image formed in the mirror. Explain why such a mirror is useful.

14 State the physical properties of a spherical lens that determine its focal length.

15 A student constructs an experiment identical to that of Young's double-slit experiment but she uses white light instead of monochromatic light. Describe the resulting interference pattern.

16 In an experiment to investigate diffraction, the width of the gap through which light passes is reduced. State whether diffraction is more or less likely to be observed. Explain your answer.

17 Explain why snowboarders and fishers are likely to prefer polarising sunglasses to standard darker lenses.

18 The idea of an 'aether' was proposed to support a particular model for the behaviour of light. Explain what the aether was and how it supported that model.

19 Young's double-slit interference experiment used two slits to create two beams from the one monochromatic light source. Determine whether two completely independent light sources can produce interference. Explain.

20 Polarised sunglasses used to be very popular for driving but have been less so in recent years. They remain popular for outdoor pursuits such as skiing and boating. Explain why this would be so.

Analysis

21 Ultraviolet (UV) has a wavelength from 10.0 nm to 400.0 nm, which is shorter than visible light but longer than X-rays. Find the frequencies corresponding to the two limits of the UV section of the electromagnetic spectrum (10.0 nm and 400.0 nm).

22 An object is placed 20.0 cm in front of a convex mirror with a radius of curvature of 30.0 cm.
- **a** Using ray tracing, determine how far the resulting image is from the mirror.
- **b** Describe the nature of the image.

23 A 1.0 m tall child stands 6.0 m from a concave mirror that has a radius of curvature of 4.0 m.
- **a** Use a ray diagram to determine the height of the image and how far it is from the mirror.
- **b** Describe the nature of the image.

24 The speed of light in air is $3.00 \times 10^8\,\text{m s}^{-1}$. As light strikes an air–perspex boundary, the angle of incidence is 43.0° and the angle of refraction is 28.5°. Calculate the speed of light in the perspex.

25 A narrow beam of white light enters a crown glass prism with an angle of incidence of 30.0°. In air, the white light travels at a speed of $3.00 \times 10^8\,\text{m s}^{-1}$. In the prism, the different colours of light are slowed to varying degrees. The refractive index for red light in crown glass is 1.50 and for violet light the refractive index is 1.53. Calculate the corresponding angles of refraction for red and violet light.

26 Calculate the critical angle for light passing from diamond ($n = 2.42$) into air.

27 A concave lens is held 20.0 cm above a page and the text appears to be one-quarter its original size. Use ray tracing to model the arrangement and determine:
- **a** the nature of the image
- **b** the distance of the image from the lens.

28 For a person sitting 75 cm away from a computer monitor, the light intensity from the monitor is $6.0\,\text{W m}^{-2}$. Calculate the new intensity if they moved to sit only 50 cm from the monitor.

29 The intensity of a distant radio signal from a small transmitter is $0.120 \times 10^{-3}\,\text{W m}^{-2}$ at a distance of 160 m from the transmitter. Calculate the intensity of the signal 4.00 m from the transmitter.

30 A ray of light passing from air, through a layer of plate glass and back into air emerges parallel to its original direction of travel. Explain whether the ray of light has been refracted, using diagrams as appropriate.

Knowledge utilisation

31 A spinning top is decorated with all the colours of the rainbow, yet when spun it appears almost white. A second top, also with all of the colours of the rainbow, appears pinkish. Explain how this could be achieved.

32 Curved mirrors are used for different purposes. Three examples are shaving and make-up, shop security, and a rear-view mirror for a truck. Use ray tracing to decide on the shape and approximate focal length suitable for the given applications, taking the position of the object and required features of the image into consideration.

33 Discuss the effect that the relative size of the refractive index has on the size of the corresponding critical angle.

34 Sarah accurately determines that her glasses have a focal length of +30 cm. Identify if she is myopic (short-sighted) or hypermetropic (long-sighted). Justify your answer.

35 You have two pairs of sunglasses that appear identical in every respect. Assuming the brand and labelling isn't available to review, describe a method by which you could determine whether the sunglasses were polarising or non-polarising without breaking the glasses.

REVIEW QUESTIONS

Topic 1: Linear motion and force

Multiple choice

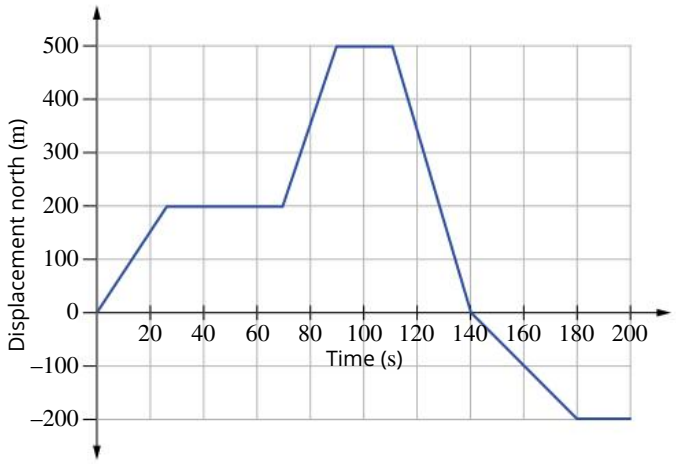
1 Select the lists below that contains only vector quantities.

A displacement, velocity, acceleration, force
B displacement, speed, acceleration, weight
C distance travelled, velocity, acceleration, force
D displacement, velocity, acceleration, mass

2 A superball hits a wall with a velocity of $7.0\,m\,s^{-1}$ east and rebounds with a velocity of $6.0\,m\,s^{-1}$ west. Determine the change in velocity of the ball.

A $1\,m\,s^{-1}$ west
B $13\,m\,s^{-1}$ east
C $13\,m\,s^{-1}$ west
D $1\,m\,s^{-1}$ east

The following information applies to Questions 3 and 4.
The graph below shows the displacement of a farmer on a motorcycle, riding north (positive) and south (negative) along a boundary of the property while counting livestock.



3 What was the total distance travelled by the farmer over the entire period?

A 500 m
B 300 m
C 700 m
D 1200 m

4 What was the total displacement of the farmer over the entire period?

A −200 m
B 0 m
C 1200 m
D −1200 m

5 A 40 kg child on a scooter is rolling down a footpath at $2.5\,m\,s^{-1}$. The momentum of the child is:

A $16\,kg\,m\,s^{-1}$ down the footpath
B $100\,kg\,m\,s^{-1}$ down the footpath
C $0.40\,kg\,m\,s^{-1}$ down the footpath
D $42.5\,kg\,m\,s^{-1}$ down the footpath

6 A 10 tonne truck collides with an unoccupied and stationary Mini. Select the statement that describes the situation at impact according to Newton's third law.

A The truck applies the same magnitude force on the Mini as the Mini applies on the truck.
B The truck applies a greater magnitude force on the Mini than the Mini applies on the truck.
C The truck applies a smaller magnitude force on the Mini than the Mini applies on the truck.
D The truck applies a force on the Mini but the Mini does not apply a force on the truck.

7 A 6.5 kg bowling ball is lifted from the floor to a shelf 2.2 m high. The amount of work done is:

A 43 J
B 140 J
C 4.3 J
D 14.0 J

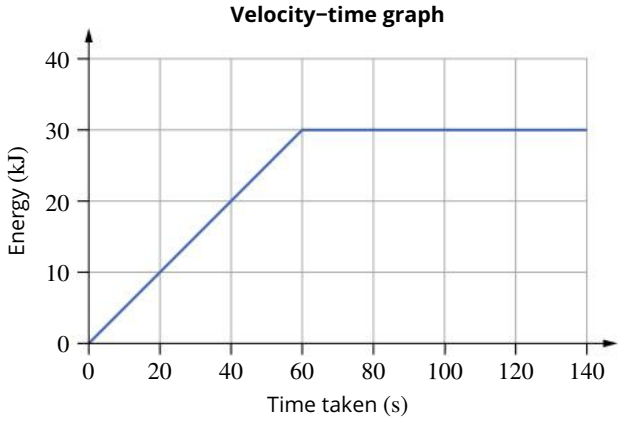
8 A gymnast is at the top of a vertical jump above the trampoline mat. Select the statement that is correct.

A She has maximal gravitational potential energy and minimal kinetic energy.
B She has maximal gravitational potential energy and maximal kinetic energy.
C She has minimal gravitational potential energy and maximal kinetic energy.
D She has minimal gravitational potential energy and minimal kinetic energy.

9 Identify the correct statement.

A In elastic and inelastic collisions, kinetic energy and momentum are not conserved.
B In elastic and inelastic collisions, kinetic energy and momentum are conserved.
C In elastic and inelastic collisions, momentum is conserved. In elastic collisions kinetic energy is conserved, but in inelastic collisions kinetic energy is not conserved.
D In elastic and inelastic collisions, momentum is conserved, but kinetic energy is not.

10 A train leaves the station, and travels on level ground. The energy of the train is shown below.



The power supplied by the engine to accelerate the train at 40 seconds is:

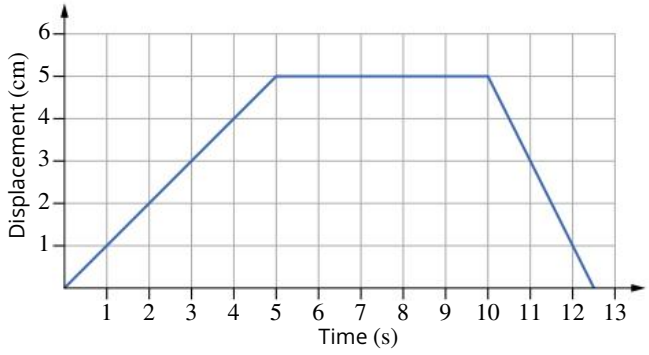
A 20 kJ
B 400 kW
C 20 kW
D 500 W

Short answer

1 A car travels 5.00 km east, 3.00 km south, 2.00 km west and 1.00 km north.

a Determine the distance, north or south, the car has travelled.
b Determine the distance, east or west, the car has travelled.
c Find the resultant displacement of the car.

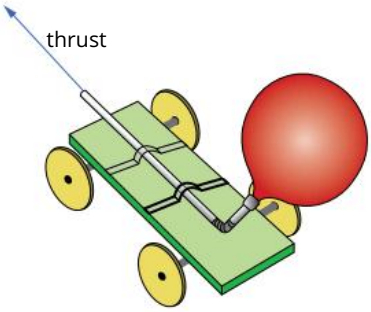
2 The graph below shows the position of an ant that is travelling in a straight line.



a Define the following terms: displacement, average velocity and instantaneous velocity.
b Calculate the average velocity of the ant in the first 2 seconds and the instantaneous velocity at 2 seconds.
c Calculate the average velocity in the first 11 seconds, and the instantaneous velocity at 11 seconds.
d Determine conditions that cause the average velocity and instantaneous velocity to be the same.

3 A hot air balloon is floating 800 m above the ground. One of the passengers accidentally drops their phone while taking photos. Calculate the velocity of the phone as it hits the ground, and how long it takes to reach the ground.

4 For the following situations, identify the reaction force to create an action–reaction pair according to Newton's third law. Sketch the force on the drawing.



a balloon-powered car

b sitting in a chair

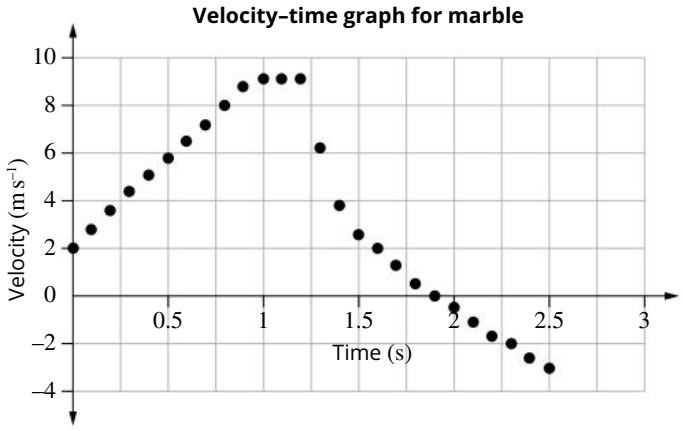
5 A high-velocity 10.0 g rifle bullet, travelling horizontally, lodges in a 1.00 kg wooden block, at rest on a horizontal, frictionless plane. The block, with the bullet stuck inside, reaches a velocity of 5.00 m s^{-1} in the same direction as the bullet.

a Find the impact velocity of the bullet.
b Calculate the impulse on the block.

6 A dog of mass 20.0 kg is running in the park on a rainy day. The dog runs towards its owner (mass 80.0 kg) at a velocity of 7.0 m s^{-1} and slides into the stationary owner.

a Assuming the dog and owner travel together after the collision, and assuming there is no friction, calculate the velocity of the dog and owner.
b Determine if the collision is elastic or inelastic. Justify your answer.

7 Students measure the velocity of a marble in a straight section of a marble run at 0.1 s intervals. The graph of their results is shown below.



Describe the motion of the marble, including the displacement, velocity and acceleration.

8 Students were conducting an experiment to measure the acceleration due to gravity. They recorded a video of a red ball, mass 500 g, as it was dropped from the second storey. The following data was obtained from the video:

Position (m)	Time (s)
11.4	0
10.616	0.4
8.264	0.8
4.344	1.2
0.07904	1.52

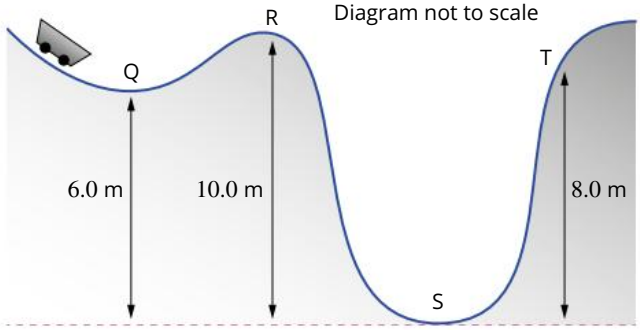
a Plot a graph of position vs time. Determine the type of relationship between distance and time from the shape of your graph.
b Linearise the data and graph the linearised data.
c Find the equation of the line of best fit.
d Write a conclusion for this experiment.

9 A bird has caught a fish and is flying to a nearby tree.

The bird has a mass of 1.4 kg, and the fish has a of mass 500 g. The bird is gliding with a constant velocity of $10\,m\,s^{-1}$ when the fish wriggles free. Immediately after losing the fish, the velocity of the bird is $12\,m\,s^{-1}$ in the same direction.

a Calculate the velocity of the fish the moment after being let go, before accelerating towards the ground.
b The bird and fish are 80.0 m above the ground when the fish wriggles free. Calculate the magnitude of the velocity of the fish when it reaches ground level.
c The fish lands in water, coming to a stop in 0.3 seconds. Calculate the force on the fish during this time.
d Recall the principle of conservation of momentum and explain how momentum is conserved when the fish lands in the water.

10 The diagram shows a section of roller-coaster track. The mass of an empty carriage is 350 kg. Ignore any effects due to friction. The carriage is momentarily at rest at point R before it rolls towards point S.

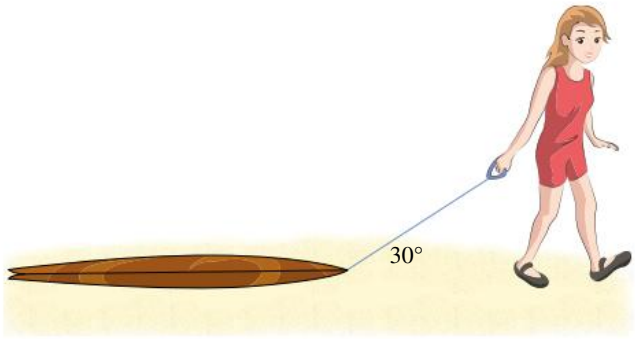


a Calculate the amount of gravitational potential energy the carriage possess at point R.
b Calculate the amount of kinetic energy the carriage possess at point R.
c Calculate the amount of kinetic energy the carriage possess at point S.
d Determine the speed at which the carriage pass through point S.
e The carriage passes point S and heads towards point T. Calculate the speed of the carriage as it passes through point T.
f During another trial run, the carriage travels through point Q with sufficient speed so that it is just able to reach point R. Determine the speed of the carriage at point Q during this trial.

11 An improvement in car safety for drivers has been the introduction of airbags. Explain, with reference to the following concepts, why this is so.

a Newton's first law of motion
b Impulse

12 A young girl was pulling a surfboard of mass 3 kg along the beach at a constant velocity.

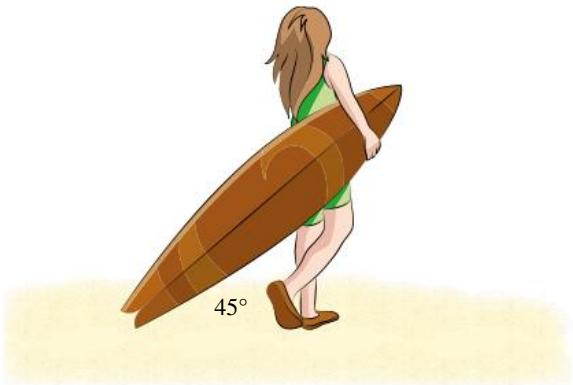


The friction force acting on the surfboard was a constant 9 N.

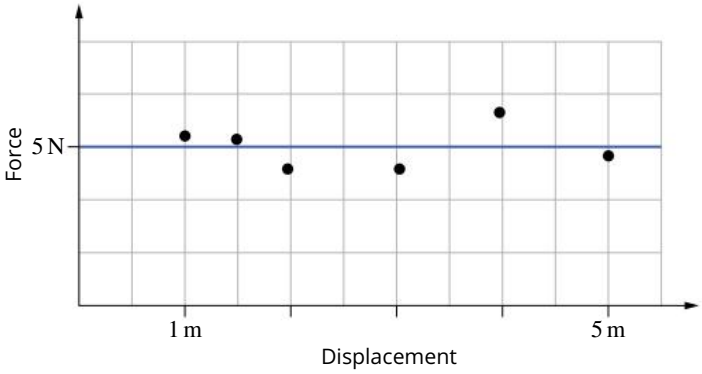
a Draw a free body diagram of the forces acting on the surfboard.

b Calculate the work required to overcome the friction force as the board travels 5 m.

c Her older sister told her that it is easier to drag a surfboard along its edge. Explain why this is the case.



d Her sister proves it to her by recording the force she applies to move the board. Use her results to calculate the work required to move the surfboard at a constant velocity by dragging it on the side.



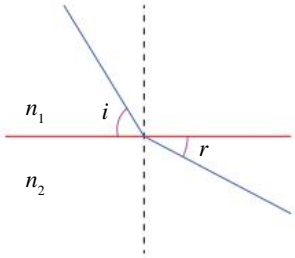
e Suggest another way to reduce the work required.

Topic 2: Waves

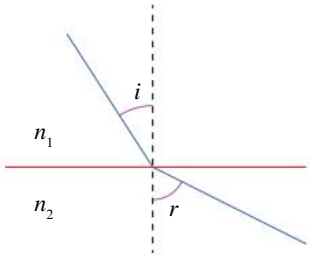
Multiple choice

1 Identify the correct version of Snell's law and the definition of the variables.

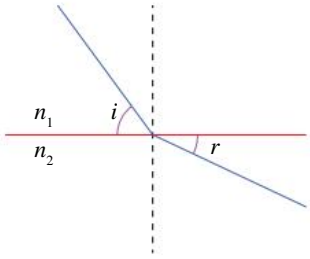
A $\frac{\sin i}{\sin r} = \frac{n_2}{n_1}$



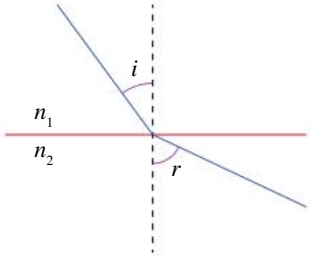
B $\frac{\sin i}{\sin r} = \frac{n_2}{n_1}$



C $\frac{\sin i}{\sin r} = \frac{n_1}{n_2}$



D $\frac{\sin i}{\sin r} = \frac{n_1}{n_2}$



2 State which of the following is/are transferred by all waves from one point to another.

A matter and information

B energy and matter

C energy

D information and energy

3 According to wave theory, when two crests collide they:
- **A** pass through each other with no visible effect
- **B** cancel out each other leaving an area of no disturbance
- **C** superimpose on one another to momentarily create a larger waveform
- **D** reflect as if each collided with a solid wall

4 Identify which of the following properties of sound is independent of the source producing the sound.
- **A** frequency
- **B** amplitude
- **C** speed

5 An image from a plane mirror is best described as:
- **A** real, upright and enlarged
- **B** real, inverted and same size
- **C** virtual, inverted and enlarged
- **D** virtual, upright and same size

6 Two identical lights are placed on either side of the room. An observer stands 3.0 m from one light and measures the intensity of that light to be 25 W m^{-2}. The second light bulb has a measured intensity of 12 W m^{-2}. Calculate the distance from the observer to the second light bulb.
- **A** 4.3 m
- **B** 6.3 m
- **C** 18.8 m
- **D** 1.4 m

7 Identify the list below that contains behaviour of light that can be explained with the wave model of light.
- **A** superposition, photoelectric effect, refraction, interference
- **B** reflection, refraction, polarisation, interference, dispersion, diffraction
- **C** polarisation, momentum, reflection, interference, dispersion
- **D** wavelets, refraction, polarisation, reflection

8 An object is placed at a distance of 5 cm in front of a convex lens with a focal length of 3 cm. The image is:
- **A** real, inverted and enlarged
- **B** real, inverted and diminished
- **C** virtual, inverted and diminished
- **D** virtual, upright and enlarged

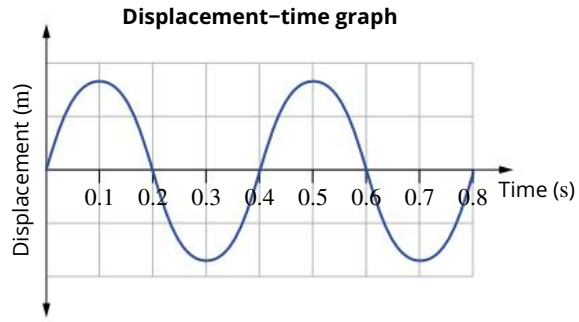
9 In a pipe with two open ends, the 4th harmonic is at 512 Hz. Determine the frequency of the 7th harmonic.
- **A** 1028 Hz
- **B** 3584 Hz
- **C** 128 Hz
- **D** 896 Hz

10 Indicate where an object should be placed for a concave lens to produce an image the same magnitude as the object.
- **A** between the focal point and the lens
- **B** at twice the focal distance
- **C** at infinity
- **D** at the focal point

Short answer

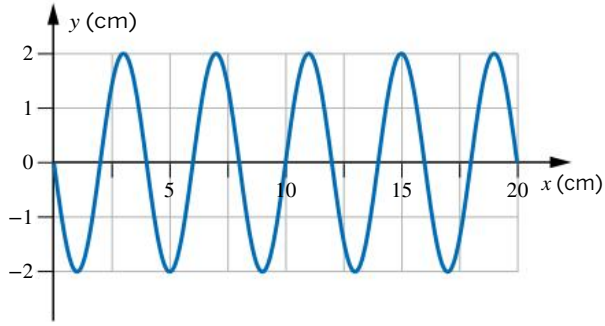
1 Explain the difference between a longitudinal wave and a transverse wave. Give an example of each.

2 **a** Determine the period of the wave responsible for the motion of the particle depicted on the graph below.



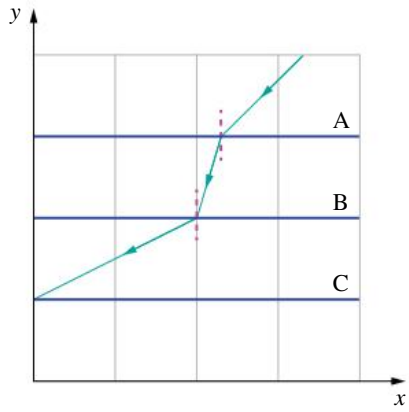
b Calculate the speed of the wave if the wave moves 2.0 m in the time for one period.

3 Determine the wavelength and amplitude of the wave depicted in the following graph.



4 A friend sits stationary on a swing and asks you to push them. Explain how the concept of resonance relates to pushing your friend so the height of swing increases over time.

5 The following diagram shows three different media through which light can pass. The path that a ray of light takes through these three media is also shown. List the media in order from highest refractive index to lowest refractive index.



6 Light travelling in air enters a second medium of refractive index 2.42 at an angle of incidence of 30.0°.

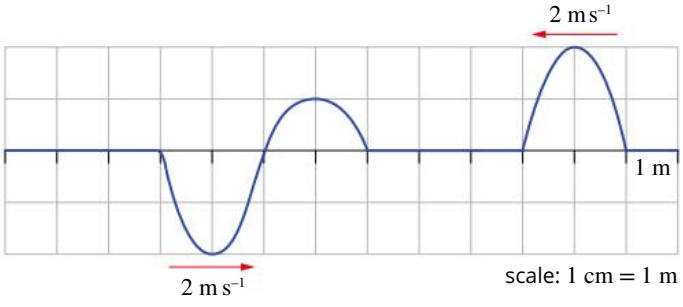
a Determine the angle of refraction.

b Calculate the speed of light in the second medium.

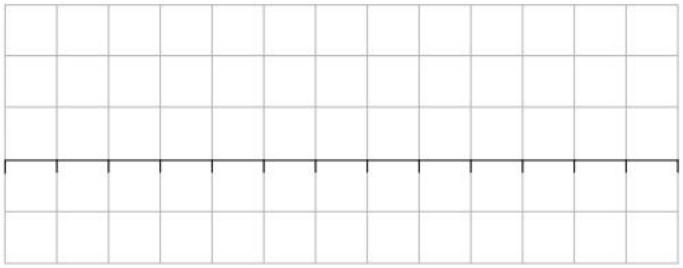
7 When ordinary white light is viewed through a single polarising sheet, the brightness of light passing through to the observer is reduced by about half. A second polarising sheet can be placed on top of the first sheet in such a way as to have no effect on the brightness of the light passing through it. If the second sheet is now rotated 90°, virtually no light now passes through to the observer.

Explain these observations using the appropriate physics principles.

8 Two pulses on a string approach each other as shown below.



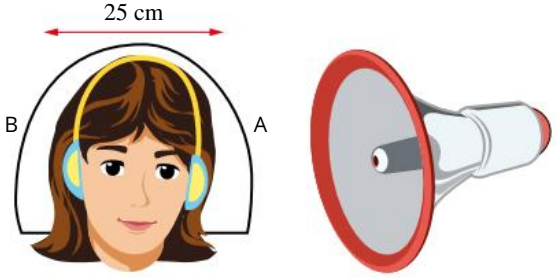
a On the grid below, draw, in one colour, the positions of the two individual pulses 2 seconds after their positions shown in the diagram above.

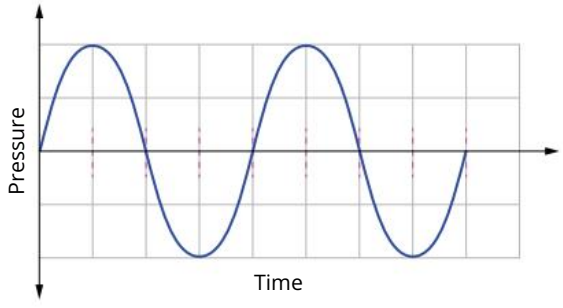


b Then, in another colour, draw the superposition of the two pulses at this time.

9 Define the concept of intensity, including the relationship that predicts how the intensity of waves changes over distance.

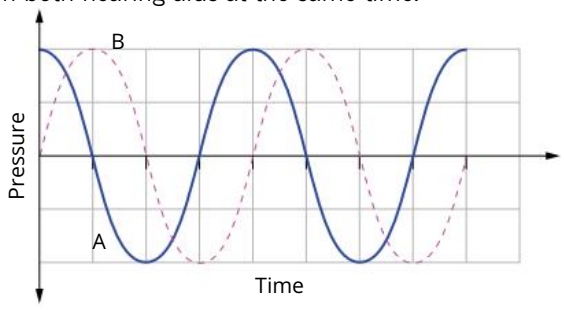
10 A simulator of the human head is used to determine the efficiency of hearing aids. The process involves a sound of set frequency being produced from a speaker at one side of the simulator as shown in the diagram. Hearing aid A is closer to the speaker and a display of its reception is given.





a On the same axes, draw the display as it will appear one-quarter of a cycle later.

Hearing aid B is 25 cm further from the speaker than hearing aid A. The graph below indicates the reception from both hearing aids at the same time.



b Calculate the wavelength of the sound.

c Given the speed of sound in air is 340 m s^{-1}, determine the frequency of the sound.

11 Two circular waves are created in a water tank. The waves are formed exactly in phase and interfere when they meet. At the edge of the tank, sensors detect two kinds of interference patterns in the water: constructive and destructive. The constructive interference occurs when two crests or two troughs meet.

a Explain when destructive interference will occur and describe what it will look like.

b Identify the type of interference the sensors will detect at the very centre of the pattern.

The waves are created at a rate of 50 crests per second and travel with a velocity of 0.60 m s^{-1}.

c Calculate the wavelength of the waves.

Consider a point X where the sensors detect the second non-central destructive interference pattern.

d Calculate the difference in path length between X and one wave source and X and the other wave source.

12 A string is attached to a ring around a pole so that it is free to move. The other end of the string is fixed. The tension in the string is constant. The effective length of the string is 75 cm and the speed of a wave created in the string is 330 m s^{-1}.

a Define natural frequency with respect to this string.

b Calculate the frequency of the fundamental frequency (also known as the first harmonic).

c Calculate the frequency of the third harmonic.

d Calculate the frequency of the next harmonic after the third that the string can produce.

13 A flute, 35 cm in length, is open at both ends. A clarinet, also 35 cm in length, has one open end and one closed end. The speed of sound in air in the instruments is 340 m s^{-1}.

a Describe how a standing wave is created inside the pipe.

b Sketch the 3nd harmonic in both instruments.

c One of the instruments was measured to have a fundamental frequency of 485 Hz. Determine if the instrument is the flute or the clarinet.

d Explain why the sound of the instruments is loud only when the input vibrations are certain frequencies.

14 A student is designing an experiment to measure the refractive index of an unknown transparent medium, using yellow light.

a Light is often modelled as a wave. Contrast light waves and sound waves.

b Describe the process that causes refraction, using the wave model of light.

c State Snell's law, and describe how it can be used to measure an unknown refractive index.

The following results were obtained.

Angle of incidence i (°)	Angle of refraction (°)
10	6.8
20	13.5
30	20.0
40	26.1
50	31.6
60	36.4

d Use the table of refractive indices of yellow light (λ = 589 nm) in different media to identify the material that was being tested.

Material	Refractive index, n
vacuum	1.00
air	1.00
ice	1.31
water	1.33
quartz	1.46
crown glass	1.52
flint glass	1.62
diamond	2.42

APPENDIX A: Symbols, units and fundamental constants

TABLE 1 Units and symbols based on the SI system*

Quantity	Symbol for physical quantity	Corresponding SI unit	Symbol for SI unit	Unit as a combination of other units
Mechanics				
length, distance and displacement	l	metre	m	fundamental unit
area	A	square metre	m^2	
volume	V	cubic metre	m^3	
mass	m	kilogram	kg	fundamental unit
density	ρ	–	$kg\,m^{-3}$	
time	t	second	s	fundamental unit
force	F	newton	N	$kg\,m\,s^{-2}$
pressure	P	pascal	Pa	$N\,m^{-2}$
energy	E	joule	J	N m
Electricity				
electric current	I	ampere	A	fundamental unit
electric charge	q or Q	coulomb	C	A s
electric potential difference	V	volt	V	$J\,A^{-1}\,s^{-1}$
Nuclear and chemical quantities				
atomic number	Z	–	–	–
neutron number	N	–	–	–
mass number	A	–	–	$Z + N$
amount of substance	n	mole	mol	fundamental unit
Thermal quantities				
temperature	T	kelvin	K	fundamental unit
specific heat capacity	c	–	–	$J\,kg^{-1}\,K^{-1}$

*Units listed in red are the arbitrarily defined fundamental units of the SI system.

TABLE 2 Some common SI prefixes, their symbols and values

SI prefix	Symbol	Value
pico	p	10^{-12}
nano	n	10^{-9}
micro	μ	10^{-6}
milli	m	10^{-3}
centi	c	10^{-2}
deci	d	10^{-1}
kilo	k	10^{3}
mega	M	10^{6}
giga	G	10^{9}
tera	T	10^{12}

TABLE 3 Some physical constants

Description	Symbol	Value
Avogadro's constant	N_A	$6.022 \times 10^{23}\,mol^{-1}$
charge of electron	e	$-1.60 \times 10^{-19}\,C$
mass of electron	m_e	$9.109\,383\,5 \times 10^{-31}\,kg$
mass of proton	m_p	$1.672\,621\,9 \times 10^{-27}\,kg$
mass of neutron	m_n	$1.674\,927\,5 \times 10^{-27}\,kg$
speed of light in a vacuum	c	$3.00 \times 10^{8}\,m\,s^{-1}$
Coulomb's law constant	k	$8.99 \times 10^{9}\,N\,m^2\,C^{-2}$
magnetic constant	k	$2 \times 10^{-7}\,N\,A^{-2}$
permeability of free space	μ_0	$4\pi \times 10^{-7} = 1.257 \times 10^{-6}\,N\,A^{-2}$
permittivity of free space	ε_0	$8.85 \times 10^{-12}\,C^2\,N^{-1}\,m^{-1}$
Planck constant	h	$6.626 \times 10^{-34}\,J\,s$, or $4.14 \times 10^{-15}\,eV\,s$
Stefan–Boltzmann constant	σ	$5.67 \times 10^{-8}\,W\,m^{-2}\,K^{-4}$
Rydberg constant	R	$1.0974 \times 10^{7}\,m^{-1}$
Boltzmann constant	k	$1.38 \times 10^{-23}\,J\,K^{-1}$
rest mass of the alpha particle	m_α	$6.644\,657\,2 \times 10^{-27}\,kg$
gravitational constant	G	$6.67 \times 10^{-11}\,N\,m^2\,kg^{-2}$
acceleration due to gravity on the surface of Earth may be assumed to be	g	$9.80\,m\,s^{-2}$
specific heat capacity of water	c	$4.18\,J\,g^{-1}\,K^{-1}$
density of water	ρ	$1.00\,g\,mL^{-1}$ at 298 K

Unit 1: Thermal, nuclear and electrical physics

Topic 1: Heating processes

Concept	
first law of thermodynamics	$\Delta U = Q + W$ *Note:* Both +Work and –Work are acceptable depending on definition.
specific heat capacity	$Q = mc\Delta T$
latent heat	$Q = mL$
energy efficiency	$\eta = \frac{\text{energy output}}{\text{energy input}} \times \frac{100}{1}\%$
Celsius to Kelvin temperature scale conversion	$T_K = T_C + 273$

Topic 2: Ionising radiation and nuclear reactions

Concept	
half-life	$N = N_0\left(\frac{1}{2}\right)^n$
mass and energy equivalence	$\Delta E = \Delta mc^2$

Topic 3: Electrical circuits

Concept	
current	$I = \frac{q}{t}$
potential difference	$V = \frac{W}{q}$
power	$P = \frac{W}{t}$
resistance in series	$R_t = R_1 + R_2 + \ldots + R_n$
resistance in parallel	$\frac{1}{R_t} = \frac{1}{R_1} + \frac{1}{R_2} + \ldots \frac{1}{R_n}$
current, voltage and resistance in a circuit	$R = \frac{V}{I}$
power in a circuit	$P = VI$ $P = I^2R$
voltage in a series circuit	$V_t = V_1 + V_2 + \ldots + V_n$
current in a parallel circuit	$I_t = I_1 + I_2 + I_3 + \ldots + I_n$
Ohm's law	$R = \frac{V}{I}$

Unit 2: Linear motion and waves

Topic 1: Linear motion and force

Concept	
equations of motion with constant acceleration	$v = u + at$ $s = ut + \frac{1}{2}at^2$ $v^2 = u^2 + 2as$ $s = \frac{(u+v)t}{2}$
momentum conservation of momentum impulse	$p = mv$ $\Sigma mv_{\text{before}} = \Sigma mv_{\text{after}}$ $\Delta p = F\Delta t$
Newton's second law	$a_{\text{net}} = \frac{F_{\text{net}}}{m}$
work done	$W = Fs$ $W = \Delta E_k$
gravitational potential energy	$\Delta E_p = mg\Delta h$
kinetic energy	$E_k = \frac{1}{2}mv^2$
conservation of momentum in elastic collisions	$\sum \frac{1}{2}mv^2_{\text{before}} = \sum \frac{1}{2}mv^2_{\text{after}}$

Topic 2: Waves

Concept	
wave equation	$v = f\lambda$
frequency	$f = \frac{1}{T}$
Snell's law	$\frac{\sin i}{\sin r} = \frac{v_1}{v_2} = \frac{\lambda_1}{\lambda_2} = \frac{n_2}{n_1}$
light intensity	$I \propto \frac{1}{r^2}$
length of a string/pipe attached at both ends and its wavelength	$L = n\frac{\lambda}{2}$
length of open-ended pipe and its wavelength	$L = n\frac{\lambda}{2}$
length of pipe/string closed at one end and its wavelength	$L = (2n-1)\frac{\lambda}{4}$

Unit 3: Gravity and electromagnetism

Topic 1: Gravity and motion

Concept	
gravitational fields	$g = \frac{F}{m} = \frac{GM}{r^2}$
Kepler's third law	$\frac{T^2}{r^3} = \frac{4\pi^2}{GM}$
weight	$F_g = mg$
velocity in a circle centripetal acceleration centripetal force	$v = \frac{2\pi r}{T}$ $a_c = \frac{v^2}{r}$ $F_{net} = \frac{mv^2}{r}$
Newton's law of universal gravitation	$F = \frac{GMm}{r^2}$
horizontal component of velocity for a projectile	$v_x = u_x$
horizontal displacement for a projectile (with no air resistance)	$s_x = u_x t$
final vertical component of velocity for a projectile	$v_y = u_y + gt$
final vertical component of velocity for a projectile	$v_y^2 = u_y^2 + 2gs_y$
vertical displacement for a projectile	$s_y = u_y t + \frac{1}{2}gt^2$

Topic 2: Electromagnetism

Concept	
Coulomb's law	$F = \frac{1}{4\pi\varepsilon_0}\frac{Qq}{r^2}$ $\frac{1}{4\pi\varepsilon_0} = \frac{9\times10^9\,\text{Nm}^2}{\text{C}^2}$
potential energy in an electric field	$V = \frac{\Delta U}{q}$
electric field strength	$E = \frac{F}{Q} = \frac{1}{4\pi\varepsilon_0}\frac{q}{r^2}$
magnetic field on a current-carrying wire	$B = \frac{\mu_0}{2\pi}\frac{I}{r}$ $\mu_0 = 4\pi\times10^{-7}\,\text{T mA}^{-1}$
force on a charged particle	$F = qvB\sin\theta$
magnetic force on a current-carrying wire	$F = BIL\sin\theta$
induced emf (in coils)	$emf = -\frac{n\Delta(BA\cos\theta)}{\Delta t}$ $emf = -\frac{n\Delta\Phi}{\Delta t}$
magnetic flux	$\Phi = BA\cos\theta$
power in transformers	$I_pV_p = I_sV_s$
voltage in transformers	$\frac{V_p}{V_s} = \frac{I_s}{I_p} = \frac{N_p}{N_s}$
magnetic field inside a solenoid	$B = \frac{\mu_0 nI}{L}$ $= \mu_0 nI$

Unit 4: Revolutions in modern physics

Topic 1: Special relativity

Concept	
length contraction	$L = L_0\sqrt{\left(1-\frac{v^2}{c^2}\right)}$
time dilation	$t = \frac{t_0}{\sqrt{\left(1-\frac{v^2}{c^2}\right)}}$
relativistic momentum	$p_v = \frac{m_0 v}{\sqrt{\left(1-\frac{v^2}{c^2}\right)}}$
mass–energy equivalence	$\Delta E = \Delta mc^2$

Topic 2: Quantum theory

Concept	
Wien's law	$\lambda_{max} = \frac{2.898\times10^{-3}}{T}$
Stefan–Boltzmann law	$P = A\sigma T^4$
photoelectric effect	$E_k = hf - W$
Bohr's model of the atom and angular momentum	$mvr = \frac{nh}{2\pi}$ $n\lambda = 2\pi r$
de Broglie wavelength	$\lambda = \frac{h}{p}$
photon energy	$E = hf$
Rydberg formula	$\frac{1}{\lambda} = R\left(\frac{1}{n_f^2} - \frac{1}{n_i^2}\right)$

Answers

Chapter 1 Physics skills and assessment toolkit

The answers to questions that involve calculations are rounded to the least number of significant figures given in the question. See page e35 in Chapter 1 for more details.

1.1 Physics

1.1 KEY QUESTIONS

1 The wave model of light, the particle model of light, the standard model of particles that make up matter, the kinetic model of matter, and many others.
2 Newton's 1st, 2nd or 3rd law of motion, Snell's law of refraction, Kepler's laws of planetary motion, and many others.
3 mechanics, thermodynamics, atomic and nuclear physics, waves, electromagnetism and relativity
4 electric field, magnetic field, gravitational field and quantum fields
5 Physical theories, laws and principles use mathematics to help explain and predict the outcomes of experiments. By the use of mathematics, physicists can make very precise predictions that can then be tested and refined if necessary.
6 Gravity: it doesn't yet fit into the quantum aspect of physics.
7 **a** Isaac Newton, Stephen Hawking, Galileo, etc.
b Marie Curie, Henri Becquerel, Ernest Rutherford, JJ Thompson, Erwin Schrödinger etc.
c Stephen Hawking, Brian Cox, etc.
d Michael Faraday, James Clerk Maxwell, Nikolai Tesla, Andre-Marie Ampere, etc.
e Edmund Halley, Johannes Kepler, Nicolaus Copernicus, Brian Schmidt, Tamara Davis, Edwin Hubble, Isaac Newton, Albert Einstein, Neil deGrasse Tyson, etc.
f James Joule, Ludwig Boltzmann, Sadi Carnot, Felix Wankel, Rudolf Diesel, etc.
g Albert Einstein, Galileo, Hendrik Lorentz, etc.
8 Police need to know the laws of motion and force to discover how traffic accidents happen and trajectories of projectiles. They would also need to understand electromagnetism and light to operate tasers and speed guns.
9 Doctors need to know how to read the images created in the various diagnostic machines in hospitals. They also need to understand the thermodynamics, forces and motion that occur inside the human body.
10 Light is a fundamental phenomenon in physics that is linked to relativity, waves, energy, quantum physics and electromagnetism. If one half of physics is the study of matter then the other half of physics is the study of light.
11 A law of physics has been shown to be experimentally true over a range of different types of experiments, and is broad in scope and covers more than one major branch of physics.
A principle is also verified experimentally but its scope is much narrower and only covers one branch of physics.
12 The captain must be aware of the direction and speed of their boat and the forces that act on the boat such as buoyancy, weight, thrust from wind and friction. The captain must also be aware of how any electrical devices in the boat works and how to repair or replace them.

1.2 Orders of magnitude and estimation

TY 1.2.1 **a** 4×10^6 m **b** 1.602×10^{-19} C
TY 1.2.2 **a** 0.000 000 082 N **b** 734 200 000 000 000 000 000 000 kg
TY 1.2.3 A light-year is 9 orders of magnitude further than the circumference of Earth, or 10^9 (one billion) times further.
TY 1.2.4 Approximately 10^9 (one billion) beats

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1 f_i: $1 : 10^{-9}$ or $1\,000\,000\,000 : 1$
2 R^*: 3 : 1.5 or 2 : 1
3 Almost none of the factors included in the equation have an exact value, so the value of N is only going to be an estimate.
4 minimum = 1.8×10^{-13} civilisations, maximum = 15 billion civilisations
5 Thousands of exoplanets have now been confirmed, which makes the statistical analysis of how many are suitable for life much easier than before when there was no data available, and guesses had to be made.

1.2 KEY QUESTIONS

1 Scientific notation keeps the number in a consistent format; long form would be very tedious for very large and very small numbers.
2 between 1 (inclusive) and 10 (exclusive)
3 100
4 If the value of the coefficient is 5 or above, then the order of magnitude is equal to the exponent plus 1. If the coefficient is less than 5 then the order of magnitude is equal to the exponent.
5 **a** 6.37×10^6 m **b** 3.19×10^{-3} s
c 7.713×10^3 kg **d** 4.5×10^1 N
6 **a** 0.000 000 000 11 m
b 7 031 000 m s^{-2} **c** 300 000 000 m s^{-1}
d 9.8 N kg^{-1} because anything to the power of zero is 1.
7 **a** 10 **b** –3 **c** –10 **d** 3
8 The Sun has a mass of about 5 orders of magnitude, or 10^5 times that of Earth.
9 B
10 Earth is about 10^{14} times more massive than all of the people on Earth combined.

1.3 Mathematical basics for physics

TY 1.3.1 5800 K

1.3 KEY QUESTIONS

1 m^2, m^2 and m^3
2 $\sin\theta = \frac{\text{opposite}}{\text{hypotenuse}}$, $\cos\theta = \frac{\text{adjacent}}{\text{hypotenuse}}$, $\tan\theta = \frac{\text{opposite}}{\text{adjacent}}$
3 Probability is used in thermal physics, quantum physics and atomic physics.
4 **a** $y = x - 7$, so $m = 1$ and y-intercept = –7
b $y = 8 - 2x = -2x + 8$, so $m = -2$ and y-intercept = 8
c $y = -0.467x + 1.556$, so $m = -0.467$ and y-intercept = 1.556
5 **a** $a = \frac{F}{m}$ **b** $f = \frac{E_k + \phi}{h}$ **c** $r = \sqrt{\frac{GMm}{F}}$
6 WASP-17b has a volume 8 times that of Jupiter.
7 **a** $\frac{5}{8}$ **b** 12.5 **c** 11.43 kg
8 **a** $t^{3.5}$ or $\sqrt{t^7}$ **b** c^4
9 γ = 12.3 (no units)
10 **a** 48 N **b** 47 N s **c** 66°
11 $x = \frac{1}{3}$
12 **a** gradient = 4.0, y-intercept = 0
b units of gradient are s^2 per m or s^2 m^{-1}
units of y-intercept are s^2.
c $g \approx 9.9$ m s^{-2}

1.4 Units and prefixes

TY 1.4.1 5.91×10^{42} am

1.4 KEY QUESTIONS

1 mass (kilogram), in 1901
2 area in m^2, volume in m^3, frequency in Hz or s^{-1}
3 metre, second, kilogram, ampere, mole, kelvin and candela

4 An ampere second is a derived unit made by *multiplying* the unit ampere with the unit second. Its symbol is As.

An ampere *per* second is a derived unit made by *dividing* the unit ampere by the units second. Its symbol is As^{-1}.

5 Fundamental units cannot be written using another other combination of units. Derived units are written using a mathematical combination of fundamental units or other derived units.

6 It is important that everyone who measures the same amount agrees on a system of units so that its value is agreed upon and can be transferred globally.

7 $656\,nm = 656 \times 10^{-9}\,m = 6.56 \times 10^{-7}\,m$

8 $1.5 \times 10^{18}\,km$

9 $1 = 1\ \frac{kg\,m^2}{A^2\,s^3}$

1.5 Uncertainties in measurement

TY 1.5.1 **a** 2 s.f. **b** 3 s.f. **c** 3 s.f. **d** 5 s.f.
TY 1.5.2 **a** 0.0459 m **b** 3.0000×10^5 m
TY 1.5.3 **a** $4.6 \times 10^4\,cm^3$ **b** 1.1×10^{-11} m
TY 1.5.4 **a** 8.5 ± 0.5 cm **b** 84.5 ± 0.5 mL **c** 167 ± 1 g
TY 1.5.5 24.65 ± 0.13 g
TY 1.5.6 $x = -1 \pm 2$ N
TY 1.5.7 $x = 0.7 \pm 0.2\,cm\,s^{-1}$
TY 1.5.8 $d = 6.1 \pm 0.6\,m\,kg^{-0.5}$

1.5 KEY QUESTIONS

1 **a** systematic errors **b** random errors
2 **a** mistake **b** random error **c** systematic error
3 **a** ± 1.0 cm **b** ± 1.0° **c** ± 0.001 g **d** ± 5 volts
4 The limit of reading of a stopwatch is the smallest division, which is 0.01 s, but the reaction time of the user of the stopwatch could not possibly be that precise, when timing a given event. So the figure of ± 0.005 s is far too small to be used as the absolute uncertainty.
5 Systematic error is due to incorrectly calibrated or zeroed instruments, which affects every measurement. So, more trials of a measurement will only confirm that a systematic error exists, not correct it.
6 11.9 ± 0.2 cm
7 **a** $(9 \pm 2) \times 10^{-31}$ kg **b** $(2.35 \pm 0.16) \times 10^{-3}$ s
8 The accuracy of a measurement is how close it is to an accepted value, whereas the precision of a measurement is how many digits can be written down describing the measurement.
9 first measurement = 8.12 g to 8.22 g
second measurement = 8.04 g to 8.14 g
There is an overlap of 0.02 g, which means the two diamond masses are within the range of both measurements, so there is no reason to doubt that this is your diamond.
10 24% **11** $c = 35 \pm 2$ m **12** $C = 25.9 \pm 0.3$ m
13 **a** 121.38 ± 0.02 g **b** 2.48 ± 0.05 cm
c $V = 15.3 \pm 0.9\,cm^3$ **d** $7.9 \pm 0.5\,g\,cm^{-3}$
14 $18 \pm 5\,m^2$

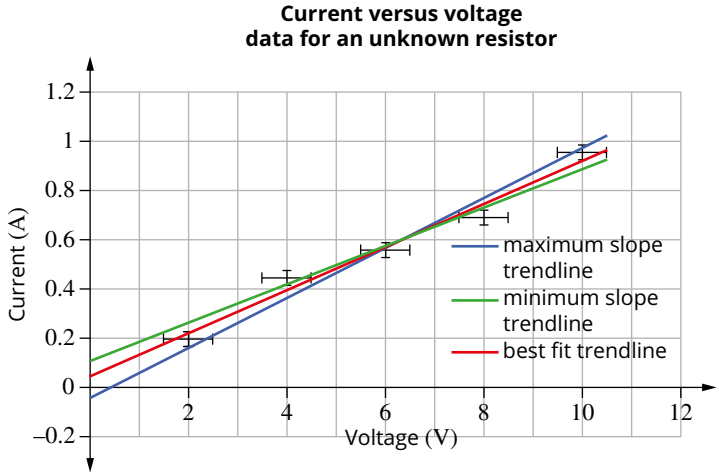
1.6 Graphing

TY 1.6.1 **a** **i** new *x*-axis variable = $\sqrt{L}$, *y*-axis variable = *T* (unchanged)
ii *y*-intercept = 0, gradient = $\frac{2\pi}{\sqrt{g}}$
Note that another acceptable answer is graphing T^2 on the *y*-axis and *L* on the *x*-axis. The *y*-intercept will be zero and the gradient will be $\frac{4\pi^2}{g}$.

b new *x*-axis variable = $\frac{1}{d_o}$, new *y*-axis variable = $\frac{1}{d_i}$
ii *y*-intercept = $\frac{1}{f}$, gradient = –1

1.6 KEY QUESTIONS

1 Systematic errors are shown as a consistent addition or multiplication by a constant value that affects every data point equally.
2 **a** linear (with negative gradient)
b parabolic or square
c square root
d hyperbolic or inverse
3 **a** **i** It has a non-descriptive heading.
ii *y*-axis does not have a label or units.
iii *x*-axis does not have units.
iv Dots for data points are far too large.
v Not every data point has an *x* or *y* error bar.
vi Line of best fit is above the minimum and maximum lines.
vii Poor use of the space available to draw the graph.
b **i** Write a much better description of how the dependent variable changes with the independent variable.
ii Give the *y*-axis a label and units.
iii Give the *x*-axis units.
iv Use much smaller circles as data points.
v Draw the *x* and *y* error bars for each data point.
vi Redraw the line of best fit, and the maximum and minimum lines.
4 Melissa should check her data, especially the uncertainties as they are probably too small. Increasing the uncertainties increases the size of the error bars, which will make the straight line of best fit easier to draw.
5 The line of best fit should pass through the origin, or the maximum and minimum lines pass below and above the origin respectively.
6 Linear graphs have gradient and *y*-intercepts that are easy to see, constant and straightforward to calculate. Curved graphs do not have constants in their relationships that can easily be read from the graph.
7 It is a parabolic relationship with a negative coefficient, such as $y = -x^2$.
8 It is a square root graph such as $y = \sqrt{x}$.
9 **a** **i** *P* is unchanged on the *y*-axis, $\frac{1}{V}$ is now graphed on the *y*-axis.
ii The *y*-intercept is zero and the gradient is *nRT*.
b **i** The graphs is already linear, so no modification is needed to either axis.
ii The *y*-intercept is zero and the gradient is $\frac{0}{2\pi r}$.
10 **a** independent variable: voltage; dependent variable: current
b–d



e Gradient of the line of best fit = $0.087\,A\,V^{-1}$
Gradient of maximum line = $0.100\,A\,V^{-1}$
Gradient of minimum line = $0.0767\,A\,V^{-1}$
f $11.5 \pm 1.6\,V\,A^{-1}$
g The *y*-intercept is 0.04 ± 0.07 A.
There is an expected zero *y*-intercept for this data because for *V* is zero, *I* should also be zero. The range of *y*-intercepts from the uncertainty of the *y*-intercept is from 0.11 A to –0.3 A, which includes zero. Therefore this experiment is accurate.

1.7 Research and planning

1.7 KEY QUESTIONS

1 **a** Variables are the factors that change during an experiment and can influence results.

b

Independent variable	Controlled variables	Dependent variable
the experimental variable: it is the factor that is being changed	factors that you want to keep the same for every trial to ensure a fair test	the factor that you are measuring to get results; it is dependent on your independent variable

2 **a** The colder a battery is, the longer it will last, or when a battery is cooled, the longer the time it takes to become flat.

b The direction that a battery is placed in a circuit does not affect the production of current, or, if a battery is placed in a circuit in the opposite direction to normal, then it will still create current.

c The voltage of a 1.2 volt battery is not enough to supply energy for a current to be created in a circuit, or the minimum voltage that a battery can have to create a current is more than 1.2 volts.

3 **a** What is the relationship between the amount of pressure inside a balloon and the charge it can carry? How does the strain force on the surface of a balloon affect the charge built up on it?

b Does the depth of a swimming pool change the time a swimmer can complete one lap? How does the depth of a swimming pool affect the speed of the swimmer?

c What is the relationship between the time of day and visibility of Earth-orbiting satellites? How does the time of day affect the visibility of Earth-orbiting satellites?

4 Quantitative data relates to numeric variables that can be counted or measured (quantified) and recorded with units (e.g. centimetres, kilograms, seconds).
Qualitative data relates to categorical variables and can be counted or described but not measured (e.g. species of element, type of road surface). Observations of categorical variables can be recorded as descriptions or images.

5

Information	Qualitative	Quantitative
cost $3.95		✓
robust aroma	✓	
coffee temperature 82°C		✓
cup height 9 cm		✓
frothy appearance	✓	
volume 180 mL		✓
strong taste	✓	
white cup	✓	

6 **a** Independent variable: temperature;
Dependent variable: rate of evaporation
Controlled variables: humidity, type of container, surface area of container

b Independent variable: the presence/absence of light or the amount of light
Dependent variable: the presence/absence of a current flowing through the photoresistor or the amount of current flowing through the photoresistor
Controlled variables: temperature, voltage supply, other parts of the circuit

c Independent variable: wavelength of incident light
Dependent variable: angle of refraction (bend angle)
Controlled variables: type of glass; thickness, width, length of glass; angle of incidence (incident angle)

d Independent variable: diameter (thickness) of the wire
Dependent variable: current flowing
Controlled variables: type of metal used in the wire, length of wire, voltage applied

7 **a** If the voltage is measured by the number of batteries attached, then it is discrete.

b If the voltage is measured in volts using a voltmeter then it is continuous.

8 An SDS contains important safety and first aid information for teachers and students about chemicals. It provides the information that employers, workers and emergency crews need to safely manage the risk of hazardous substance exposure.

9 Immediately inform your teacher, remove your lab coat and any clothing, and thoroughly wash any skin the substance has come into contact with. If it is a large spill covering lots of your body, you will need to use the safety shower.

10 C. A hypothesis should only test one independent variable and it should predict the relationship between the independent and dependent variables.

1.8 Conducting and experimenting

1.8 KEY QUESTIONS

1 The choice of equipment and instruments will influence the reliability of the experiment.

2 There is less chance of error when using higher precision instruments. This lowers the uncertainty of the measurements, which makes scientific conclusions more accurate.

3 Not enough data was collected: only two data points; a mix of quantitative and qualitative data; brand of copper wire is irrelevant; not all variables have been controlled e.g. thickness and length.

1.9 Results

1.9 KEY QUESTIONS

1 raw data and processed data

2 A systematic error is a constant bias in measurement.

3 Random errors are errors that follow no regular pattern.

4 Processing data is the manipulation of the numbers or observations to understand and ascertain true values, uncertainties, anomalies and relationships.
Interpreting data is placing this understanding into words and providing an in-depth explanation of what the numbers mean in the context of the relevant theory.

5 It cannot be concluded that the copper box provides any shielding to Earth's magnetic field as the values of 50 μT and 51 μT are within the ranges of the uncertainties inside and outside the box.

1.10 Communicating and writing a scientific report

1.10 KEY QUESTIONS

1 **a** Outlines exact details for other scientists to repeat the experiment, including specific details about instruments, equipment models and precision, techniques employed.

b It provides an explanation of the results and relates the results to current scientific understanding (theory).

2 results

3 A bibliography is a list of all the sources used during research. A reference list only lists the sources used and citied in the report.

4 **a** A **b** C **c** E **d** D

e There is no relationship, as the graph is straight and horizontal; the dependent variable is the same value regardless of the value of the independent variable.

5 Time restraints, limited resources such as equipment availability or equipment range might limit sample size.

6 An increase in current from 0.03 A to 0.05 A produced an increase of 0.88 V across the resistor.

1.11 Developing the research question from a claim

1.11 KEY QUESTIONS

1 A claim is an assertion made without any accompanying supporting evidence.
2 It identifies the relationship between the dependent and independent variables.
3 Knowledge and understanding about the variables is developed and therefore a more specific or appropriate question can be written.
4 The ISMG requires a rationale for the development of the research question from the claim, and this is achieved by applying your understanding of scientific concepts to the development, which is from research.
5 Answers will vary. Possible responses include:
   a Can aluminium foil absorb gamma rays? What thickness of aluminium foil will stop a gamma ray?
   b Do external magnetic fields cause biochemical reactions? How strong does an external magnetic field have to be to show any biological effects?
   c What type of radiation is emitted by high voltage power lines? How powerful must a radio wave be to cause measureable effects in living tissue?

1.12 Finding and choosing suitable resources

Skill builder: test the skill

Decision	Support/justification
Secondary	Literature review.
Yes	Includes information on four phenomena: quantum entangled particles, Cerenkov radiation, inflation of the universe and wormholes.
Mostly	Outlines the theories, but no evidence or data.
Yes	Originally published in 2016.
Yes	Physics is sound and up to date.
Yes	Equivalent to other sources, and also references listed.
No	Author's credentials aren't stated but they are a writer for a business magazine.
None	literature review
None	literature review

1.12 KEY QUESTIONS

1 **a** secondary source **b** primary source
   c primary source
   d secondary source (but could be a primary source if the site includes original research articles or images)
2 A primary source is written by the observer/witness of an event or the scientist who conducted the research and therefore there has only been a primary manipulation of the data in the original analysis.
   A secondary source has manipulated the primary evidence further, therefore undertaking a secondary analysis.
3 C. It caters for a very wide range of audiences from primary school to university. The book may not contain enough detailed information for the use of a high school physics student. The article in the journal may be far too detailed.

1.13 Research: Taking and organising notes

TY 1.13.1 The weather forecast expects (made a prediction based on computer simulations) that the temperature during the day will be cooler (12–15°C) and there will be more precipitation (3–5 mm) due to a low-pressure system, which increases cloud cover.

1.13 KEY QUESTIONS

1 This list is not exhaustive but should include dates of all practical work, observations, extra ideas to try, questions, refinements, results, data, evidence, reference/sources of information, background theory, diagrams of apparatus, contacts.
2 To record in a journal, you summarise information in your own words, using a variety of forms such as diagrams, written text with full details, noting the entry date and the source used and using a title.
3 Journals provide guidance, link ideas and concepts, develop understanding, summarise key information.
4 **a** Student answers will vary, but could include: Metals have the same ability to absorb beta radiation.
   b Student answers will vary, but could include: Mixing a conductor with semiconductor material and lowering the temperature reduces the mixture's resistance.
   c Student answers will vary, but could include: Mass and amplitude (pull-back distance) do not affect the period of a pendulum.

1.14 Writing a report for the research investigation

1.14 KEY QUESTIONS

1 The flow of information should follow a logical sequence and be grouped into paragraphs with an appropriate use of headings.
2 Universal with some flexibility, including an introduction, body and conclusion.
3 A literature review critically analyses information and convinces the reader of the significance or importance of the topic being investigated.
4 Identify strengths and weaknesses in the methodology, sample size selection and the results by considering the validity, reliability and statistical analysis. Consider which variables were controlled and whether precision instruments were used to measure data. Was sufficient data collected? Identify any gaps and/or conflicting evidence in the methodology and results.

Chapter 2 Heating processes

2.1 The kinetic particle model

2.1 KEY QUESTIONS

1 All matter is made up of many very small particles (atoms or molecules).
   The particles are in constant motion.
   No kinetic energy is lost or gained overall during collisions between particles.
   There are forces of attraction and repulsion between the particles in a material.
   The distances between particles in a gas are large compared with the size of the particles.
2 plasma
3 Kinetic energy is the energy the atoms and molecules possess as they are in constant motion.
   Potential energy is stored energy and is due to the spacing of the atoms and molecules from each other.
4 Measure the temperature (the temperature measures the average kinetic energy of a sample).
5 The heat will flow from the coffee into the mug (flows from hotter substances to colder substances).
6 The molecules in a solid are held in place so are unable to move away from each other. In a liquid, the molecules can more freely and so move way from each other.
7 Heating the air increases the kinetic energy of the air molecules. This increased kinetic energy leads to the molecules hitting the balloon more often, expanding the balloon. This decreases the density of the air in the balloon and causes the balloon to rise.

8 A solid is hard to compress as the particles (atoms/molecules) are already tightly packed and there is little room for them to compress further.
9 Temperature only measures the average kinetic energy. There will be molecules with much more kinetic energy and some with much less kinetic energy.
10 Ice, water and water vapour are different phases of the same material, with kinetic and potential energy increasing from solid to gas phase.

2.2 Temperature

2.2 KEY QUESTIONS

1 Mercury expands linearly as it gets warmer, taking up more volume in the thermometer and so indicating a higher temperature. Mercury also contracts linearly as it gets cooler to take up less volume in the thermometer and indicate a smaller temperature.
2 Absolute zero temperature is the temperature at which all internal motion of a substance stops. It is a theoretical limit. The Kelvin scale uses this absolute zero as its zero; the step sizes are the same as the Celsius scale.
3 **a** 303 K **b** 102°C
4 The temperature of the gas is just above absolute zero so the particles have very little energy.
5 absolute zero, 10.0 K, –180°C, 100.0 K, freezing point of water
6 300 K is 27°C. At higher temperatures molecules have greater average kinetic energy. So the average kinetic energy of the hydrogen particles in tank B is greater than the average kinetic energy of the hydrogen particles in tank A.
7 303°C
8 A number of experiments were carried out to examine the change of pressure with temperature for a number of different substances. When the graphs for all the substances were extrapolated back to where volume was zero, it was found they all had the same temperature value of –273°C.

2.3 Heat flow

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1 Overhanging eaves, deciduous trees, blank walls shaded by trees or overhangs, using double glazing or curtains, and insulation can all be used.
2 **a** The heat loss is due mostly to conduction.
b The air in the gap between the glass panes is a poor conductor of heat.

2.3 KEY QUESTIONS

1 Thickness, surface area, nature of the material and the temperature difference between it and the second material all affect its ability to conduct heat.
2 The insulation batts stop the thermal energy from **escaping** the house. The air in the batts has **low** conductivity and the thermal energy is **not able** to move easily through the batts.
3 liquids and gases
4 upwards
5 The process is quite slow because the mass of the particles is relatively large and the vibrational velocities are fairly low.
6 Air over certain places, such as roads, heats up and as a result becomes less dense. The less dense air rises to form a column of rising air called a thermal.
7 The **higher** the temperature of the object, the **higher** the frequency and the **shorter** the wavelength of the radiation emitted. For example, if a particular object emits radiation in the visible range, a cooler one could emit light in the **infrared** range of the electromagnetic spectrum.
8 Conduction and convection require the presence of particles to transfer heat. Heat transfer by radiation can occur in a vacuum, as the movement of particles is not required.
9 A lot of air is trapped in the down. As air is a poor conductor of heat, the down-filled quilt limits the transfer of heat away from the person.
10 Copper is a better conductor of heat than stainless steel.
11 Plastic and rubber have low conductivity, so they do not allow the heat from your hand to transfer very easily. Metal has high conductivity, so heat transfers easily from your hand and your hand feels cold.
12 No; solids do not contain the free molecules that are required to establish convection currents.
13 The source of heat, the Sun, is above the water. It takes much longer to heat a liquid when the source is at the top as the convection currents will also remain near the top. The warm water is less dense than the cool water and will not allow convection currents to form throughout the water.
14 **a** matt black beaker **b** gloss white surface
15 Heat sinks are made of dark-coloured metals that radiate heat energy strongly and keep the computer cool. They work by increasing the surface area to increase thermal contact with the air and so transfer the heat away quickly.
16 The stopper reduces heat loss by convection and conduction. The vacuum between the walls reduces heat transfer by conduction and convection. Also, the space between the walls is small enough that convection currents will not form. The flask's shiny surface reduces heat transfer by radiation.

2.4 Specific heat capacity

TY 2.4.1 63 MJ
TY 2.4.2 2.1

2.4 KEY QUESTIONS

1 Water requires more energy per degree Celsius heated because the specific heat capacity of water is much greater than that of aluminium.
2 As aluminium has the higher value for specific heat capacity, it will contain more thermal energy than iron, assuming all other variables are the same.
3 2100 J **4** 25 200 J
5 4.67 **6** 10 kJ **7** 30.0°C **8** 1.0 kg

2.5 Phase changes and latent heat

TY 2.5.1 1.4×10^2 kJ
TY 2.5.2 8×10^6 J
TY 2.5.3 2 260 000 J kg^{-1}
TY 2.5.4 2000 J kg^{-1} K^{-1}

2.5 KEY QUESTIONS

1 Any two of the following:
- Surface area: greater evaporation occurs when greater surface areas are exposed to the air.
- Temperature: hotter liquids evaporate faster.
- Humidity: less evaporation occurs in more humid conditions.
- Movement: if a breeze is blowing over the surface of the liquid, evaporation is more rapid.

2 Latent heat is the 'hidden' heat that goes into a substance during a phase change. This heat increases the potential energy of the molecules to change their separation and phase. It is called a hidden heat as the temperature does not change during this process.
3 The substance is changing state from liquid to a gas. It is boiling; temperature does not change during phase transitions as average kinetic energy does not change. The energy going into the substance is increasing the potential energy of the molecules.
4 2.26×10^5 J
5 During evaporation the hottest (fastest) molecules leave the liquid phase. Losing the fastest molecules reduces the overall average kinetic energy, which reduces the temperature.
6 Steam has much more internal energy than boiling water, an extra 2.25×10^6 J of energy per kg, and that thermal energy is transferred to your skin until your skin reaches thermal equilibrium with the heat source, or you pull away.

7 A lid limits the movement of air over the surface of the coffee and so limits evaporation. Because evaporation will cool things, by limiting evaporation you are limiting the cooling effect.
8 34 kJ
9 **a** The mercury is changing state from solid to liquid. It is melting; temperature does not change during phase transitions, as average kinetic energy does not change.
b –39°C **c** 357°C
d 12 600 J kg^{-1} **e** 285 000 J kg^{-1}
10 0.4 kg
11 The curved line when heating a gas implies that the specific heat capacity for that gas is not constant over the range of temperatures displayed.

2.6 Calorimetry

TY 2.6.1 1213 J kg^{-1} K^{-1}

2.6 KEY QUESTIONS

1 Calorimetry is measuring the heat output from a substance due to its internal energy or due to a chemical reaction.
2 Thermal equilibrium is when two objects are in thermal contact and are at the same temperature.
3 This is the zeroth law of thermodynamics. If object A is in thermal equilibrium with object C, they are both at the same temperature. If object C and object B are at thermal equilibrium, they are also at the same temperature. Because you know that C is the at the same temperature as A, then A and B must also be at the same temperature.
4 The heat gained by the ice in melting and coming up to the temperature of the drink is the same heat lost by the drink cooling down. The ice absorbs more heat than water of the same temperature due to the phase change. Quite a large amount of energy is stored in a phase change, so melting the ice will cool your drink more than just adding in water at the same temperature.
5 c = 900 J kg^{-1} K^{-1}, which is aluminium.
6 28.6°C **7** c = 2780 J kg^{-1} K^{-1}

2.7 Mechanical work and efficiency

TY 2.7.1 2770 J
TY 2.7.2 27%

2.7 KEY QUESTIONS

1 **J**oule used this experiment to prove that heat and mechanical energy are equivalent, and that the two forms of energy that can be transformed from one to the other form.
2 Conservation of energy states that energy cannot be created or destroyed; it only changes forms.
3 No, due to energy conservation, energy cannot be created, so you can't have more energy than you started with in the system.
4 36%
5 Conservation of energy states that no energy can be created or destroyed. This means that in every energy transfer energy is not destroyed but it may not transform into useful energy. Efficiency measures how much of the energy transformed goes into the desired form as opposed to other forms of energy.
6 0.54 K **7** –70 kJ **8** 225 J **9** –550 J

Chapter 2 review

1 A
2 **a** C and D **b** B
3 C and D **4** E **5** B **6** D
7 The first law of thermodynamics states that energy simply changes from one form to another and the total energy in a system is constant.
8 **a** The light can be partially reflected, partially transmitted and partially absorbed.
b Absorption of light is associated with temperature increase.
9 In a closed system the heat lost from one object is equal to the heat gained by the second object.
10 The temperature is what will determine the direction of heat transfer. Heat will flow from the hotter object to the colder object.
11 Heat refers to the energy that is transferred between objects, whereas temperature is a measure of the average kinetic energy of the particles within a substance.
12 **a** 278 K **b** –73°C
13 Metals conduct heat by free moving electrons as well as by molecular collisions. Wood does not have any free moving electrons, so it is a poor conductor of heat.
14 Convection requires the molecules to move, which is not possible in a solid.
15 3.03×10^6 J
16 This situation describes a change of state, in this case, melting. It occurs because the heat energy is used to increase the potential energy of the particles in the solid instead of increasing their kinetic energy. The energy needed to change from solid to liquid is the latent heat of fusion.
17 7.0 kJ **18** 6.05°C
19 Thermal energy is the energy transferred between bodies. The internal energy is the combination of the kinetic and potential energies of the particles within a substance. If this internal energy is transferred to another body, it is thermal energy for that process.
22 **a** No heat has been exchanged. **b** 300.0 K
c 3.0×10^6 J
23 Rubber is a good insulator whereas metal is a good conductor. The metal conducts heat away from Briana's hand quickly to heat the whole bike, whereas the rubber does not.
24 18 000 J **25** 251 J kg^{-1} K^{-1} **26** 2000 J kg^{-1} K^{-1}
27 Both have the same kinetic energy, as their temperatures are the same; however, steam has more potential energy due to its change in state. Therefore steam has greater internal energy.
28 14.3 min **30** 70.5°C **31** 750 J s^{-1}
32 Students' own answers.
33 The design needs to minimise conduction, convection and radiation. Consideration should be given to the insulating wall design, placement of the refrigeration unit, placement of a door or opening, and minimisation of radiation.
34 One way to do this is to heat the cube in boiling water. Measure the cube's temperature then put in into cold water (in a foam cup). Measure the change in temperature of the water in the cup. The change in temperature of the water and the metal and the masses of both should allow you to determine the specific heat capacity of the metal.

Chapter 3 Ionising radiation and nuclear reactions

3.1 The nucleus

TY 3.1.1 Z = 90, A = 230, N = 140

3.1 KEY QUESTIONS

1 The plum pudding model consisted of negatively charged electrons (the plums) that are evenly spread out and embedded in an extended positively charged substance (the pudding).
2 The nucleus is made up of positively charged protons and neutral neutrons.
3 If the atom is neutral then it will have the same number of positive charges (protons) as negative charges (electrons). Therefore, the number of electrons will be equal to the number of protons, which is the atomic number of the element.
4 Electrons are about 2000 less massive than the proton or neutron so will only contribute 0.05% of the total mass of the atom.
5 126 **6** Z = 79, A = 197, N = 118
7 235 nucleons
8 Isotope refers to the atom and nuclide refers to the nucleus. Isotopes are written as 'element name'-'mass number' (e.g. uranium-235), while nuclides are written using the ${}^{A}_{Z}\mathrm{X}$ notation (e.g. ${}^{235}_{92}\mathrm{U}$).

9 A nucleon is one of the two particles that make up the nucleus of an atom. It is either a proton or neutron. A neutron is a neutral particle that makes up the nucleus of an atom.

10 $^{12}_{6}C$

11 $^{19}_{9}F$

3.2 Stability of the nucleus

TY 3.2.1 **a** $^{108}_{48}Cd$ is a stable nuclide.

b $^{80}_{30}Zn$ is radioactive and will try to become stable by turning a neutron into a proton.

3.2 KEY QUESTIONS

1 The electrostatic (or coulomb) force

2 A Segre plot is a discrete graph showing how the neutron number of various isotopes changes with atomic number. It is used to predict how a radioactive nuclide will decay into a more stable nuclide.

3 Yes. Most elements have only a few stable isotopes but many more radioactive isotopes. There are many examples across the first 94 elements, such as uranium-238, polonium-210, potassium-40 and carbon-14.

4 No. All synthetic elements, and therefore their isotopes, are always radioactive. Elements beyond atomic number 94 are all synthetic and are all radioactive.

5 The strong nuclear force is an attractive force therefore, the nucleus stays together for some nuclei.

6 When the atomic number is small (less than about 20), there needs to be approximately the same number of neutrons as protons (a 1 : 1 ratio) to allow the strong nuclear force to balance the electrostatic force.

7 For nuclei with more protons than neutrons, the strong nuclear force is not large enough to balance the coulomb force of repulsion between protons and the nucleus is unstable.

8 A stable isotope will not change the number of protons or neutrons in its nucleus, nor will the net energy content of its nucleus change, indefinitely. A radioisotope has a nucleus that is unstable. This means that the number of protons or neutrons (or both) or the energy content of its nucleus will change over time.

9 **a** Atomic numbers are the same ($Z = 35$) because they are the same element. Mass numbers are different at 79 and 76, respectively.

b Chemically they should react in the same way, because they are still both bromine.

10 $^{204}_{80}Hg$ has 80 protons and 124 neutrons, which is just enough to keep the electrostatic force balanced with the strong nuclear force. In $^{205}_{80}Hg$ the electrostatic force is balanced by the strong nuclear force; but it has too many neutrons, which causes instability, so $^{205}_{80}Hg$ is unstable.

11 **a** $^{16}_{8}O$ has 8 protons and 8 neutrons in its nucleus. 8 is a 'magic number', so $^{16}_{8}O$ is expected to be very stable. Both numbers are less than 10, so the proton to neutron ratio of 1 : 1 helps to make this nuclide stable.

b $^{78}_{28}Ni$ has 28 protons and 50 neutrons in its nucleus, almost twice the number of neutrons as protons, which means that this nuclide should be very unstable. Both numbers are 'magic' and this means that $^{78}_{28}Ni$ is not as unstable as it would normally be.

c $^{100}_{50}Sn$ has 50 protons and 50 neutrons in its nucleus, exactly the same number of protons as neutrons. But only very light nuclides are stable with this ratio, so $^{100}_{50}Sn$ should be quite unstable. 50 is a 'magic' number, which means $^{100}_{50}Sn$ is unstable, but not as unstable as it should be.

d $^{4}_{2}He$ has 2 protons and 2 neutrons in its nucleus, i.e. the same number of protons as neutrons, and is very light, so it is expected to be stable. 2 is a 'magic' number, which means $^{4}_{2}He$ should be very stable. In fact, it is one of the most stable nuclides known.

e $^{39}_{20}Ca$ has 20 protons and 19 neutrons in its nucleus, more protons than neutrons. Only $^{1}_{1}H$ and $^{3}_{2}He$ are stable with more protons than neutrons, so $^{39}_{20}Ca$ must be very unstable. However, it has has a 'magic' number of 20 protons, and so is not as unstable as it should be.

12 **a** 2: $^{1}_{1}H$ and $^{3}_{2}He$

b The only stable isotopes of beryllium has a neutron number of 5 so the mass number is: 4 + 5 = 9

c $^{40}_{18}Ar$, $^{41}_{19}K$ and $^{42}_{20}Ca$

d 4

e $^{40}_{20}Ca$

13 **a** $^{36}_{16}S$ is stable because it is on a yellow square.

b $^{33}_{13}Al$ is unstable. It has too many neutrons and will probably become more stable when its nucleus turns a neutron into a proton to reduce the number of neutrons.

c $^{58}_{27}Co$ is unstable as it has too many protons. For it to become more stable the nucleus will change one proton into a neutron to reduce the number of protons.

d $^{20}_{9}F$ is unstable. It has too many neutrons to be stable and therefore the nucleus will change one neutron into a proton for it to become more stable.

e $^{1}_{0}n$ is a single neutron and it is unstable. A single neutron will turn into a proton to become stable. Technically, this will only occur if the neutron is outside the nucleus, as it is quite stable inside the nucleus of an atom.

3.3 Nuclear decay

TY 3.3.1 **a** $^{23}_{11}Na$ or ^{23}Na. Sodium-23 is stable.

b $^{8}_{4}Be$ or ^{8}Be. Beryllium-8 is unstable.

c $^{218}_{84}Po$ or ^{218}Po. Polonium-218 is unstable.

TY 3.3.2 $^{4}_{2}He$ or ^{4}He or helium-4, which is also an alpha particle.

TY 3.3.3 **a** $^{11}_{5}B$ or ^{11}B or boron-11. A positron ($^{0}_{1}\beta$) and neutrino ($^{0}_{0}\nu_e$) are emitted by the parent nucleus.

b $^{1}_{1}H$ or ^{1}H; hydrogen-1 or a proton. An electron ($^{0}_{-1}\beta$) and antineutrino ($^{0}_{0}\overline{\nu}_e$) are emitted by the parent nucleus.

TY 3.3.4 lead-214 or $^{214}_{82}Pb$

TY 3.3.5 **a** $^{238}_{94}Pu$ by alpha decay

b X_1 is an electron, $^{0}_{-1}\beta$, and X_2 is the antineutrino $^{0}_{0}\overline{\nu}_e$ (or vice-versa). This is beta negative decay.

c X_1 is oganesson-294 or $^{294}_{118}Og$. X_2 is the energy released by the alpha decay process.

3.3 KEY QUESTIONS

1 They all originate inside the nucleus.

2 It is a positively charged electron with the same properties as an electron but with a positive charge.

3 beta radiation

4 40, 42, 43, 44, 46

5 alpha, beta and then gamma

6 **a** gamma radiation

b beta (negative) radiation

c alpha radiation

d beta (negative and positive) radiation

e gamma radiation

7 Beta negative radiation consists of an electron and antineutrino being emitted from the nucleus when a neutron turns into a proton. Beta positive radiation consists of a positron and neutrino being emitted from the nucleus when a proton turns into a neutron.

8 When a nucleus has too many protons, one of those will turn into a neutron via beta-positive decay.

9 Alpha particles are relatively heavy (about 8000 times heavier than a beta particle), have a double positive charge and fairly slow moving. Therefore, they are attracted to negatively charged particles, i.e. electrons, very easily and thus will not get the chance to continue to pass through an object.

10 Alpha particles will be stopped by the metal sheet. Gamma rays will pass through. Beta particles will lose some of their energy, and if this is measured and compared with the initial energy then the thickness of the sheet can be determined.
11 Alpha and beta radiation are particles that are emitted from a radioactive nucleus, but gamma radiation is electromagnetic radiation emitted from a radioactive nucleus.
12 Beta, because alpha radiation will not penetrate skin, and gamma radiation will either pass straight through or interact with the surrounding tissue that is probably healthy.
13 $^{4}_{2}\text{He}$
14 Beta negative decay. Y is an electron, $^{0}_{-1}\beta$, and Z is an antineutrino, $^{0}_{0}\overline{\nu}$.
15 **a** X is a nuclide of thorium, $^{231}_{90}\text{Th}$. $A = 231$, $Z = 90$.
b Y is a nuclide of actinium, $^{228}_{89}\text{Ac}$. $A = 228$, $Z = 89$.
16 **a** 7 protons and 7 neutrons
b $^{14}_{6}\text{C}$ has been transformed into a proton, an electron, $^{0}_{-1}\beta$, and an antineutrino, $^{0}_{0}\overline{\nu}$.
17 **a** This is beta-negative decay because the atomic number of the daughter nucleus has increased by 1, therefore an electron, $^{0}_{-1}\beta$, and an antineutrino, $^{0}_{0}\overline{\nu}$ are missing along with energy.
b This is alpha decay because the daughter nucleus has an atomic number two less than the parent nucleus, therefore an alpha particle is missing along with energy.

3.4 Half-life

TY 3.4.1 **a** 2.7×10^{10} **b** 590 days **c** 190 days **d** 3.4×10^{9}
TY 3.4.2 3.9×10^{7}
TY 3.4.3 21 hours

Science as a Human Endeavour

1 Stone and metal do not contain any carbon, so carbon dating cannot be used in these cases.
2 11 500 years old
3 Lead-207 is stable and the amount of it will not change over time. Therefore a larger mass of lead-207 means more time passed since the uranium-235 decayed.
4 4.26 billion years old

3.4 KEY QUESTIONS

1 It is a curve that starts at a maximum value on the *y*-axis, and then decreases at a decreasing rate, as exponential decay. It does not touch the *x*-axis.
2 50%
3 After each half-life the percentage of remaining nuclei decreases by 50%. This means that after two half-lives 50% of 50% (25%) of the original nuclei remain.
4 ≈2.8 s to 3.0 s
5 4.0×10^{10}
6 192 µg
7 **a** about 10 half-lives **b** 240 000 years
8 **a** 7 kg **b** 2.3 kg **c** 22.5 years
d 12.5 years **e** 0.9 kg **f** 0.2 kg
9 **a** 3.0×10^{25} **b** 2.9×10^{26}

3.5 Mass–energy equivalence

TY 3.5.1 1.41×10^{5} eV, 141 keV, 0.141 MeV
TY 3.5.2 $^{4}_{2}\text{He}$, $^{239}_{94}\text{Pu} + {}^{4}_{2}\text{He} \rightarrow {}^{242}_{96}\text{Cm} + {}^{1}_{0}\text{n}$
TY 3.5.3 5×10^{13} J
TY 3.5.4 4668 MeV
TY 3.5.5 7.591 MeV
TY 3.5.6 $^{238}_{92}\text{U} \rightarrow {}^{4}_{2}\text{He} + {}^{234}_{90}\text{Th}$, 4.27 MeV
TY 3.5.7 $^{3}_{1}\text{H} \rightarrow {}^{0}_{-1}\beta + {}^{0}_{0}\overline{\nu} + {}^{3}_{2}\text{He}$, 0.018 61 MeV or 18.61 keV
TY 3.5.8 $^{189}_{80}\text{Hg} \rightarrow {}^{0}_{1}\beta + {}^{0}_{0}\nu + {}^{189}_{79}\text{Au}$, 2.930 MeV
TY 3.5.9 92 MeV

3.5 KEY QUESTIONS

1 $5.0 \times 10^{6} \times 1.602 \times 10^{-19} = 8.0 \times 10^{-13}$ J
2 3.7×10^{4} eV = 0.037 MeV
3 $1.660\,54 \times 10^{-27}$ kg **4** Nickel-62
5 Radioactive decay is a naturally occurring process because energy is *released* when a radionuclide becomes more stable. Artificial transmutation reactions (i.e. nuclear bombardment) *require* energy to be added to the system in order to proceed.
6 If the mass defect is negative, then the sum of the masses of the products is more than the sum of the masses of the reactants. To balance the nuclear reaction, energy must be *added* to the reactants, hence the reaction will not proceed naturally.
7 $^{1}_{0}\text{n}$ or a single neutron
b $^{1}_{0}\text{n}$ or a single neutron
c $^{141}_{56}\text{Ba}$ or the nucleus of barium-141
8 $^{59}_{27}\text{Co} + \text{X} \rightarrow {}^{60}_{27}\text{Co}$, so X is $^{1}_{0}\text{n}$ or a single neutron.
9 **a** $\Delta m = -0.011\,304$ u
b No; Δm is negative, so energy has to be added to make the reaction proceed, and therefore it will not proceed naturally.
10 The mass of an electron is 0.000 548 6 u, therefore its energy equivalent = $0.000\,548\,6 \times 931.6 = 0.511$ MeV.
11 4.26×10^{9} kg s^{-1}
12 **a** $^{8}_{4}\text{Be} \rightarrow {}^{4}_{2}\text{He} + {}^{4}_{2}\text{He}$ or $^{8}_{4}\text{Be} \rightarrow 2\,{}^{4}_{2}\text{He}$ **b** 90.46 keV
13 **a** $^{32}_{15}\text{P} \rightarrow {}^{0}_{-1}\beta + {}^{0}_{0}\overline{\nu} + {}^{32}_{16}\text{S}$ **b** 1.711 MeV
14 **a** $^{64}_{29}\text{Cu} \rightarrow {}^{0}_{1}\beta + {}^{0}_{0}\nu + {}^{64}_{28}\text{Ni}$ **b** 653.1 keV
15 **a** Iron-56; it has the highest binding energy per nucleon (about 8.8 MeV).
b 340 MeV **c** 11.996 46 u

3.6 Fission and fusion

TY 3.6.1 **a** $^{239}_{94}\text{Pu} + {}^{1}_{0}\text{n} \rightarrow {}^{134}_{54}\text{Xe} + {}^{103}_{40}\text{Zr} + 3\,{}^{1}_{0}\text{n}$ **b** 0.085%
TY 3.6.2 **a** $^{12}_{6}\text{C} + {}^{4}_{2}\text{He} \rightarrow {}^{A}_{Z}\text{X} + {}^{0}_{0}\gamma$ **b** $^{12}_{6}\text{C} + {}^{4}_{2}\text{He} \rightarrow {}^{16}_{8}\text{O} + {}^{0}_{0}\gamma$
c 7.163 MeV **d** 0.048%

Science as a human endeavour

1 France
2 Radionuclides for medicine and research in nuclear physics
3 $\oplus\frac{1}{3\,000\,000}$ or about 3 000 000 times less energy than uranium hexafluoride.
4 In a fission reaction, nothing is burnt to produce carbon dioxide from oxygen.
5 A meltdown would be the most drastic economically and for humanitarian reasons, as this will cause the release of radioactive particles into the air, ground and water. Many of these particles will have long half-lives and be dangerously radioactive for many centuries, forcing industry and people to move.

3.6 KEY QUESTIONS

1 uranium-235, plutonium-239, and several others.
2 hydrogen-1, hydrogen-2, hydrogen-3, helium-3, helium-4 and most other nuclei lighter than nickel-62
3 A nucleus is fissile if it can undergo nuclear fission. A chain reaction is one that occurs when a single fission reaction causes a subsequently larger number of fission reactions, which then cause even more fission reactions.
4 Nuclear fission produces two approximately equal-sized nuclei, while radioactive decay produces a nucleus that is about the same size as the parent nucleus.
5 A smaller particle such as a neutron or proton must be fired at a target nucleus for the fission reaction to occur. This process does not normally occur in nature. Also, without the mass of the neutron added to the mass of the target nucleus, the mass defect of any fission reaction would be negative, which means fission would not occur. Hence, energy in the form of the neutron's mass must be added for fission to occur.
6 If a neutron is moving too fast it will simply bounce off a target fissile nucleus; therefore, the neutron must be moving slowly enough for it to be absorbed by the fissile nucleus and cause fission but fast enough for it to get close enough to the target for the strong nuclear force to take over and cause the reactants to fuse.

7 Particles must be moving very fast to overcome the coulomb repulsive force so they can get close enough for the strong nuclear force to take over and the particles to fuse. A high temperature will cause particles to move at high speed. A high speed will also cause the particles to spread out over a large volume, decreasing the chances of fusion; therefore, high pressure squeezes the particles closer so that the chances of fusion occurring are greater.

8 In nuclear fission, a larger nucleus splits into two smaller nuclei. In nuclear fusion two smaller nuclei join together to form a larger nucleus.

9 **a** 2 neutrons

b $^{239}_{94}\text{Pu} + {}^{1}_{0}\text{n} \rightarrow {}^{145}_{56}\text{Ba} + {}^{93}_{38}\text{Sr} + 2\,{}^{1}_{0}\text{n}$

c $\Delta m = 0.201\,842\,4$ u, energy released = 188.0 MeV

d 0.084%

10 **a** $Z = 2$, $A = 3$, so the particle is $^{3}_{2}\text{He}$.

b 3.68×10^{-12} J **c** $\Delta m = 0.025$ u

Chapter 3 review

1 D **2** B **3** B and D **4** 20 protons, 25 neutrons

5 27 protons, 33 neutrons. 60 nucleons

6 a gamma ray $^{0}_{0}\gamma$

7 **a** electron **b** proton **c** alpha particle

d neutron **e** gamma ray *or* neutrino **f** positron

8 D **9** C **10** B **11** D

12 **a** $^{100}_{5}\text{B}$ will undergo beta-negative decay in which a neutron turns into a proton. This is because the number of neutrons is much greater than the number of protons in this nuclide.

b $^{31}_{30}\text{Zn}$ will undergo beta positive decay in which a proton turns into a neutron. This is because the number of protons is much greater than the number of neutrons in this nuclide.

c $^{156m}_{72}\text{Hf}$ will undergo gamma decay as this nuclide is in a higher energy state and will become more stable by emitting a gamma ray to reach a lower state of energy.

13 **a** Technetium-99 is the most stable as it has the longest half-life.

b Technetium-99m is the least stable as it has the shortest half-life.

14 The energy released in a single nuclear fission reaction is between two and ten times more than that released by a single fusion reaction.

15 Half-life is an average time calculated from a very large number of nuclei. An individual nucleus may decay at any time, but half of a large number of nuclei will decay by one half-life. Therefore, for uranium-236, the probability that a single nucleus will decay is very small, but over a large number of nuclei, half of them will be expected to have decayed in 23.4 million years.

16 C **17** B **18** A **19** D **20** 3.0×10^{11}

21 0.000 831 u

22 **a** binding energy = 1445 MeV, binding energy per nucleon = 7.984 MeV

b binding energy: 341.6 MeV, binding energy per nucleon: 8.539 MeV

23 0.94%

24 **a** Initially there are no nitrogen-15 nuclei present because the entire sample is carbon-16.

b about 0.7 s

c As carbon-16 decays into nitrogen-16 and then nitrogen-15, the number of its nuclei decreases and the number of nitrogen-16 nuclei increases at the same rate. The total number of nuclei of the two isotopes stays the same.

d The intersection point occurs after exactly one half-life, when half of the carbon-16 nuclei have decayed into nitrogen-15 nuclei. Therefore, there is an equal number of carbon-16 and nitrogen-15 nuclei.

e This number is always constant and equal to the total number of carbon-16 nuclei at the start.

f First, nitrogen-15 is stable, so its half-life is effectively infinite. Second, the number of nitrogen-15 nuclei is not decreasing so a decay pattern cannot be found.

25 **a** beta-negative decay **b** $^{1}_{0}\text{n} \rightarrow {}^{1}_{1}\text{H} + {}^{0}_{-1}\beta + {}^{0}_{0}\bar{\nu}$

c 782.9 keV = 0.7829 MeV **d** 4.035×10^{13} J

26 **b** 7.9 days

c It is assumed he did not know anything about the half-life of iodine-131, so he measured the mass remaining at increasingly larger time intervals until he obtained a large enough change in mass to indicate that the half-life is measured in days, but not too large to lose accuracy in his mass measurements.

d Max would need to keep the sample in a lead-lined container, as the lead will absorb the fastest moving electrons. He will also need to wear protective clothing (also probably lead-lined) and glasses to prevent any electrons from entering his body or eyes.

e The daughter nuclide of iodine-131 is xenon-131, a gas. Any xenon-131 produced in the outer layers of the crystal will escape to the air and be lost, but any produced inside the crystal will be trapped inside the crystal and contribute to the recorded mass.
Grinding the iodine crystal to a power would increase the surface area and minimise the xenon-131 gas trapped inside the crystals. The measured mass then reflects the remaining mass of the iodine-131 only.

Chapter 4 Electricity

4.1 Charge and the atom

TY 4.1.1 -6.4×10^{-13} C

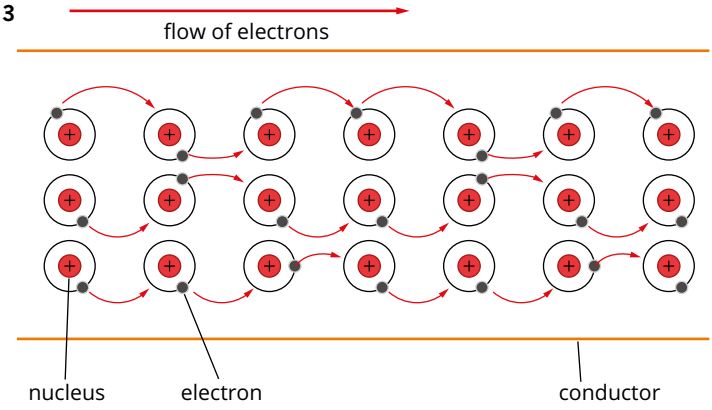
TY 4.1.2 3.0×10^{13}

4.1 KEY QUESTIONS

1 coulomb

2 Electric charge cannot be created or destroyed.

3



4 **a** Rub two insulating materials together, forcing the electrons in one object to interact closely with the nuclei of atoms in the other object. The object with the greater pull on electrons gains electrons; the other object loses electrons becomes and becomes positively charged.

b Induction occurs when a charged object is placed near a neutral object. This causes like charges to be repelled away from the charged object and unlike charges to be attracted towards the charged object. This results in an uneven distribution of charges in the once-neutral object, causing it to become charged.

c Charging by conduction occurs when a charged object (positive or negative) touches a neutral or uncharged object, therefore transferring its charge to that object.

5 Copper is a good conductor and allows electrons to flow readily. Rubber is an insulator and electrons cannot easily flow through it. This protects people from experiencing a shock as electrons cannot flow from the wire to their hand.

6 Strip A and strip C will attract.

7 3.1×10^{19} **8** 6.7 C

9 **a** 3.8×10^{13} **b** 5.2×10^{19} **c** 1.0×10^{13}

10 The overall net charge of $+6q$ will spread out evenly over the two spheres.

4.2 Potential difference

TY 4.2.1 43 kJ
TY 4.2.2 9450 J

4.2 KEY QUESTIONS

1 Potential difference is the electrical potential energy available per unit charge.
2 chemical energy → electrical potential energy of the battery → kinetic energy of free electrons in the wire of the circuit → kinetic energy of atoms in the filament → thermal energy and light
3 $V = \frac{W}{q}$, where V is potential difference, W is the electrical potential energy (or the work done) and q is the charge
4 voltmeter **5** $W = VIt$
6 A battery is a number of cells connected together. In practice, the two terms are often used interchangeably.
7 As each bird has both of its feet on the same wire, there is no potential difference between its feet. Therefore no current will flow through the bird.
8 Charge flows when the rod is a conductor and there is a potential difference between the two bodies.
9 200 J **10** 120 J **11** 20 V **12** 167 C **13** 2700 J
14 **a** thermal energy and light **b** 0.25 A
15 16.7 min
16 the gravitational potential energy of the water

4.3 Electric current

TY 4.3.1 4.7×10^{18}

4.3 KEY QUESTIONS

1 The links can be compared with the electrons flowing through the circuit.
2 $I = \frac{q}{t}$, where I is current, q is charge and t is time
3 Drift velocity is the average velocity at which charges move through the conductor in a circuit.
4 Copper wire
5 A battery (or other power supply) to make the current flow and a complete path for the current to flow
6 Electron flow is the flow of electrons in an electrical circuit from the negative terminal to the positive terminal of the power supply. Conventional current is in the opposite direction, because originally the charges flowing in a circuit were thought to be positive.
7 The electrons flowing through the circuit are conserved; they are not used up or destroyed. Their electrical potential energy is transformed into heat and light, but the same number of electrons leave the light bulb as enter it.
8 Current is a measure of the number of charged particles (electrons) that pass through a conductor per second. Potential difference is the electrical potential energy given to each electron to make it flow through the circuit.
9 Max is incorrect. The electrons move around the circuit fairly slowly, but because a wire is full of electrons that all repel each other; moving one electron affects all the others around it, so the effects of closing the switch are fairly instantaneous.
10 **a** 3.00 A **b** 0.50 A **c** 0.0080 A
11 **a** 5.0 C **b** 300 C **c** 18000 C
12 **a** 9.00 A **b** 4.0 A
13 **a** 3.0 C **b** 1000 C **c** 1440 C
14 **a** 16 C **b** 4.0 A
15 **a** 2×10^{19} **b** 0.32 A

4.4 Resistance

4.4 KEY QUESTIONS

1 Resistance is a measure of how much a material opposes the flow of current.
2 ohms (Ω)
3 cross-sectional area, length and temperature
4 It provides detailed information in a small space about the resistance and tolerance of the resistor.
5 **a** increase **b** decrease **c** 1.6 Ω
6 The copper ions in the wire would have more thermal energy, so they would vibrate faster about their equilibrium positions. There would be a greater chance that the free electrons flowing through the wire would collide with the copper ions, thereby increasing the resistance of the wire.

4.5 Ohm's law

TY 4.5.1 24 Ω
TY 4.5.2 9600 mA
TY 4.5.3 4.0 V
TY 4.5.4 $I_1 = 0.60$ A, $V_2 = 12$ V
TY 4.5.5 0.78 Ω

4.5 KEY QUESTIONS

1 $V = IR$, where V is the voltage, I is current and R is the resistance.
2 **a** The graph is linear and passes through the origin. The resistance is equal to the gradient of the graph.
b The graph is nonlinear (a curve). The gradient is not constant because the resistance is not constant. Use Ohm's law, $V = IR$, for values of V and I on the curve to find the resistance at that particular potential difference.
3 Ohm's law can also be used to determine the current flowing through a resistor when a particular potential difference is applied across it.
4 **a** 0.71 Ω
b The resistor is ohmic, as its resistance is constant (both V and I have doubled).
5 They are both right. The device is non-ohmic and the resistance is different for different values of V and I.
6 80 mA
7 **a** A, B, C **b** C, B, A
8 $I_1 = 0.38$ A, $V_2 = 4.8$ V
9 **a** The wire is ohmic because there is a proportional relationship between the voltage and the current, as shown by the linear nature of the I–V graph, which means the resistance is a constant.
b 3 A **c** 2.5 Ω
10 **a** It is non-ohmic, as the I–V relationship is nonlinear.
b $I = 0.5$ A **c** $V = 15$ V
d **i** 20 Ω **ii** 13 Ω

4.6 Power in a circuit

TY 4.6.1 720 W
TY 4.6.2 20 mW

Science as a human endeavour

1 approximately 10%
2 less than 5%
3 They can be made thinner, and can be printed on different/flexible materials.

4.6 KEY QUESTIONS

1 Power is the rate at which work is done; i.e. the rate at which energy is transformed by components in a circuit.
2 **a** $P = \frac{W}{t}$ **b** $P = VI$ **c** $P = I^2R$
3 In an energy-efficient light bulb, a greater proportion of the energy supplied is transformed into light. In an incandescent light bulb, most of the energy supplied is transformed into heat, and only a small proportion is transformed into light.
4 **a** 138000 J (or 138 kJ) **b** 2.0 A
5 60 W **6** 0.64 W **7** 96 kJ

Chapter 4 review

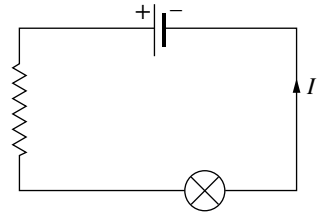
1 2×10^{19} **2** A **3** 6.7 C **4** C **5** D **6** C
7 Electrons generally do not travel in straight lines through conductors; they constantly collide with other particles in the wire. There will therefore be some resistance to current even in a good conductor.
8 3.2×10^{-19} C **9** 3.8×10^{-3}
10 **a** 160 C **b** 10^{21}

11 **a** 0.8C **b** 20s
12 7.6J **13** 4.0V **14** 1.39W **15** 8.8V **16** 8.7A
17 0.50Ω **18** 960Ω **19** 330Ω **20** 20V **21** 30Ω
22 **a** 1Ω **b** 2Ω **c** 3Ω
23 216kJ **24** 2.0Ω **25** 120W **26** 36Ω
27 when cold $R = 9.6\,\Omega$; when hot $R = 150\,\Omega$
28 5.0×10^{18}
29 **a** 18C **b** 54J
c This energy has come from the chemical potential energy in the battery (or from the potential energy in the power supply).
30 125J **31** 3.75×10^{19}

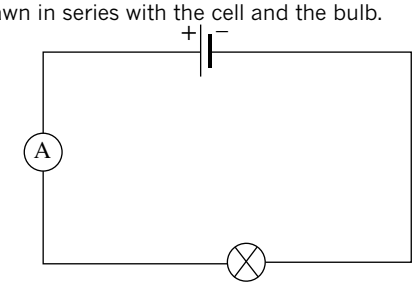
Chapter 5 Electrical circuits

5.1 KEY QUESTIONS

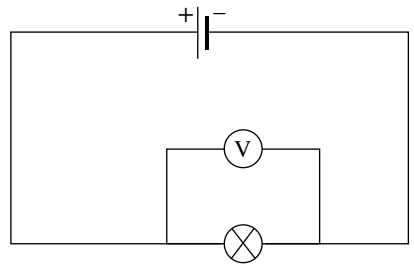
1 The circuit must be made of a conducing material, there must be a voltage applied across the circuit, and the circuit must be a closed loop.
2 cell (or battery), ammeter, resistor, switch and light globe
3 **a** an ammeter connected in series
b a voltmeter connected in parallel
4 series
5 Originally, scientists thought charge carriers were positive.
6 The order of the components may vary. The current must be in the direction shown, towards the negative terminal of the cell.



7 **a** The order of the components may vary, but the ammeter must be drawn in series with the cell and the bulb.



b The voltmeter must be connected in parallel with the bulb.



8 An ammeter has negligible internal resistance so that it can measure the current that flows through it without affecting that current. If it is connected in parallel, it would draw all of the current in the circuit and would create a short-circuit. A voltmeter measures the potential difference or change in voltage across a component, so must be wired in parallel with that component. A voltmeter has a high internal resistance, so if it is wired in series, no current flows in the circuit.
9 The readings will all be the same, because the current is the same at all points in a series circuit.
10 The internal resistance of the ammeter is negligible. When connected in series, the ammeter creates a short circuit and draws a high current. It will most likely be damaged.
11 The internal resistance of the voltmeter is large.
12 B is correct. In A and D, the ammeter is incorrectly set up in parallel with the light bulb. In C, when the switch is closed it creates an alternative (lower-resistance) path to the light bulb, so the light bulb on the left would not light.

5.2 Series circuits

TY 5.2.1 160Ω
TY 5.2.2 $V_t = 12.0\,V$, which is the same as the supply voltage.

5.2 KEY QUESTIONS

1 A **2** the same **3** 3.0V
4 **a** $R_t = 400.0\,\Omega$ **b** 7.5mA **c** 0.75V
5 **a** 0.02A **b** 2.0V
6 **a** 40.0Ω **b** 0.03A **c** 6.0V

5.3 Parallel circuits

TY 5.3.1 14.3Ω
TY 5.3.2 **a** 19Ω **b** $I_{30} = 0.33\,A$, $I_{50} = 0.20\,A$ **c** 0.53A
TY 5.3.3 **a** 0.900W **b** 0.144W
c $\frac{P_{parallel}}{P_{series}} = \frac{0.900}{0.144} = 6.25$, the parallel circuit draws 6.25 times as much power as the series circuit.

5.3 KEY QUESTIONS

1 It allows appliances to be switched on and off independently, and allows each appliance to have a potential difference of 240V across it rather than the potential difference being shared between each appliance.
2 It will always be smaller than the smallest resistor in the set.
3 $R_1 = R_2 = 136\,\Omega$
4 **a** 0.75A **b** 0.25A **c** 0.5A
5 **a** 12.0V **b** 200mA
6 **a** $R_t = 10.0\,\Omega$ **b** $I_{20} = 0.50\,A$, $I_{30} = 0.33\,A$, $I_{60} = 0.17\,A$
7 **a** 1.25W **b** 20.0W

5.4 Kirchhoff's laws and complex circuit analysis

TY 5.4.1 $V_1 = 29.6\,V$, $V_{2-4} = 21.2\,V$, $V_{5-6} = 4.9\,V$, $V_7 = 44.4\,V$; $I_1 = 1.48\,A$, $I_2 = 0.42\,A$, $I_3 = 0.85\,A$, $I_4 = 0.21\,A$, $I_5 = 0.98\,A$, $I_6 = 0.49\,A$, $I_7 = 1.48\,A$
TY 5.4.2 **a** 100.0Ω **b** 5.0V
c $V_{supply} = V_{50} + V_{50}$; Kirchhoff's law holds, so the answers for the potential difference across each resistor are correct.
TY 5.4.3 $I_3 = 0.10\,A$, $R_1 = R_2 = R_3$

Science as a human endeavour

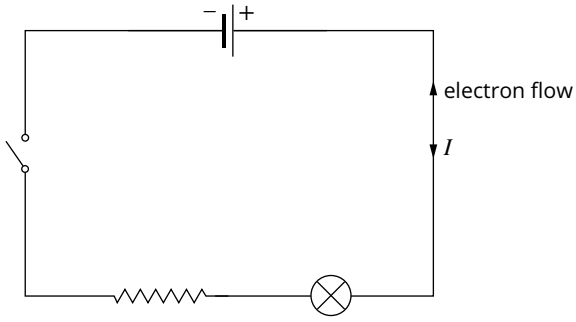
1 Any of: low population density outside cities, large distances between communities, increased demand for power, the need to reduce cost and carbon emissions.
2 Problems include the need for consistent power when the sun doesn't shine or the wind doesn't blow, and the difficulties connecting home-generated power to the grid.
3 Improved battery storage will help relocate power from times of high sunshine or fast winds to times when energy is not available.

5.4 KEY QUESTIONS

1 Kirchhoff's voltage law states that the sum of the potential drops **across a circuit** must equal the total potential gain in the circuit.
2 He is incorrect. First, he should work out the equivalent parallel resistance of the pair of 2Ω resistors ($R_{parallel} = 1\,\Omega$), then he should add this to the 4Ω resistor for the equivalent resistance: $R_t = 1 + 4 = 5\,\Omega$.
3 She is incorrect. The current flowing in each of the parallel branches of the circuit is half of the current that flows in the main part of the circuit.
4 $I_1 = I_2 = 0.300\,A$, $I_3 = I_4 = 0.150\,A$; $V_1 = 6.00\,V$, $V_2 = 4.50\,V$, $V_3 = V_4 = 1.50\,V$
5 **a** $R_{parallel} = 4.3\,\Omega$ **b** $I_{top\ branch} = 1.4\,A$, $I_{bottom\ branch} = 0.91\,A$
c $I_t = I_1 + I_2 = 2.3\,A$ (with some error for rounding), so Kirchhoff's current law holds.
6 **a** 4.5V **b** 0.30A
7 $I_1 = I_2 = 0.480\,A$, $I_3 = I_4 = 0.240\,A$; $V_1 = V_2 = 4.80\,V$, $V_3 = V_4 = 2.40\,V$

Chapter 5 review

1 A and C
2 series: A and D; parallel: B and C
3 A **4** B
5 **a** The energy given to the charges (potential gain) must be equal to the energy lost by the charges (potential drop).
b The total amount of current flowing into a junction must be the same as the total current flowing out of the junction.
6 Answers will vary, but will contain the components shown in the figure, connected in series. Current should be marked as flowing from the positive terminal of the battery towards the negative terminal of the battery. Electron flow is in the opposite direction.



7 **a** A **b** B
c The multimeter is wired in parallel, so it should be used as a voltmeter. If it is used as an ammeter, as it is currently wired, it would create a short-circuit and draw a large current that might damage it.
8 The equivalent series resistance would be greater than the resistance of the individual resistors. In this case it would be double their individual resistances.
9 The equivalent series resistance would be less than the resistance of the smallest individual resistor. In this case it would be half the resistance of the individual resistors.
10 The lights connected in parallel would be the better choice. If a light globe blew, the rest of the lights would stay lit. For the lights connected in series, if one light globe blew, all of the lights would go out.
11 D
12 **a** The internal resistance of the ammeter is very small. It therefore draws a very large current when it is wired in parallel.
b The internal resistance of the voltmeter is very large. Most of the potential is therefore across the voltmeter, and not enough energy is left to light the bulb.
13 10.0 Ω
14 **a** 20.0 Ω **b** $R_1 = 10.0\,\Omega$, $R_2 = R_3 = 20.0\,\Omega$
c $I_3 = 250$ mA
15 **a** $R_t = 1.3\,\Omega$
b $I_1 = 3.3$ A, $I_2 = 2.5$ A, $I_3 = 2.0$ A
c $I = 7.8$ A and using Kirchhoff's current law $I = 7.8$ A. The values are equivalent.
16 **a** 24.0 Ω **b** 0.42 A
c $V_1 = 1.7$ V, $V_2 = 3.4$ V, $V_3 = 5.0$ V
Using Kirchhoff's voltage law, total potential drop = 1.7 + 3.4 + 5.0 = 10.1 V. This is the total potential gain of the circuit, with a minor rounding error.
17 **a** 3.5 Ω **b** 0.35 A **c** $V_{1-2} = 1.8$ V
d 0.12 A **e** 0.23 A **f** 7.7 Ω
18 **a** ammeter **b** 8.57 Ω
19 Students' answers will vary but should show two resistors in series combined in parallel with two other resistors in series.
20 **a** 2.4 W **b** 21.6 W
c The parallel circuit draws 9 times more power.
21 **a** 60.0.0 Ω **b** 2.000 A
c $I_1 = 1.200$ A, $I_2 = 0.600$ A, $I_3 = 0.200$ A
d $I_t = I_1 + I_2 + I_3$, so Kirchhoff's current law holds for these answers.
e 240.0 W
f $P_1 = 144.0$ W, $P_2 = 72.0$ W, $P_3 = 24.0$ W
22 **a** 75.0 V **b** 37.5 W
23 Four 20.0 Ω light bulbs are connected to a 10.0 V battery. Determine the total power output of the circuit if the light bulbs are connected in the following ways.
a 1.25 W **b** 20.0 W
24 **a** 4.0 V
b The LDR has a high resistance when it is very dark; so the voltage drop across the LDR approaches 12.0 V. Therefore V_{out} approaches zero.

Unit 1 Review: Worked solutions

Topic 1: Heating processes

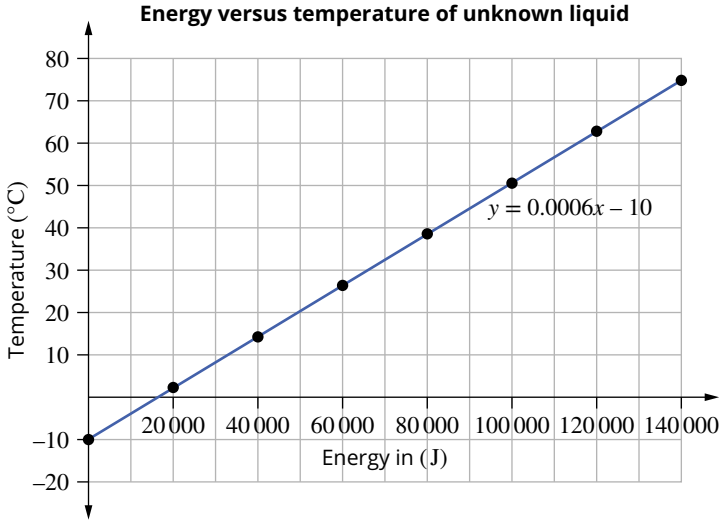
Multiple choice

1 C **2** D **3** C **4** C **5** D **6** D **7** A
8 D **9** A **10** B

Short answer

1 Temperature is a measure of the average kinetic energy of particles within a system, so objects that have the same average kinetic energy will have the same temperature.
2 Specific heat capacity of unknown metal = 930 J kg^{-1}, which most closely matches aluminium.
3 No change in temperature occurs as all of the extra energy supplied is used in overcoming the interparticle or intermolecular forces between water particles.
4 Energy received from the cooling of 0.10 g of water at 100°C to = 2.6×10^4 J
Energy received from the cooling of 0.10 g of steam originally at 100°C = 4.85×10^4 J
(i.e. turning steam to water transfers almost as much heat as then cooling the water to 37°C)
5 $T = 40$°C
6 Glass conducts thermal energy from inside to outside the house in the evening. Closing the curtains reduces convection currents/airflow from the warm room to the glass.
7 Initially, the particles in the copper block have a higher kinetic energy than the particles in the water. The temperature of the block and internal energy of its particles decreases until the average kinetic energy of the copper atoms is equal to that of the water molecules, when thermal equilibrium is reached.
8 When the ball is hit, mechanical energy is transferred from the racquet to the ball. With every energy transfer, the amount of usable energy is reduced through some heat loss. This heat raises the temperature of the balls.
9 Metals are good conductors of heat. Heat moves easily from your warm hand to the metal and so the metal 'feels colder'.
Wood is a poor conductor of heat and little heat is transferred from your hand to the wood, so that your hand does not sense it is touching something cooler.
10 Sweat cools the skin by evaporation. As the liquid evaporates, a large amount of heat is transferred from the body to the sweat to provide enough energy to change the state. But humid climates do not allow sufficient evaporation.
Elephants transfer excess heat into the environment through a process of conduction and convection. Heat is conducted from the blood through the thin skin to the surface. The air flow then transfers the heat away from the elephant into the air. Heat transfer in this way requires large areas of skin, and a mechanism to increase convection, but is not effected by humidity.

11 a



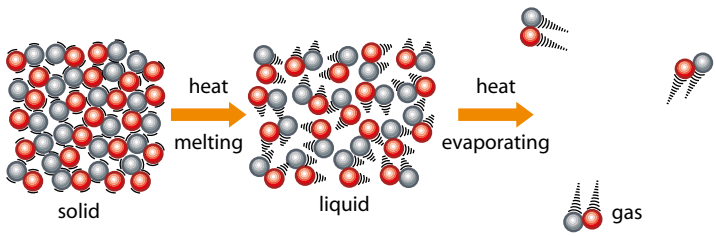
b The *y*-intercept, –10, is the initial temperature of the liquid. The gradient of the graph (0.0006) represents $(mc)^{-1}$; $c = 2487.56\,\text{J kg}^{-1}\,\text{K}^{-1}$.

c The liquid is likely to be ethanol.

12 a When the candle burns, chemical potential energy is transformed into heat energy. This is transferred to the molecules in the air in the balloon, increasing their kinetic energy. The energy is then transferred to the balloon, increasing the gravitational potential energy and kinetic energy of the balloon as it rises.

b Efficiency is the percentage of usable energy transferred and transformed. In this case, the efficiency is the amount of mechanical energy of the balloon as a percentage of the energy output of the candle.

13 a At point A the iron is a solid. The molecules are vibrating and held in place by intermolecular forces. At point F the iron is a gas, and the atoms are able to move freely at a fast pace.



b Between C and D the iron is a liquid. As heat is added, the kinetic energy of the molecules increases and the molecules move faster. This is measured as an increase in temperature. The molecules move further apart, reducing the density.

c Between D and E the iron is boiling. Energy added at this stage is used to overcome intermolecular bonds, changing the liquid to a gas.

Topic 2: Ionising radiation and nuclear reactions

Multiple choice

1 C **2** D **3** C **4** C **5** C **6** D **7** B
8 D **9** A **10** B

Short answer

1 a ${}^{14}_{6}\text{C} \rightarrow {}^{14}_{7}\text{N} + {}^{0}_{-1}\beta$ **b** ${}^{214}_{82}\text{Pb} \rightarrow {}^{214}_{83}\text{Bi} + {}^{0}_{-1}\beta$

c ${}^{60}_{27}\text{Co}^{*} \rightarrow {}^{60}_{27}\text{Co} + \gamma$

2 a 12.5 µg **b** 6.25 µg **c** 3.125 µg

3 a 8 hours **b** 4 hours **c** 7 g **d** 0.63 g

4 Binding energy is the mechanical work that must be done against the forces holding a nucleus together to disassemble it into component parts.

Mass defect is the mass that is converted into energy during a nuclear reaction, and can be calculated by subtracting the mass of the products from the mass of the reactants.

5 1.0 MeV per nucleon

6 $m = 3.7 \times 10^{14}\,\text{kg}$

7 a ${}^{210}_{82}\text{Pb} \rightarrow {}^{210}_{83}\text{Bi} + {}^{0}_{-1}\text{e} + \overline{\nu}_{e} + \gamma$

${}^{210}_{83}\text{Bi} \rightarrow {}^{210}_{84}\text{Po} + {}^{0}_{-1}\text{e} + \overline{\nu}_{e} + \gamma$

${}^{210}_{84}\text{Po} \rightarrow {}^{206}_{82}\text{Pb} + {}^{4}_{2}\text{He}^{2+} + \nu_{e} + \gamma$

b This polonium isotope emits alpha particles, which have high ionisation levels, and would cause severe damage if ingested. Alpha particles have low penetration levels, and are easily blocked by clothing and skin, so are relatively safe to observe.

8 Half-life is the time it takes, on average, for half of the nuclei to decay. In a living organism, the relative levels of carbon-14 and carbon-12 will be equal to the relative abundance. When the organism dies, it stops taking in carbon. The carbon-14 begins to decay but the carbon-12 does not. By comparing the carbon-14 to carbon-12 levels, it is possible to estimate of the age of the organic material.

9 Beta negative radiation would be used, as it is able to penetrate short distances, so it will reach all the surrounding cancer cells, but few, if any, of the healthy cells further away. Alpha radiation lacks penetrating power and would not reach all cancer cells. Gamma is too penetrating and would affect too many healthy cells.

10 a ${}^{1}_{0}\text{n}$

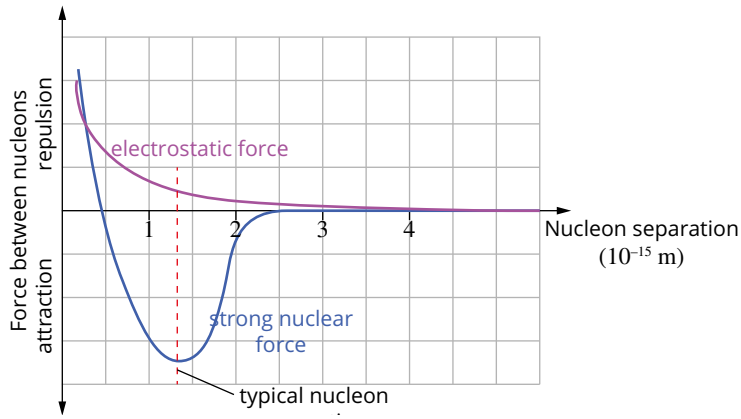
b $2.72 \times 10^{-11}\,\text{J}$

c $N = 1.10 \times 10^{20}$

d $4.3 \times 10^{-5}\,\text{kg}$

11 a The strong nuclear force acts between all nucleons but only over short distances, and the electrostatic force only acts between protons but decreases more slowly, and so is the dominant force over a larger distance.

Strength of force versus distance between nucleons of stable atom



b Nuclei with more neutrons than the stable isotope of the same element will have an excess of the strong nuclear force acting, causing the nucleus to be unstable. The electrostatic force will not be strong enough to counter the strong nuclear force.

c beta negative decay

d alpha decay in the larger nuclei or beta positive decay in the smaller nuclei

12 a Natural radioactive decay occurs spontaneously due to an unstable nucleus. Artificial transmutation is the altering of the nucleus purposefully, usually to create an unstable excited nucleus that fissions.

b 3 neutrons

c When one U-235 nucleus fissions, it releases three neutrons with high kinetic energy. The moderator absorbs some of this energy, slowing down the neutrons to the right speed to be captured by another U-235 nucleus and so start another fission reaction. Control rods are used to capture neutrons to control the number of reactions, and hence the energy produced.

d No, it could not be used. Many different daughter particles are produced in nuclear fission, which results in the production of many different elements. Most of the daughter nuclei are radioactive, as is iodine-131, making purification dangerous and not reasonable within the half-life of the nuclei.

e 174.1 MeV

13 **a** 17.8 MeV

b Generally speaking, as the mass number increases up to nickel-62, the binding energy per nucleon increases. These elements release energy by nuclear fusion in which two lighter atoms fuse to become one heavier atom.

c For fusion to occur, the smaller nuclei must be travelling very fast. This requires high temperatures (high kinetic energy) and great pressure to overcome the electrostatic repulsion force that acts between two positively charged nuclei.

d Elements beyond nickel have a reduction of binding energy as the mass number increases. For these elements, energy is released through nuclear fission, in which a large heavy nucleus fissions into two smaller nuclei, and releases the difference in binding energy.

Topic 3: Electrical circuits

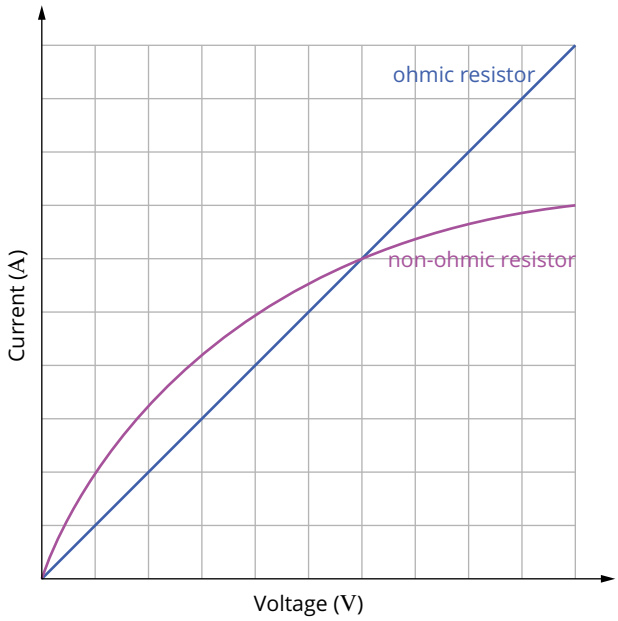
Multiple choice

1 C **2** B **3** C **4** A **5** B **6** D **7** B
8 C **9** B **10** A

Short answer

1 The positively charged confetti will be attracted to the negatively charged balloon due to the potential difference between them. This potential difference will cause an electromotive force, which will result in the confetti moving towards the balloon.

2 ***I–V* graph for a light bulb**



3 **a** 0.26 A to 0.60 A **b** 3.9 V to 9.0 V

4 **a** 8.7 A **b** 360 kJ **c** 1600 C **d** 9.8×10^{21}

5 34.2 W

6 **a** Electric current (amperes or A) is the flow of charge through a circuit. It can be quantified by the number of charges that pass a point per second.

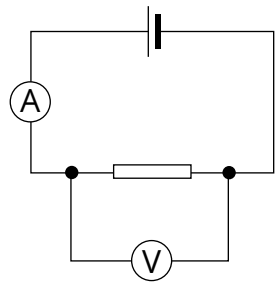
b Electric potential difference (volt or V) is the difference in electrical potential energy between two points that is available per unit charge.

c Power dissipation over resistors (watts or W) is the energy per second that is transformed from electrical energy into heat energy by the resistor.

7 $I_3 = 0.03$ A, $P_2 = 0.72$ W

8 $R = 100\,\Omega$

9



10 Friction between the balloon and Nick's hair causes electrons to be moved. Hair and balloon gain opposite charges due to gain or loss of electrons. Oppositely charged objects attract. Hence, hair is attracted to the balloon.

11 **a** Parallel. If 1 bulb goes out, the rest remain on, all bulbs dissipate maximum power as the supply voltage is not divided.

b The total circuit resistance decreases.

c 6 bulbs

d Total circuit resistance would increase.

e Fuse would not blow. Lights would be on, but not at maximum brightness.

12 **a** The copper wire has a low resistance, so the supplied voltage will cause a large current, which means large numbers of electrons are moving. The electrons bump into the atoms in the wire, transferring some of their kinetic energy. As the kinetic energy (and internal energy) of the molecules increases, the temperature of the wire increases. Plastic is an insulator; no current is passing through it and it does not heat up.

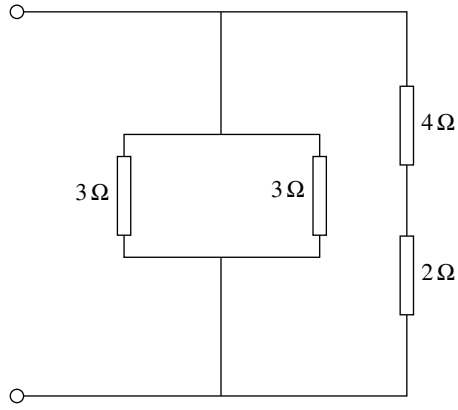
b Electrical resistance is a measure of how difficult it is for electric charges to flow through the material. The copper wire has delocalised electrons that are able to move fairly easily, so it has a low resistance. The plastic has tightly held electrons that are unable to move, so it has a very high resistance.

c Various answers are possible. Ensure method allows for repeatable measurements, with 5–8 different data points collected. Electrical safety should be considered, including connection of components and choice of voltage supplied and resistors to have suitable currents.

d Three data points is not enough to determine the resistance of the component. More measurements are needed.
The voltages being tested (0.5–1.5 V) are much lower than the voltage that needs to be predicted (24 V). This is extrapolation and is unreliable. Voltages above and below 24 V need to be included in the practical.

13 **a** 6 A **b** 2.83 Ω **c** 17 V

d Various answers are possible.
One solution includes placing the 2 Ω resistor and 4 Ω resistor in series, and placing the other two in a parallel arm.



Chapter 6 Vectors and linear motion

6.1 Vectors

TY 6.1.1 **a** 50 N west **b** –50 N
TY 6.1.2 19 N down
TY 6.1.3 1988 m s^{-1} up

6.1 KEY QUESTIONS

1 direction
2 **a** vector **b** vector **c** scalar **d** vector
e scalar **f** scalar **g** vector
3 **a** *F* **b** *v*
4 **a** 4 N right

b 10 N left

c 8 N right

5 4 m west **6** 2 m down **7** 11 m forwards
8 The resultant vector is drawn from the tail of vector A to the head of vector B. Adding vector B to vector A is equivalent to saying A + B. Therefore, draw vector A first, then draw vector B with its tail at the head of A. The resultant is drawn from the tail of the first vector (A) to the head of the last vector (B).
9 8 m s^{-1} east **10** 2 m s^{-1} left **11** 7 m s^{-1} downwards
12 14.0 m s^{-1} backwards

6.2 Distance and displacement

6.2 KEY QUESTIONS

1 Displacement is the change in the position of an object. It is a measure of the difference between the start and end points of the motion of an object—it does not take into account actual distance travelled by the object or the route it took.
2 Any activity where the person has returned to their starting point, such as a complete lap of a track or several laps of a pool.
3 **a** 250 m
b 0 m, as she starts and ends at the same place.
4 **a** 40 cm **b** 0 cm **c** 20 cm **d** 80 cm
5 **a** 80.0 km
b +20.0 km or 20.0 km north
6 **a** –10 m or 10 m downwards **b** +60 m or 60 m upwards
c 70 m **d** 50 m or 50 m upwards

6.3 Speed and velocity

TY 6.3.1 **a** 0.92 m s^{-1} east **b** 3.3 km h^{-1}
c 4.00 m s^{-1} **d** 14.4 km h^{-1}

6.3 KEY QUESTIONS

1 **a** $v_{av} = \frac{d}{t}$ **b** $v_{av} = \frac{s}{t}$
2 Speed is a scalar, and is a measure of distance travelled over time. Velocity is a vector, and is a measure of displacement over time. A direction is needed to describe velocity.
3 **a** 33 m s^{-1} **b** 25 m
4 **a** 17 km h^{-1} **b** 4.6 m s^{-1}.
5 **a** 0.90 m s^{-1} **b** 0.10 m s^{-1}
6 **a** 21 km **b** 15.0 km **c** 14 km h^{-1}. **d** 10 km h^{-1}.

6.4 Acceleration

TY 6.4.1 **a** –2.00 m s^{-1} **b** Δv = 16.0 m s^{-1} up
TY 6.4.2 460 m s^{-2} up

6.4 KEY QUESTIONS

1 **a** Acceleration is the rate of change of velocity, which is the change in velocity over time.
b $a_{av} = \frac{v}{t}$
c $a_{av} = \frac{v - u}{t}$
2 –7 km h^{-1}
Note that speed is a scalar so the negative value indicates a decrease in magnitude, rather than a negative direction.
3 5.0 m s^{-1} up **4** 8.0 m s^{-1} up
5 5.0 m s^{-2} south **6** 43 km h^{-1} s^{-1}
7 **a** –10 m s^{-1} **b** 40 m s^{-1} west **c** 800 m s^{-2}
8 **a** 8.0 m s^{-1} **b** 8.0 m s^{-1} south **c** 6.7 m s^{-2}

6.5 Equations of motion

TY 6.5.1 **a** 3.8 m s^{-2} west **b** 4.0 s **c** 7.5 m s^{-1} east
TY 6.5.2 **a** 2.5 s **b** 3.5 s **c** *v* = –34 m s^{-1} or 34 m s^{-1} downwards

6.5 KEY QUESTIONS

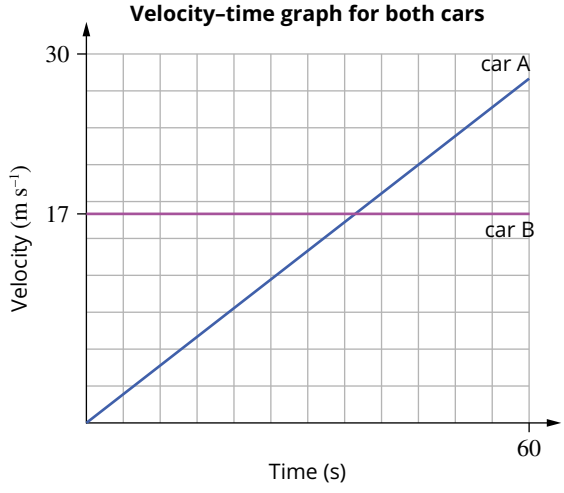
1 **a** $s = vt - \frac{1}{2}at^2$ **b** $s = \frac{1}{2}(u + v)t$ **c** $v = u + at$
e $s = ut + \frac{1}{2}at^2$ **f** $v^2 = u^2 + 2as$
2 $v^2 = u^2 + 2as$
3 The acceleration remains constant at 9.80 m s^{-2} (if the effects of air resistance are ignored).
4 **a** 29 m s^{-1}
b 24 m s^{-1}
c 12 m s^{-1} (down)
5 **a** *v* = 0 **b** *u* = 15 m s^{-1} **c** 11.25 or 11 m
6 **a** 3.9 m s^{-1} **b** 0.78 m
c 0.20 m **d** 0.58 m
7 **a** 2.0 s (assuming no air resistance)
b 20 m s^{-1} **c** 20 m **d** –20 m s^{-1}
8 **a** 3.1 m s^{-2} **b** 50 m s^{-1} **c** 180 km h^{-1}
9 **a** 2.0 m s^{-2} **b** 8 m s^{-1} **c** 64 m
10 **a** 40 m s^{-2} **b** 1.12 or 1.1 km **c** 580 km h^{-1}
d 80 m s^{-1} **e** 120 m s^{-1}
11 **a** 5.0 m s^{-2} **b** 2.7 m **c** 5.5 m s^{-1}
12 **a** 98 m s^{-2} **b** 0.29 s **c** 20 m s^{-1}
13 **a** 21 m s^{-1} **b** 5.2 m
c 36 m **d** 41 m

6.6 Graphs of motion

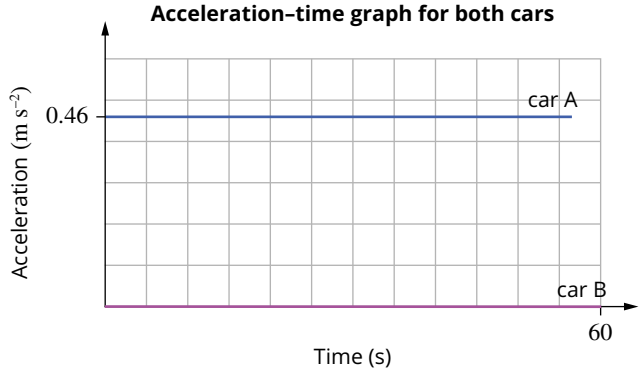
TY 6.6.1 **a** –15 m s^{-1} or 15 m s^{-1} backwards
b The cyclist is stationary and *v* = 0 m s^{-1}.
TY 6.6.2 **a** 4 m west **b** 2 m s^{-1} west
TY 6.6.3 –2 m s^{-2} east (or 2 m s^{-2} west)

6.6 KEY QUESTIONS

1 **a** The gradient is the displacement over the time taken, so it represents velocity.
b The gradient is the velocity over the time taken, so it represents acceleration.
c The area is the velocity multiplied by the time taken, so it represents displacement.
d The area is the acceleration multiplied by the time taken, so it represents the change in velocity.
2



b



c The displacement of car B is greater than that of car A, so car A will not pass car B in 1 minute.

3 The car initially moves in a positive direction and travels 8 m in 2 s. It then stops for 2 s. The car then reverses direction for 5 s, passing back through its starting point at 8 s. It travels a further 2 m in a negative direction before stopping after 9 s.

4 **a** +8 m **b** +8 m **c** +4 m **d** −2 m

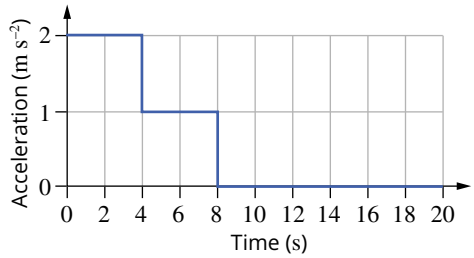
5 8 s

6 **a** +4 m s^{-1} **b** Velocity is zero. **c** −2.0 m s^{-1}
d −2.0 m s^{-1} **e** −2.0 m s^{-1}

7 **a** 18 m **b** −2 m

8 **a** 2 m s^{-2} **b** 10 s **c** 80 m **d** 7 m s^{-1}

9 **a**



b +12 m s^{-1}

Chapter 6 review

1 B and D **2** A and D

3 Signs are useful in mathematical calculations, as the words 'north' and 'south' cannot be used in an equation.

4 Vector A is drawn twice the length of vector B, so it has twice the magnitude of B.

5 B **6** A and D **7** D **8** B

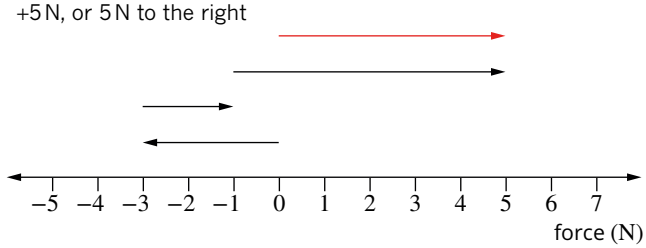
9 The vector must be drawn as an arrow with its tail at the point of contact between the hand and the ball. The arrow points in the direction of the 'push' of the hand.

10 + 80 N or just 80 N **11** 26 m s^{-1} **12** 54 km h^{-1}

13 **a** from 10 to 25 s **b** from 30 to 45 s
c from 0 to 10 s, from 25 to 30 s and from 45 to 60 s
d 42.5 s or 43 s

14 **a** B **b** A **c** C

15 +5 N, or 5 N to the right



16 21.0 m backwards **17** 6 m s^{-1} **18** 15 km h^{-1}

19 **a** 10 km h^{-1} north **b** 2.8 m s^{-1} north

20 10.0 m s^{-1} **21** −6 m s^{-2}

22 **a** 114 m north **b** 10.4 m s^{-1} **c** 0 m s^{-2}
d −7 or 7 m s^{-2} south **e** A

23 16 m s^{-1}

24 **a** 4.0 m s^{-2} **b** 4.0 m s^{-1} **c** 6.0 m

25 **a** −5.0 m s^{-2} **b** 2.0 s

26 **a** +4 m **b** sections A and C
c section B with a v = +0.8 m s^{-1}
d D, 2.4 m s^{-1} **e** 0.8 m s^{-1}

27 **a** 8.0 s **b** 16 s **c** 192 m

28 **a** 3.5 s **b** 2.9 s

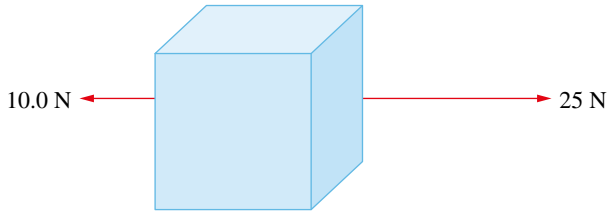
29 **a** 1.7 s **b** 3.2 s

30 **a** 4.0 m s^{-1} **b** 5.7 m s^{-1} **c** 2.0 s **d** 0.83 s

Chapter 7 Force and momentum

7.1 Forces

TY 7.1.1 15 N forwards



7.1 KEY QUESTIONS

1 magnitude, direction and units (N)

2 The weight of the suitcase acts downwards and the girl provides a pull upwards. The forces are in equilibrium if she is not moving.

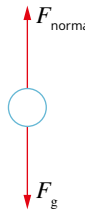
3 The weight of the suitcase still acts downwards, and a normal reaction force from the floor acts upwards.

4 The force the swimmer exerts on the water with his hands.

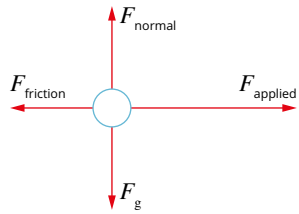
5 The paper clip can be picked up without it touching the magnet, and the magnet can make the paperclip move towards it without touching it. Therefore the force is a non-contact force.

6 Contact forces act directly on an object (e.g. friction and a push or a pull). Non-contact forces act at a distance (e.g. gravity and an electromagnetic force).

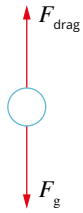
7 **a**



b



c The apple falls towards the ground at constant velocity.



8 F_{net} = 0 N **9** F_{net} = −10 N or 10 N west

10 F_{net} = 0 N, so the box will not move.

7.2 Newton's laws of motion

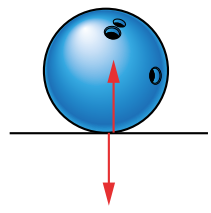
TY 7.2.1 307 N south **TY 7.2.2** 4.23 m s^{-1} left

TY 7.2.3 2.50 m s^{-2} forwards

TY 7.2.4 **a** 7.0 m s^{-2} forwards **b** 5.0 m s^{-2} forwards

TY 7.2.5 **a** $F_{on\ floor\ by\ bowling\ ball}$ **b** $F_{on\ floor\ by\ bowling\ ball}$

c



7.2 KEY QUESTIONS

1 **a** Every object continues to be at rest, or moves with a constant velocity, unless an unbalanced force acts upon it.
b The acceleration of a body experiencing an unbalanced force is proportional to the net force and inversely proportional to the mass of the body:
$a = \frac{F_{net}}{m}$ or $F_{net} = ma$
c When one body exerts a force on another body (an action force), the second body exerts an equal force in the opposite direction on the first (the reaction force): $F_{AB} = -F_{BA}$.

2 The box has changed its velocity so the student can use Newton's first law to conclude that an unbalanced force must be acting on the box to slow it down.

3 It is incorrect. Phil appeared to have been thrown backwards but, in accordance with Newton's first law of motion, as the tram started off, Phil's inertia meant that he remained at rest until an unbalanced force acted to change that.

4 Although the car has maintained its speed, its direction has changed, which means its velocity has changed. Using Newton's first law, it can be concluded that an unbalanced force has acted on the car to change its direction.

5 The ball maintains a constant velocity, so according to Newton's first law there must not be an unbalanced force. There is no forwards force, friction or air resistance acting on the ball.

6 There is a force on the hammer by the nail, and a force on the nail by the hammer. These two forces are equal in magnitude and opposite in direction.

7 **a** $F_{\text{on the astronaut by the Earth}}$ **b** $F_{\text{on the Earth by the astronaut}}$

8 The force on the balloon by the escaping air. The balloon's elasticity compresses the air inside and pushes it out of the mouth of the balloon. This is the action force. The air must therefore exert an equal and opposite forwards force on the balloon, which in turn moves the balloon around the room.

9 $F_{\text{on the racquet by the ball}} = 100.0\,\text{N east}$

10 Tania is correct. For an action–reaction pair, the action force is a force on object A by object B, and the reaction force is a force on object B by object A. That is, the two forces act on different objects. In this case, both the weight force and the normal force are acting on the same object: the lunch box.

11 20 N **12** 25 N

13 The aircraft slows down as it travels along the runway because of the large retarding forces acting on it. The passengers wearing seatbelts would have retarding forces provided by the seatbelt and would slow down at the same rate as the aircraft. A passenger standing in the aisle would tend to maintain their original velocity and move towards the front of the aircraft.

14 **a** If the cloth is pulled quickly, the force on the glass acts for a short time only. This force does not overcome the tendency of the glass to stay where they is, i.e. its inertia.
b Using a full glass makes the trick easier because the force will have less effect on the glass due to its greater mass. The inertia of the full glass is greater than that of an empty glass.

15 The fully laden semitrailer will find it most difficult to stop. Its large mass means that more force is required to bring it to a stop.

16 lift = 50 kN up, and drag = 12 kN west.

17 $6.61\,\text{m s}^{-2}$ north

18 78 500 kg **19** $0.288\,\text{m s}^{-1}$ north

20 **a** 490 N **b** 20 N south **c** $0.31\,\text{m s}^{-2}$

21 **a** $1.6\,\text{m s}^{-2}$ **b** $0.80\,\text{m s}^{-1}$ **c** $0.2\,\text{m s}^{-2}$

22 4 boxes

23 **a** 140 N in the opposite direction to the leaping fisherman
b $3.5\,\text{m s}^{-2}$ in the opposite direction to the fisherman
c speed of the fisherman = $1.0\,\text{m s}^{-1}$, speed of the boat = $1.8\,\text{m s}^{-1}$

24 The astronaut should throw the tool kit in the opposite direction from the ship. The action force on the tool kit by the astronaut will result in a reaction force on the astronaut by the tool kit that will be towards the ship.

7.3 Momentum

TY 7.3.1 $20\,500\,\text{kg m s}^{-1}$ north
TY 7.3.2 $803\,\text{kg m s}^{-1}$ south
TY 7.3.3 $4.5\,\text{m s}^{-1}$ north

7.3 KEY QUESTIONS

1 **a** $p = mv$, where p is the object's momentum, m is its mass, and v is its velocity
b $\Delta p = mv - mu$, where u is the initial velocity, and v is the final velocity

2 He is not correct because he has changed direction; his velocity has changed, even if his speed is the same. Therefore his momentum has also changed.

3 She could double the mass of the trolley.

4 $8.75\,\text{kg m s}^{-1}$ south **5** $9610\,\text{kg m s}^{-1}$ west **6** $3.97\,\text{kg m s}^{-1}$ south

7 first ball: $p = 15.75\,\text{kg m s}^{-1}$, second ball: $p = 17\,\text{kg m s}^{-1}$ so second ball has the greater momentum

8 $83.1\,\text{kg m s}^{-1}$ south **9** $23500\,\text{kg m s}^{-1}$ east

10 $40.0\,\text{kg m s}^{-1}$ east **11** $2.40\,\text{m s}^{-1}$ north

7.4 Impulse

TY 7.4.1 **a** $3.94 \times 10^4\,\text{N s}$ south **b** 3150 N
TY 7.4.2 **a** $0.192\,\text{kg m s}^{-1}$ up **b** 0.192 N s up
c 54.1 N up
TY 7.4.3 **a** $0.192\,\text{kg m s}^{-1}$ up **b** 0.192 N s up
c 0.591 N up
TY 7.4.4 101 N s
TY 7.4.5 **a** 32 N **b** 0.36 N s up

7.4 KEY QUESTIONS

1 **a** $I = mv - mu$ **b** $I = F_{net}\Delta t$

2 The impulse is the area below the force-time graph.

3 **a** kg m s^{-1} **b** N s

4 The impulse due to the collision can't be changed, but by moving his hands into his body he makes the duration of the catch longer and so reduces the force on his hands.

5 The impulse due to the collision with the helmet can't be changed, but the foam allows the head to be brought to a stop in a longer time and so reduces the force and the level of injury.

6 The impulse due to the collision of the egg with the cardboard can't be changed, but the corrugated cardboard has more ability to compress, making the time of collision longer and the force on the egg smaller. The egg onto the corrugated cardboard is less likely to break.

7 83.1 N s south **8** 235 000 N s east

9 40.0 N s east **10** 38 N

11 6.89 N s **12** 2140 N upwards

13 **a** $1.39 \times 10^6\,\text{kg m s}^{-1}$ **b** $I = 1.39 \times 10^6\,\text{kg m s}^{-1}$

14 Jacinta is correct. Because the higher pressure ball bounces back further, its change in momentum is greater. The impulse is the force applied multiplied by the interaction time, so you'd expect that the higher the impulse, the greater the force. You would also expect that the interaction time for the harder ball would be less, further increasing the force, and hence the pain of the player. Sarah is quite right that both balls have the same initial momentum, but she has not taken the final momentum into account.

15 200 N s **16** 1000 N

17 $p_{bull} = 8\,\text{kg m s}^{-1}$, $p_{bullet} = 5.25\,\text{kg m s}^{-1}$ so bull would require the larger impulse to stop.

7.5 Conservation of momentum

TY 7.5.1 $0.80\,\text{m s}^{-1}$ north
TY 7.5.2 $1.00\,\text{m s}^{-1}$ south
TY 7.5.3 $1630\,\text{m s}^{-1}$ south

Science as a Human Endeavour

1 The impulse, or change in momentum, due to the collision can't be changed, but the airbag slows the motion of the car's occupant so that the impulse happens over a longer time and the force acting on the car's occupants is reduced.

2 Anything that increases the time over which the occupants of the tank would come to rest in the event of a collision would help protect the soldiers; e.g. airbags or padded covering of the inside of the tank.

3 A collision from behind would produce a sudden acceleration of a person's body from the seat. Without a headrest, the person's head would obey Newton's first law—it would stay at rest (or move at its original speed) until a force acted. Therefore the head would not move forwards until pulled by the neck as the body moves forwards. This can injure the neck, and is called whiplash. The head rest ensures that the head moves with the body in the event of a collision from behind, and so reduces injury from whiplash.

7.5 KEY QUESTIONS

1 **a** $m_1u_1 + m_2u_2 = m_1v_1 + m_2v_2$ **b** $m_1u_1 + m_2u_2 = m_3v_3$
c $m_1u_1 = m_2v_2 + m_3v_3$

2 **a** Conservation of momentum says that the total momentum before any interaction equals the total momentum after the interaction, i.e. Mutruck $= (M + m)v$. Now as M is much larger than m, $(M + m)$ will be only be slightly larger than M, hence u is only slightly larger than v and the train hardly slows down.
b The initial velocity of the target is horizontal. After the collision, the target breaks into many pieces, but the total of the momentum of the pieces must add to give the total initial momentum ($m_1u_1 + m_2u_2$) in the same initial direction. This means that pieces will be forced in every direction, with slightly more of them flying off in the forwards horizontal direction.

3 $-0.438\,m\,s^{-1}$ or $0.438\,m\,s^{-1}$ backwards
4 $70.4\,m\,s^{-1}$ **5** 14 200 kg **6** $1.75\,m\,s^{-1}$
7 $3.0\,m\,s^{-1}$ in the direction opposite to that of the exhaust gases.
8 **a** $40\,m\,s^{-1}$ **b** 4.5×10^3 N **c** $10\,m\,s^{-2}$

Chapter 7 review

1 **a** B Newton's second law **b** A Newton's first law
c C Newton's third law **d** C Newton's third law
e B Newton's second law **f** A Newton's first law
g B Newton's second law

2 C

3 You would try to increase the time the occupants took to stop as increasing the time the occupants take to stop reduces the force they experience.

4 The forces acting are the gravitational force (or weight) downwards, and the normal reaction force upwards. These forces are equal in magnitude and opposite in direction as the book is at rest.

5 D **6** A, C and D

7 She would need to run twice as fast.

8 A force has not pushed the passengers backwards. The passengers have inertia, and as the train starts to move forwards the passengers' masses resist the change in motion. According to Newton's first law, their bodies are simply maintaining their original state of being motionless until an unbalanced force acts to accelerate them.

9 D **10** D **11** $F_{net} = 30.0$ N downwards
12 $F_{net} = 10.0$ N east, so the box will move in an easterly direction.
13 $F_{net} = 2300$ N forwards. The car would move as there is a net force acting on it.
14 38.3 kg **15** $5.40\,m\,s^{-2}$ north **16** $1.5\,m\,s^{-2}$
17 1.05 ms−2 **18** 90.0 N **19** 130 N
20 $0.50\,kg\,m\,s^{-1}$ north **21** $2.0 \times 10^5\,kg\,m\,s^{-1}$ south
22 $5.11\,m\,s^{-1}$ west
23 Newton's third law states that every action has an equal and opposite reaction. Therefore, the reaction of the board acting on the student results in a force of 75.0 N north.
24 $504\,kg\,m\,s^{-1}$ west **25** 221 Ns backwards
26 1.00 Ns backwards **27** 1.5×10^{-3} Ns
28 $0.558\,m\,s^{-1}$ towards the space station **29** $5.0\,m\,s^{-1}$
30 1.68 N east **31** $10\,kg\,m\,s^{-1}$
32 $10\,kg\,m\,s^{-1}$ **33** $59\,m\,s^{-1}$
34 12.9 N
35 Jordy would have to reduce the change of momentum by moving the bat in the direction of the ball's motion. (A player usually slides one hand along the bat and squares up to face the ball. They can then make a softer contact with the ball.)
36 The team that wins will be the one that pushes the ground away most strongly, so they need to maximise the forces pushing the ground away by angling their push as close to the ground as possible and getting the team to push in unison to maximise the force.
37 His action would change the motion of the spacecraft but the normal reaction from the wall would push the astronaut backwards. He would drift backwards across the spacecraft and would collide with the opposite wall, pushing the spacecraft back in the other direction.
38 Newton's first law states that a moving object stays in motion unless a force acts. This can be seen when an object moves on a surface with minimal friction, e.g. a stone sliding on ice in curling, or a glider sliding on an air track.
39 The basketball lands first and starts to move upwards, colliding with the tennis ball. This transfers momentum to the tennis ball, which has a much smaller mass than the basketball, so it has a much higher upwards velocity and travels much higher.
40 In each collision of the balls momentum is conserved. The first collision transfers momentum through each ball in turn until one is released from the other end with the same momentum as the original ball. If two or more balls are used the same number of balls is released so that the mass remains the same and thereby momentum is conserved.

Chapter 8 Energy

8.1 Work

TY 8.1.1 7400 J
TY 8.1.2 440 J
TY 8.1.3 0.05 J

8.1 KEY QUESTIONS

1 $W = Fs$ **2** joule
3 Although a force is being exerted on the wall, the wall moves through a distance of $s = 0$ m. So $W = F \times 0 = 0$.
4 Hooke's law, $F = -kx$, shows that the force changes with the distance moved, while $W = Fs$ requires the force to remain constant with changing distance.
5 10 000 J **6** 1.6 J
7 18 N **8** 310 J
9 The box does not move, so no work is done.
10 3.6 J **11** $W_A \approx 3.0$ J, $W_B \approx 2.4$ J, $W_C \approx 1.0$ J

8.2 Potential energy

TY 8.2.1 15 J **TY 8.2.2** 32 J

8.2 KEY QUESTIONS

1 $\Delta E_p = mg\Delta h$
2 Gravitational potential energy is measured in relative rather than absolute terms. As long as you consistently use a particular level as 'zero', lifting a mass above it will yield a positive value of gravitational potential energy while lowering a mass below it will yield a negative value.
3 As we are ignoring any form of drag or friction, there will be no force acting in the horizontal direction, so the work done will be given by $W = Fs$, where $F = 0$ so $W = 0$. We are also not doing any work to increase or decrease the object's gravitational potential energy as long as we move only horizontally: $W = \Delta E_p = mg\Delta h$, where $\Delta h = 0$ so $W = 0$.
4 2.5×10^6 J
5 **a** 4.6 J **b** 2.3 J
6 2.36×10^6 J
7 **a** 7.84×10^3 kJ **b** 7.84×10^3 kJ
c The answers are the same. The change in gravitational potential energy is the same as the work done by gravity.

8.3 Kinetic energy

TY 8.3.1 78 J

8.3 KEY QUESTIONS

1 kinetic energy **2** $E_k = \frac{1}{2}mv^2$

3 The relationship between kinetic energy and mass is directly proportional, so doubling the mass doubles the kinetic energy.

4 Kinetic energy increases fourfold.

5 57 000 J **6** 370 kJ **7** 11 m s^{-1}

8 The velocity increases by only 50% but kinetic energy more than doubles.

8.4 Conservation of energy

TY 8.4.1 1.1×10^3 J

TY 8.4.2 20 m s^{-2}

TY 8.4.3 3.9 m s^{-1}

8.4 KEY QUESTIONS

1 Efficiency $(\eta) = \frac{\text{energy output}}{\text{energy input}} \times 100\%$

2 Gravitational potential energy → kinetic energy as it falls → spring potential energy as ball is compressed → kinetic energy and the ball rises to a point lower than the point from which it was dropped → gravitational potential energy; some is lost as sound and heat energy.

3 **a** 26 kJ **b** 18 kJ

4 1.5 m

5 **a** 336 J **b** 29.0 m s^{-1}

6 19 J

7 E_k before = 2.0 J, E_k after = 1.36 J, so the collision is inelastic.

8.5 Power

TY 8.5.1 370 W

TY 8.5.2 20 W

8.5 KEY QUESTIONS

1 Power is the rate at which work is done. It is measured in watts (W).

2 Calculating the gradient (slope) of the energy–time graph at a particular time gives the power being expended.

3 600 J **4** 1.2 m **5** 113 000 W **6** 80.0 kW

7 1800 N **8** 5.1 m s^{-1} **9** 2.0×10^5 J **10** 35 kW

11 1500 N

Chapter 8 review

1 $\Delta E_p = mg\Delta h$, where ΔE_p is the gravitational potential energy and g is the acceleration due to gravity (9.80 m s^{-2}).

2 elastic collision **3** mechanical energy

4 The kinetic energy varies as the square of velocity, so doubling the velocity will quadruple the kinetic energy.

5 160 kW

6 Approximately 31 squares, so 31 J.

7 59 000 J **8** 1164 J **9** 8.16 m **10** 73 N

11 139 J **12** 10.8 m s^{-1} **13** 345 J **14** F_r = 15 kN

15 **a** 96 N **b** 1920 J

16 1562 J

17 **a** 8 J **b** 4.5 J

c Some energy is lost as sound and heat energy from the compression of air in the ball and heat energy in the rubber where it deforms. Less energy is available to be converted back into kinetic energy.

18 17.4 m s^{-1}

19 **a** 8.8 J **b** 8.8 J. **c** 2.2 m s^{-1}

Chapter 9 Properties of waves

9.1 Describing a wave

TY 9.1.1 $A = 2.0 \times 10^{-3}$ m, $\lambda = 3.0 \times 10^{-2}$ m

TY 9.1.2 $A = 2.0 \times 10^{-3}$ m, $T = 2.5 \times 10^{-4}$ s, f = 4000 Hz

TY 9.1.3 f = 8.0 Hz **TY 9.1.4** $T = 5.0 \times 10^{-7}$ s

9.1 KEY QUESTIONS

1 Sound, visible light, radio waves, waves in the string of an instrument, the wave of a hand, the 'Mexican wave' at a stadium and the recently discovered gravitational waves.

2 All waves transfer energy.

3 A single wave or pulse is formed from a single up and down motion; all particles in the medium move up and down once. In a travelling wave, the particles vibrate up and down continuously about an average position (or rest position). This produces a repetitive or periodic pattern (also called a sinusoidal pattern).

4 **a** False

b True: The speaker vibrates back and forth creating a change in air pressure in front of the speaker. The change in pressure allows the air particles to vibrate back and forth transferring the energy from the speaker to Max.

c True. As the air particles transfer the energy, they vibrate back and forth and so there is no net movement of the air.

5 Particle A moves down the page, until it reaches its minimum point, or trough, and then moves up the page through the rest point (dashed line) and back to its position shown. Particle B initially moves upwards to its maximum point (crest), then moves down past the rest position (dashed line) to a maximum position below the dashed line (trough) and then proceeds upwards past the dashed line to its original position.

6 A = 1.0 m, $T = 2.5 \times 10^{-2}$ s, f = 40 Hz

7 **a** True

b False. Sound, ripples on a pond and vibrations in a rope are mechanical waves as they require a medium to transfer energy. Light is the exception, as it does not need a medium to transfer energy and so is not a mechanical wave.

c True

8 λ = 4 cm, A = 1.0 m **9** v = 0.1 m s^{-1} **10** 500 Hz

9.2 Types of waves

TY 9.2.1 $A = 2.0 \times 10^{-1}$ m, λ = 0.66 m, f = 1.7 Hz, T = 0.60 s, v = 1.1 m s^{-1}

TY 9.2.2 $A = 1.0 \times 10^{-1}$ m, λ = 2.7 m, f = 1.3 Hz, T = 0.8 s, v = 3.3 m s^{-1}

TY 9.2.3 P-wave: 7:35:30 a.m., S-wave: 7:36:00 a.m.

Science as a Human Endeavour

1 **a** The ability to detect seismic waves is essential in determining the distance of the seismograph station from the epicentre, and the amount of destructive energy released by the earthquake. This allows stations to release alerts and warnings and inform as to the potential destruction of the surrounding buildings in built-up populated areas.

b The difference in arrival times between the P- and S-waves on a seismogram and knowledge of the differing travelling speeds of these waves allows a distance to be determined to the seismograph station. Three seismograph stations are required to determine the epicentre of the earthquake. The amplitude of the strongest S-wave is used to determine the destructive energy or magnitude of the earthquake.

2 They enhance the ability to detect a tsunami early. Changes in the height of a water column are communicated from a pressure sensor on the floor of the ocean to the surface buoy, and then relayed via satellite to the tsunami-warning centre. Thus, real-time reporting of tsunamis can be achieved before tsunami reaches land.

3 Sea-level variations can be reported in real time, meaning there is no noticeable delay between the change in height of the sea level and the signal being transmitted to the tsunami warning centre. This allows the information to be communicated more quickly to coastal populations, and warm people in possible danger from an oncoming tsunami.

9.2 KEY QUESTIONS

1 **a** False: Longitudinal waves occur when the particles vibrate parallel to the direction of energy transfer of the wave.

b False: Transverse waves occur when the particles vibrate perpendicular to the direction of energy transfer of the wave.

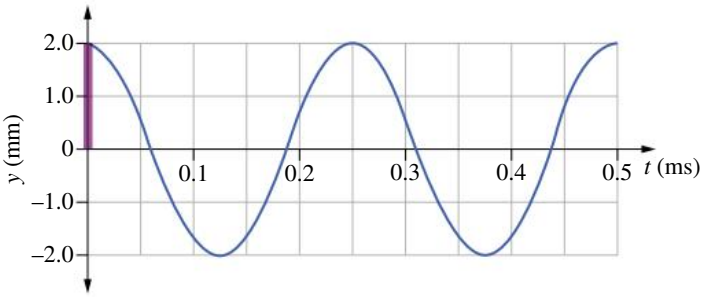
c True
d False: The vibrating string of a guitar is an example of a transverse wave.

2 **a** False: The wavefronts could also be drawn from troughs of a transverse wave, or any other points on the wave that are in phase.
b False: On a longitudinal slinky wave, the compressions are regions where the slinky hoops are compressed close together.
c True
d False: A ray is drawn in the direction of the net energy transfer of the wave.
e True

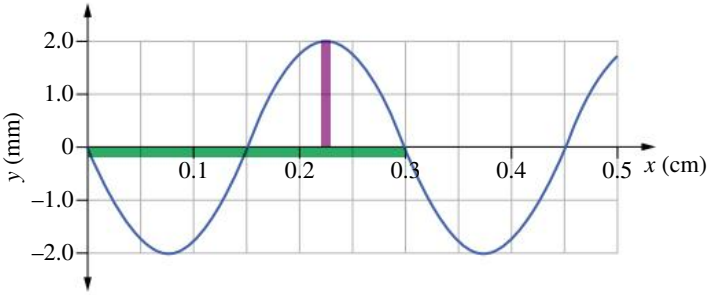
3 **a** transverse **b** longitudinal **c** transverse
d longitudinal **e** longitudinal

4 These two graphs are examples. They will not necessarily be identical to your graphs.

Graph 1



Graph 2



Both graphs are identical representations for transverse and longitudinal waves.

- The amplitude **(purple line)** of each graph refers to either up and down oscillations (for a transverse wave) or back and forth oscillations (for a longitudinal wave).
- The distance between crests on a displacement–distance graph is the wavelength **(green line)**.
- The distance between crests on a displacement–time graph is the period.
- The key difference is that displacement–time shows how one particle moves during the oscillations, and the bottom graph (displacement–distance) shows the waveform at an instant in time.

5 $A = 4.0 \times 10^{-2}$ m, $\lambda = 0.4$ m

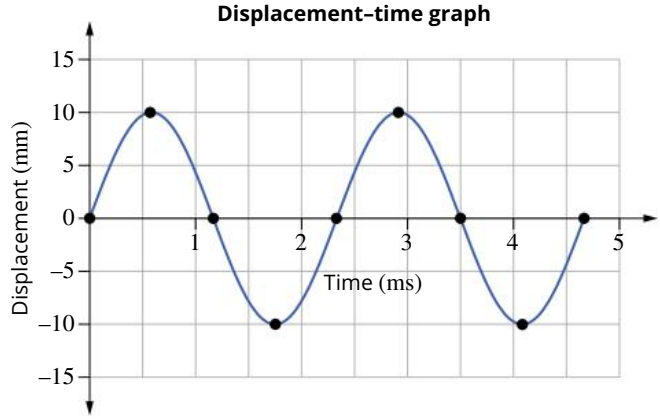
6 $A = 4.0 \times 10^{-2}$ m, $T = 3.3 \times 10^{-3}$ s, $f = 300$ Hz

7

P-waves	S-waves
longitudinal waves	transverse waves
travel at speeds of 1.5 to 8.0 km s^{-1}	travel at almost half the speed of P-waves
first to be detected by seismic stations	second to be detected by seismic stations
travel through the Earth's core	do not travel through liquids

8 **a** $\lambda = 0.77$ m **b** $T = 2.3 \times 10^{-3}$ s

Displacement–time graph



c The sound wave is a longitudinal wave. The air particles are vibrating back and forth with a displacement from the average position of 10 mm with a period $T = 0.0023$ s or 2.3 ms.

9.3 Reflection

TY 9.3.1 **a** The reflected pulse will be inverted.
b The reflected pulse will not be inverted.

TY 9.3.2 $\theta_i = p$, $\theta_r = q$; $p = q$; angle BON = angle $B'ON$

TY 9.3.3 A. Stepping closer to the mirror increases the angle of incidence and (due to the law of reflection) also the angle of reflection. So the reflected rays appear to originate from an image that is closer to the mirror and behind it.

TY 9.3.4 42.5 m

9.3 KEY QUESTIONS

1 The wave will be reflected from the fixed end with a phase change of 180° (in other words it will be inverted).

2 The energy of the pulse is partially transmitted, partially absorbed by the medium, and partially reflected.

3 **a** False: Only pulses reflecting off a fixed boundary condition will be inverted, or have a phase change of 180°.
b True
c False: Some of the pulse is transmitted through the lighter string and a smaller portion of the pulse is reflected in the heavier string.
d True

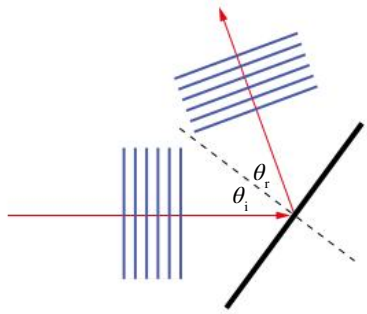
4 Amplitude is changed, frequency is not.

5 $\theta_r = \theta_i = 52°$

6 The light rays travelling from the mountain strike the surface of the flat lake and are reflected upwards towards the observer. The inverted image of the mountain below the lake's surface is seen because these reflected rays appear to originate from below the surface of the lake.

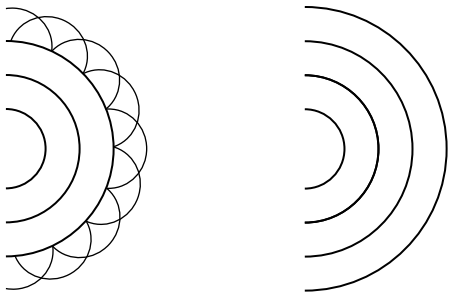
7 Depth of the lake floor = 2.8 km, but this value is unlikely to be correct if the deepest known lake is approximately 1642 m deep. This result would suggest more data (e.g. water temperature) needs to be collected.

8



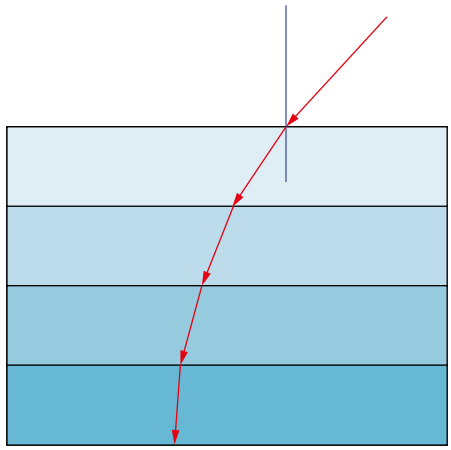
9.4 Refraction

TY 9.4.1



TY 9.4.2 **a** angle of incidence = θ_1, angle of refraction = θ_2
b The wave refracts (bends) due to the wave having different velocities in the different mediums.
c Wave velocity is less in medium 2.

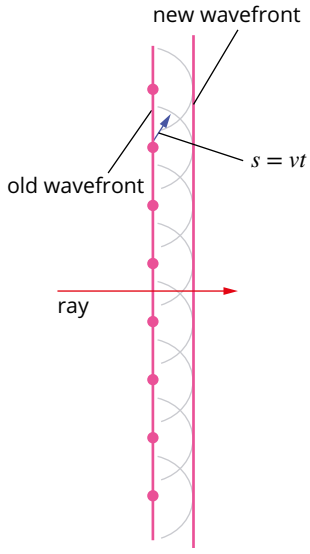
TY 9.4.3 The effect of the layers of Earth's atmosphere is to bend the light ray as it travels downwards to the observer.



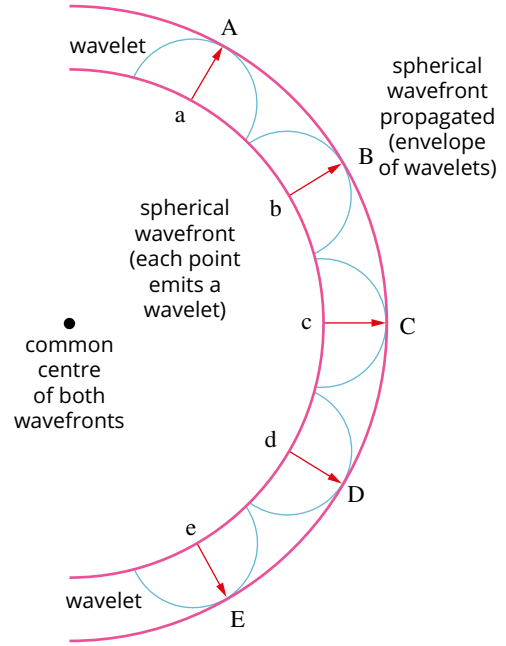
9.4 KEY QUESTIONS

1 Waves are refracted when they travel from one medium into another and as a result their velocity changes. The direction of propagation of the wave changes, and they either refract towards the normal (if they slow down) or refract away from the normal (if they speed up).

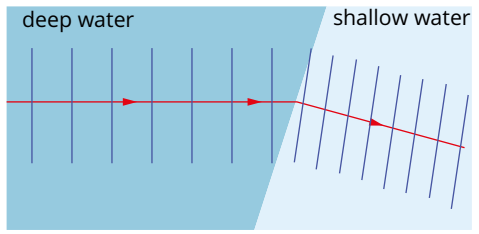
2 A new wavefront of a plane wave after one period. The new wavefront is a tangent to the envelope of secondary wavelets.



3 A single circular wave propagating from a common centre. The letters a–e represent particles on the original wavefront propagating to the new positions represented by A–E.

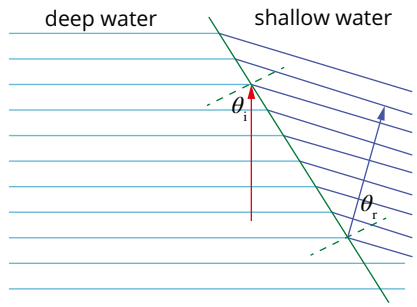


4



5 A

6 Note the direction of the wavefronts, the ray, the angle of incidence θ_i and the angle of refraction θ_r. The water waves slow down and bunch up in the shallow water.

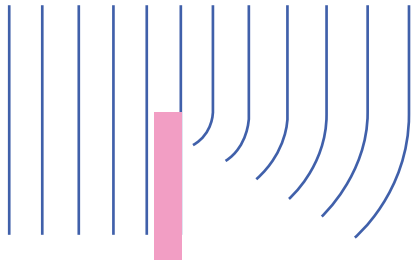


7 **a** True
b True
c False—The statement should say that this occurs only when a temperature inversion occurs in the atmosphere, meaning that the higher part of the sound wave travels through warmer air and faster than the lower part of the sound wave travelling through cooler air. This causes the sound waves to bend back down or refract towards Earth's surface.
d False—The lower part of the Sun being closer to the horizon is refracted more than the higher part of the Sun further from the horizon. The observed effect is that the bottom of the Sun is lifted up more than the top of the Sun.
e True

9.5 Diffraction

TY 9.5.1 The doorway is about 1.0 m wide and the average wavelength of the produced sound waves is 17 cm (0.17 m). The most likely cause is reflection of sound waves from other surfaces such as the walls of the hallway and back to the observer.

TY 9.5.2



9.5 KEY QUESTIONS

1 When a plane (straight) wave passes through a narrow opening, it bends around the object. Waves will also bend as they travel around obstacles. This kind of 'bending' phenomenon is known as diffraction. Examples include:
- water waves passing around a barrier such as a small island
- water waves bending in a bay before reflecting off the beach
- light waves diffracting with artificially constructed materials such as CDs or commercially produced diffraction gratings.
- red laser light shone onto a strand of human hair.

2 If the wavelength is a similar size or larger than the width of a gap ($\lambda \geq w$), then significant diffraction occurs and the waves emerge as circular waves.

If the wavelength is smaller than the width of a gap ($\lambda < w$), then only partial diffraction of the wavefront may occur. This occurs mostly around the edges.

3 **a** False. The wavelength range of visible light waves is from about 400 nm to 700 nm. The opening width needs to be of the order of 10^{-4} mm or smaller.
b True
c False. The opening with a width of 1.3 m or smaller would cause this sound wave to diffract.
d False. Although red light does have a longer wavelength compared to violet light, the diffraction opening widths for red light are also larger than for violet light.
e False. Although waves will diffract if the wavelength is of the order (close to) the opening width ($\lambda \approx w$), waves will also diffract if the opening width is smaller than the wavelength of the wave ($w < \lambda$).

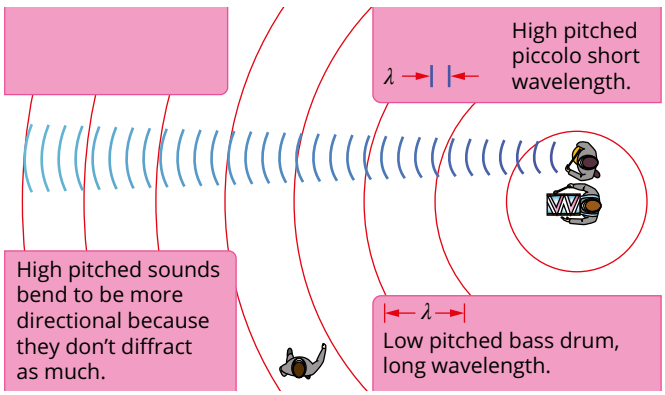
4 $w = 0.0007$ mm

5 Optical instruments cannot create images of objects that are smaller than the wavelength of the light they use; otherwise, diffraction effects are too significant. Any objects smaller than the wavelength of visible light (400 nm to 700 nm) cannot be imaged with an optical instrument.

For optical telescopes, atmospheric distortion has a much larger effect than the limits of wave diffraction.

6 λ of C_4 note = 1.3 m, which is only slightly greater than the doorway (1 m), so it is possible for the listener to hear this note due to diffraction.

7 The long-wavelength sounds of the bass drum will diffract around the corner more than the directional short-wavelength sounds of the higher-pitched instruments.

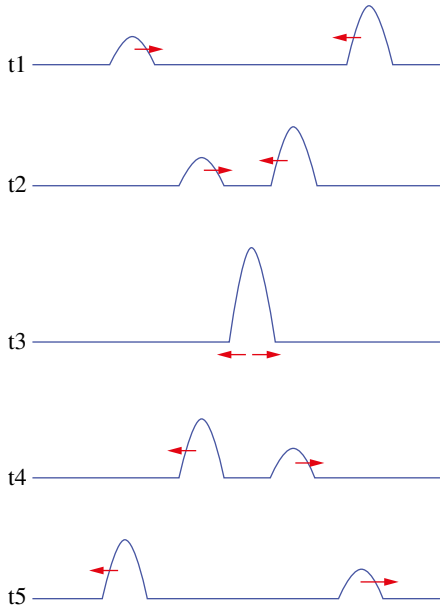


8 Refraction is the change in direction of a wave due to the change in the medium the wave is travelling through. Wavelength and velocity of the wave changes, but frequency does not.

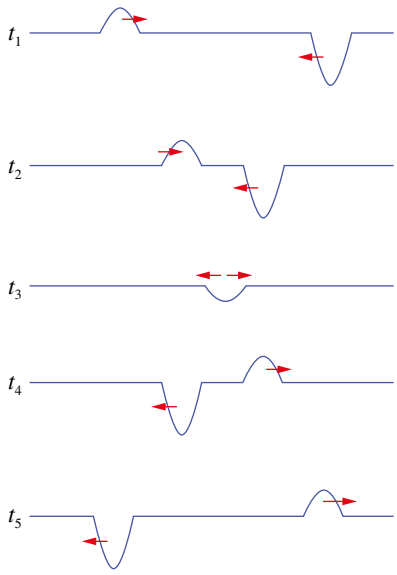
Diffraction is the bending of waves around an obstacle or through a narrow opening. The conditions for diffraction through an opening to occur involve comparing the width of the opening, w, to the wavelength of the wave, λ.

9.6 Interference and superposition

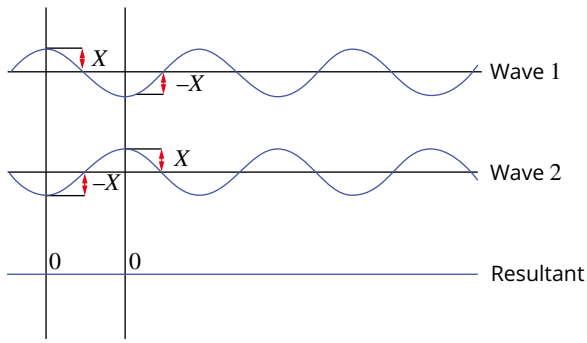
TY 9.6.1 **a**



b



TY 9.6.2



TY 9.6.3 **a** $d_2 = 3.5\,\text{m}$ **b** $d_1 = 0.5\lambda$, $d_2 = 3.5\lambda$
c Path difference $= 3.0\lambda$
d This is complete constructive interference as the path difference is 3λ.

They would hear a noticeable increase in loudness of sound.

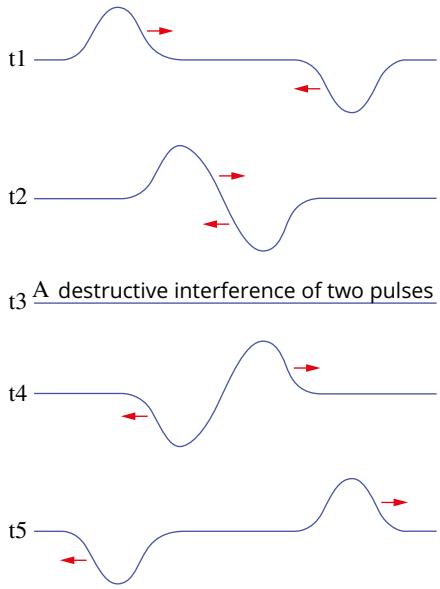
9.6 KEY QUESTIONS

1 The displacement of the resultant wave is the vector sum of the individual wave displacements.

2 Complete destructive interference occurs when two identical waves meet with a phase difference of 180°, or when two waves have a path difference of $(n + \frac{1}{2})\lambda$.
Complete constructive interference occurs when two identical waves meet with a phase difference of 0° or 360°, or when the two waves have a path difference of $n\lambda$.

3 **a** something between constructive and destructive interference
b destructive interference
c something between constructive and destructive interference
d constructive interference

4



5 **a** Constructive interference: G, I, K, M, O
b Destructive interference: F, H, J, L, N, P

6 **a** True
b False. If two waves are in phase at a point then constructive interference occurs, and if the two waves are out of phase at a point then destructive interference occurs.
c False. The principle of superposition occurs for all waves, which includes both transverse and longitudinal (or compression) waves.
d True

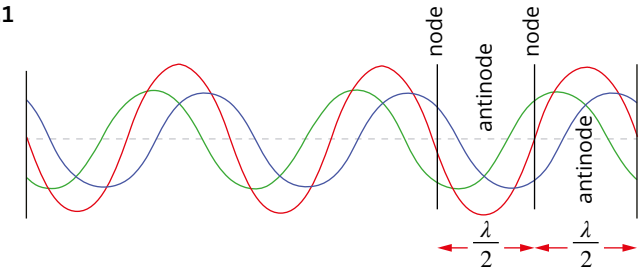
7 **a** $\lambda = 0.5\,\text{m}$
b $2A$
c Constructive interference would occur at any distance when the path difference is $n\lambda$. Destructive interference would occur at any distance when the path difference is $(n + \frac{1}{2})\lambda$.

8 The path difference $= \frac{\lambda}{2}$. The two waves will combine out of phase (phase difference = 180°) and interfere destructively.

9 **a** $\lambda = 0.40\,\text{m}$
b path difference $= 0.4\,\text{m}$
For constructive interference the path difference $= (n)\lambda = 1.0\lambda$. So the listener would notice constructive interference at this point.

9.7 Standing waves

TY 9.7.1



TY 9.7.2 **a** There are antinodes at the openings of the instrument, which indicates that this is an air-displacement standing wave pattern.
b $\lambda = 40.0\,\text{cm}$

WAVELENGTHS OF STANDING WAVES

9.7 KEY QUESTIONS

1 Waves travelling down the rope will be reflected back from the fixed end with a 180° phase change. These reflected waves will interfere with those moving down the rope (superposition). Shaking the rope at just the right frequency will create a new wave that constructively interferes with the reflection in such a way that the two superimposed waves create a single, larger-amplitude standing wave.

2 In summary, nodes occur at the closed end, and antinodes occur at the open end of an air column.

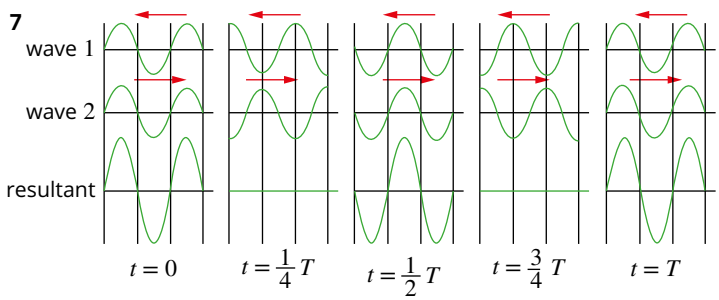
3 A standing wave doesn't travel along the rope. The rope simply seems to oscillate up and down with a fixed pattern of nodes and antinodes. Except at the nodes where the amplitude is zero, the wave seems to be just 'flipping' up and down in a fixed pattern. This is why a standing wave does not transfer any energy and thus 'stands still' while the rope oscillates up and down.

4 A standing or stationary wave occurs as a result of the interference between two waves of equal amplitude and frequency travelling in opposite directions. The resultant standing wave formed has points that oscillate with maximum displacement, the antinodes, and points that oscillate with zero displacement, the nodes. The antinodes are formed by the constructive interference between the two opposing travelling waves, hence producing a larger amplitude. The nodes are formed by the destructive interference between the two opposing travelling waves, hence producing a point that does not oscillate.

5 For the resultant standing wave pattern produced at $t = 0\,\text{s}$, the larger resultant wave amplitude is due to constructive interference between wave 1 and wave 2.
Other time intervals at which constructive interference occurs is at $t = \frac{T}{2}$ and $t = T$.
For the standing wave pattern produced at $t = \frac{T}{4}$ and $t = \frac{3T}{4}$, destructive interference occurs between wave 1 and wave 2.

6 Travelling waves transfer energy from one point to another; all parts of the wave have a constant amplitude.
Standing waves do not transfer energy from one point to another point; no parts of the wave have a constant amplitude.

7



Chapter 9 review

1 A travelling wave (also called a progressive wave) travels out from the source in a regular, repetitive or periodic pattern and transfers energy from one point to another.

A pulse is a single disturbance that travels through a medium.

2 Mechanical waves need a medium for the transfer of energy. As light waves do not need a medium to transfer energy, they are not mechanical waves. Sound waves and water waves both require a medium.

3 **a** It will undergo a 180° phase change.
b It will undergo no phase change.

4 The wave phenomena is called refraction, as the light slows down and bends in the glass prism, and speeds back up in the air and thus bends again. There is also some reflection of the light at both boundaries of the prism, as indicated by the paler beams. The beam reflected from the glass–air boundary is also refracted as it leaves the prism.

5 The water surface particles will oscillate vertically up and down while the ripples propagate horizontally along the ponds surface.

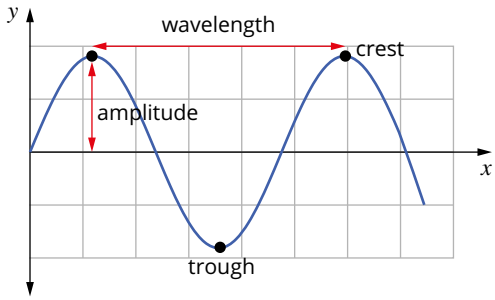
6 They both involve the transfer of energy as the particles oscillate through an equilibrium position. There is no net movement of matter; there is net movement of energy.

In a transverse wave, the particles vibrate perpendicularly to the movement of energy transfer (the wave movement). In a longitudinal wave, the particles vibrate parallel to the movement of energy transfer (the wave movement).

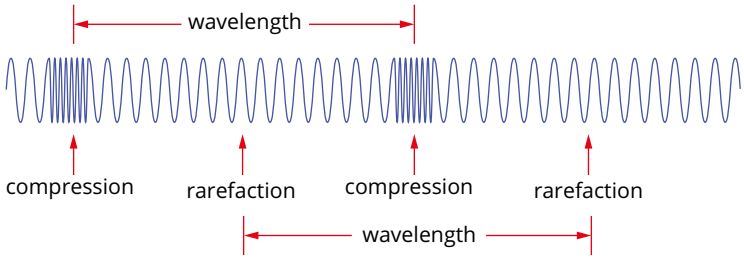
7

Transverse waves	Longitudinal waves
light waves	sound waves
seismic S-waves	seismic P-waves
vibration of a stringed instrument	
ripples in a pond	
tsunami waves	

8 **a** Transverse wave



b Longitudinal wave



9 Amplitude and the period can be determined from the displacement–time graph: $A = 10\,\text{cm}$, $T = 2$ seconds.

10 Amplitude and the wavelength can be determined from the displacement–position graph: $A = 5\,\text{cm}$, $\lambda = 40\,\text{cm}$.

11 **a** Transmitted: The room inside the house is illuminated.
b Reflected: You can see some of the sunlight from outside the house.
c Absorbed: The window glass would start to warm up.

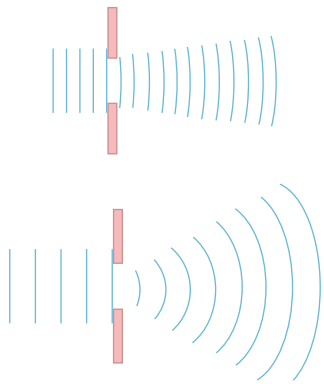
12 Light emanating from an object and reflecting off the surface of a mirror, reflects at the same angle as the angle at which the light was incident. The reflected light rays are seen by the observer as coming from a position behind the mirror. Hence the image seen is at an apparent position the same distance from the mirror as the real distance from the mirror of the object.

13 **a** The light ray does not refract as the angle of incidence is 0°. The wave model shows, using Huygens' principle, that the secondary wavelets do not travel as far in the glass medium in the same time interval (period). As the wavefronts are parallel with the glass boundary there is no change in direction but a bunching up of wavefronts in the glass.
b The waves slows down in glass and its wavelength also decreases, but the frequency does not change. Using the wave equation, the frequency is $f = \frac{v}{\lambda}$. So a decrease in wave speed, v, and a decrease in wavelength, λ, means the frequency is unchanged.

14 The light ray slows down as it enters the glass prism. An application of Huygens' principle states that the secondary wavelets do not travel as far in the glass as they do in the air in the same time interval. The light ray thus bends towards the imaginary normal line.

15 C

16 The shorter wavelength shows a small diffraction effect and the larger wavelength shows significant diffraction.



17 The principle of superposition states that the resultant wave patterns from two overlapping waves is the vector sum of the individual displacements of the waves.

The resultant wave has an amplitude greater than that of each individual wave. This is constructive interference.

A 180° shift in phase of wave A either to the right or left, would produce a resultant wave pattern with an amplitude less than the individual amplitudes of wave A or wave B; this would be destructive interference.

18 Particle B is moving down the page, as the crest has passed this location. It is moving towards the equilibrium position and will continue through it.

Particle D is moving up the page, as the wave is moving to the right.

Particle F is moving up the page towards the equilibrium position.

Particle K has stopped shortly before moving down the page towards the equilibrium position.

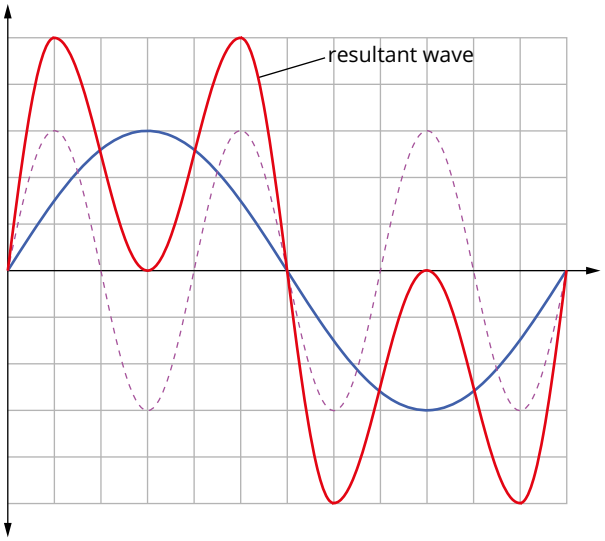
19 $2.5\,\text{m s}^{-1}$

20 **a** $\lambda = 4.29\,\text{m}$
b $\lambda = 0.97\,\text{m}$

21 **a** $T = 15\,\text{s}$
b $f = 6.7 \times 10^{-2}\,\text{Hz}$

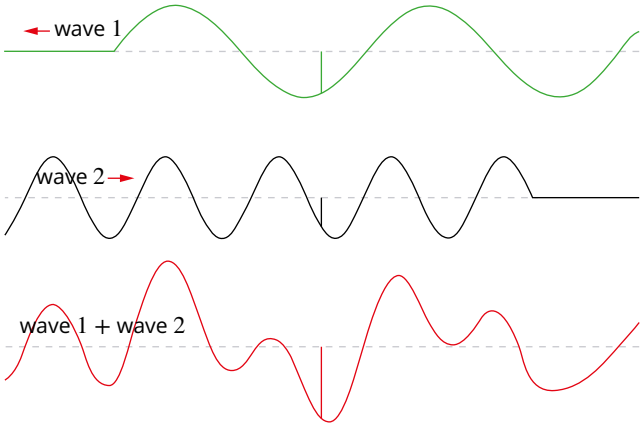
22 D

23



24 S_1 to A: $d_1 = 5\lambda$, S_2 to A: $d_2 = 6\lambda$, Path difference = λ
Constructive interference occurs at position A. This is called an antinodal point.

26 The resultant wave is shown in red.



27 λ = path difference = 0.4 m
This is a point of constructive interference between the two sound wave signals from speaker 1 and from speaker 2. The observer will hear a loud sound.

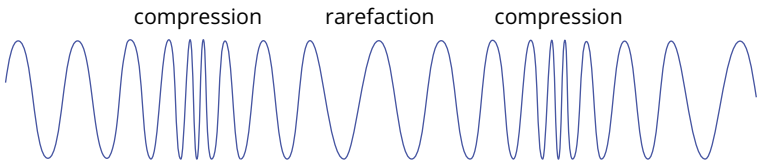
Chapter 10 Sound

10.1 Sound waves

TY 10.1.1 1220 Hz

10.1 KEY QUESTIONS

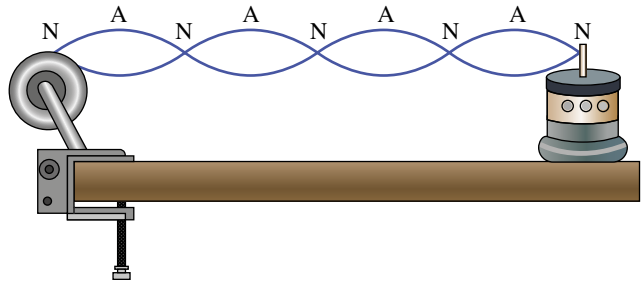
1



2 B
3 It is the fundamental frequency or first harmonic.
4 Sound is a mechanical wave so requires a material to be present to transmit the energy.
5 The speed of sound is higher in helium. Your vocal cords produce certain wavelengths and these wavelengths in helium produce higher frequencies, making your voice sound higher.
6 By blowing harder you get higher order harmonics, which have higher frequencies.
7 $\lambda = 12.8\,\text{m}$
8 The speed of sound in water at 20°C is $1483\,\text{m s}^{-1}$. The speed of sound in air at 20°C is $343\,\text{m s}^{-1}$. So the speed of sound is $1140\,\text{m s}^{-1}$ faster in water than in air.
9 Mechanical waves move energy via the interaction of particles. The molecules in a solid are closer together than those in a gas. A smaller movement is needed to transfer energy and, hence, the energy of the wave is usually transferred more quickly in a solid than in other states of matter.
10 $T = 0.002\,\text{s}$

10.2 Strings

TY 10.2.1 $\lambda = 0.5\,\text{m}$



TY 10.2.2 **a** $L = 0.25\,\text{m}$ **b** $\lambda = 0.17\,\text{m}$
TY 10.2.3 **a** $L = 0.020\,\text{m}$ **b** $\lambda = 0.016\,\text{m}$

10.2 KEY QUESTIONS

1 No, it is only the pattern made by the amplitude along the rope that stays still at the nodes. The rope is still moving, especially at the antinodes.
2 A transverse wave moving along a slinky spring is reflected from a fixed end. The interference that occurs during the superposition of this reflected wave and the original wave creates a standing wave. This standing wave consists of locations called nodes, where the movement of the spring is cancelled out, and antinodes where maximum movement of the spring occurs.
3 This wave has a frequency five times the fundamental frequency, which means that it will have a wavelength $\frac{1}{5}$ of the fundamental wavelength, due to the inverse relationship between frequency and wavelength.
4 $L = 1.5\,\text{m}$
5 $\lambda = 1.6\,\text{m}$
6 The wavelength of the standing wave in the diagram is 5.0 m. The wavelength of the fundamental frequency is twice the length of the string. Therefore, a string length of 2.5 m would produce a standing wave with wavelength 5.0 m.
7 $\lambda = 0.74\,\text{m}$
8 $f = 300\,\text{Hz}$
9 $f = 600\,\text{Hz}$
10 $f = 900\,\text{Hz}$

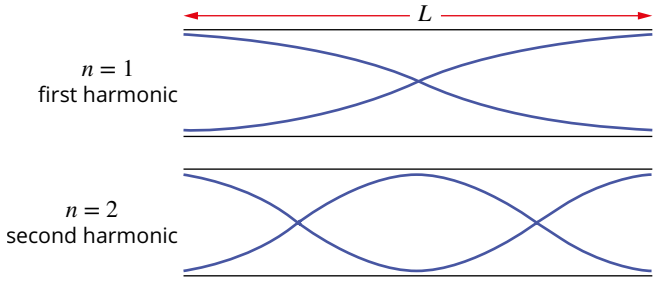
10.3 Pipes

TY 10.3.1 **a** $L = 0.19\,\text{m}$ **b** $\lambda = 0.095\,\text{m}$
TY 10.3.2 **a** $L = 2.77\,\text{m}$ **b** $\lambda = 3.69\,\text{m}$

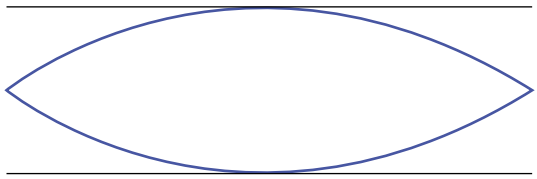
10.3 KEY QUESTIONS

1 A string with two fixed ends has a node at each end.

2 The ends are open so they will always be antinodes.



3



4 In a stringed instruments, the strings need tension to create a sound. A string with a free end is not able to create tension.

5 $L = 0.159\,\text{m}$ **6** $f = 730\,\text{Hz}$ **7** $f_3 = 368\,\text{Hz}$

8 $L = 0.43\,\text{m}$ **9** $f = 40.5\,\text{Hz}$, $T = 0.025\,\text{s}$

10.4 Resonance and natural frequency

Science as a Human Endeavour

1 The walls would be coated in soft materials (foam or fabric) and non-flat surfaces (such as pyramids of foam).

2 These walls are to minimise the transmission of road noise to the areas near the road. They are often built out of heavy materials that will reflect some of the noise back and dampen the sound waves that travel through the wall.

3 Examples are:
- Suspension acts as a vibration isolation.
- Choice of tyres can affect road noise (also vibration isolation as well as vibration dampening).
- Mass of the car (like mass of building materials, higher density absorbs more sound).
- Insulation.
- The design of the firewall between the engine and the cabin.
- Aerodynamics of the shell of the car.

10.4 KEY QUESTIONS

1 Resonance occurs when an object is exposed to vibrations at a frequency equal to its resonant frequency. Resonance occurs when a weak vibration from one object causes a strong vibration in another.

2 An object subjected to forces varying with its natural oscillating frequency will oscillate with increasing amplitude. This could continue until the structure can no longer withstand the internal forces and fails.

3 The increasing amplitude of the swing is due to your motion driving the motion of the swing at its natural frequency.

4 Normal walking results in a frequency of 1 Hz or 1 cycle per second, i.e. two steps per second. This frequency may result in an increase in the amplitude of oscillation of the bridge over time, which could damage the structure.

Chapter 10 review

1 **C**

2 B

3 True

4 D

5 C

6 B

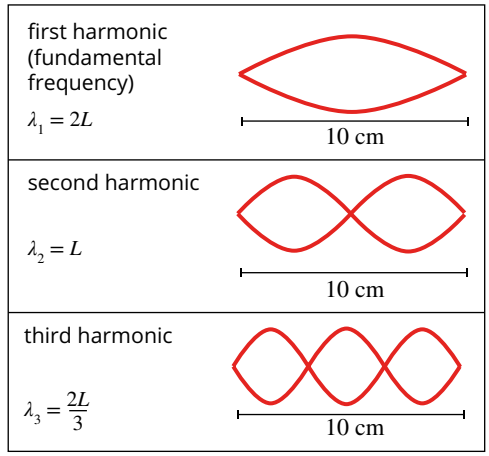
7 B

8 B

9 The speed of sound in a medium increases as the temperature increases (speed of sound and temperature are proportional).

10 Different frequencies produced by a given length of string of pipe. Frequencies of harmonics, where $n > 1$, are multiples of the fundamental frequency for that pipe or string.

11



12 The different sizes provide different lengths of string or pipe and so produce different ranges of frequencies.

13 All objects/materials have a resonant frequency. If the object is made to vibrate at this frequency, the amplitude of the object's vibrations will increase with time. If a building or bridge was subjected to wind that made it vibrate at its natural frequency, this vibration may increase in amplitude so much that the structure is damaged or collapses.

14 $\lambda = 0.044\,\text{m}$

15 $\lambda = 5.0\,\text{m}$

16 $\lambda = 1.1\,\text{m}$

17 $\lambda = 0.144\,\text{m}$

18 **a** $\lambda = 0.64\,\text{m}$
b $\lambda = 0.32\,\text{m}$

19 $\lambda = 0.30\,\text{m}$

20 $f = 100\,\text{Hz}$

21 $f = 300\,\text{Hz}$

22 $t = 1.08\,\text{s}$

23 **a** $f = 780\,\text{Hz}$
b $f = 752\,\text{Hz}$
c In a temperature difference of 20°C (20 K) the frequency of the same note has changed by 28 Hz. Temperature changes won't be so marked, but this means the instrument's frequency changes significantly as the instrument changes temperature. If the instrument is tuned while it is still cold, it will be out of tune (at a different frequency) with the other instruments as it warms.

24 **a** $\lambda = 0.60\,\text{m}$ **b** 7.5 cm of water

25 $v = 336\,\text{m s}^{-1}$

26 **a** $\lambda_2 = 0.15\,\text{m}$
b $\lambda_2 = \frac{1}{2}\lambda_1$
c The relationship (from part b) does not hold for other harmonics.

27 **a** $L = 0.40\,\text{m}$ **b** $L = 0.20\,\text{m}$

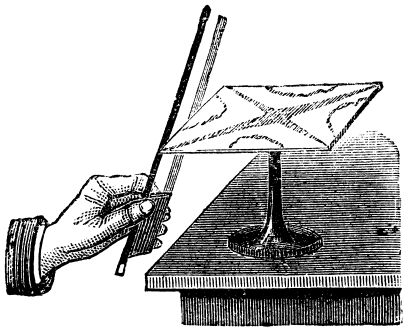
28 $f_2 = 0.50\,\text{Hz}$

29 $d = 0.091\,\text{m}$ or 9.1 cm

30 Students' own answers.

31 One way to do this in the laboratory is to take a tube and place it with one end closed by a wall or similar. Set up a microphone with a data logger and then create a short, sharp sound at the open end of the tube. The microphone and data logger will record the original sound and its echo and so you can determine the time between these two events. Using twice the length of the pipe, you can now calculate the speed of sound.

32 One version of a Chladni plate. They are often now created using loudspeakers as the source of vibration. The sand or similar medium maps the vibrations in the plate.



Chapter 11 Light

11.1 Light as a wave

Science as a Human Endeavour

1 $3 \times 10^8\,m\,s^{-1}$ or $2.997\,924\,58 \times 10^8\,m\,s^{-1}$
2 Bradley used calculations of the apparent change in position of stars due to Earth's orbit around the Sun.
3 The aether was a theoretical substance required for light to travel through if light was a mechanical wave.
4 The beam splitter produces two perpendicular rays of light from the one source and interference between the two would be evidence of the aether.
5 Mechanical waves need a medium in which to travel. Proving that a theoretical aether didn't exist established that light was not a mechanical wave.

11.1 KEY QUESTIONS

1 Huygens proposed a wave model for light, based on the propagation of wavelets.
2 reflection, refraction, transverse (straight-line) propagation
3 light rays
4 refraction
5 More particles or a bigger bundle of rays would produce a brighter light. A wave would transfer more energy through a larger amplitude.
6 For light to refract in the direction observed, it must slow down in a more optically dense medium. A particle model predicts that it would speed up.
7 Huygens' wavelets explained the transverse propagation of light as rays.
8

Supports particle model	Supports wave model
transverse propagation	transverse propagation
reflection	reflection
refraction: speeds up in a denser medium	refraction: slows down in a denser medium
doesn't require a medium to propagate	doesn't require a medium to propagate
	diffraction
	interference

11.2 The electromagnetic spectrum

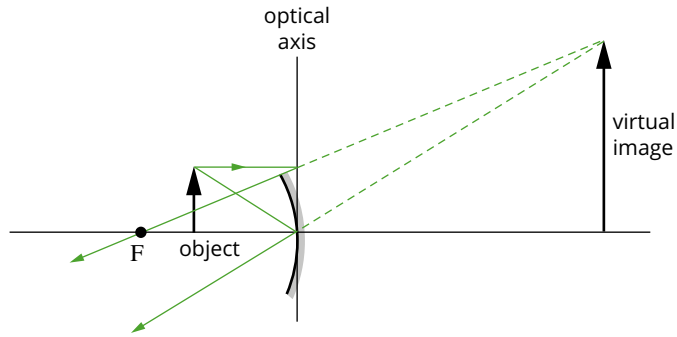
TY 11.2.1 $f = 610 \times 10^{12}$ Hz, which is in visible section of spectrum.

11.2 KEY QUESTIONS

1 List any three: radio waves, microwaves, infrared waves, visible light, ultraviolet waves, X-ray waves, gamma waves
2 They all travel at the speed of light ($3 \times 10^8\,m\,s^{-1}$), do not require a medium in which to travel, and are produced by accelerating charges creating magnetic and electric fields.
3 400×10^{12} Hz to 800×10^{12} Hz
4 radio waves, microwaves, infrared waves, visible light, ultraviolet waves, X-ray waves, gamma waves
5 The lower energy is associated with the longer wavelength. The 780 nm source would hence have the lower energy.
6 X-rays are used in medical diagnosis because they are high-energy EMR, capable of penetrating body tissue. Other answers should emphasise the high energy of X-rays.
7 Microwaves have a higher frequency and shorter wavelength than radio waves, so they have the higher energy.
8 **a** $\lambda = 1.0$ cm
b $\lambda = 300$ mm
9 $f = 3.0 \times 10^{12}$ to 4.3×10^{14} Hz

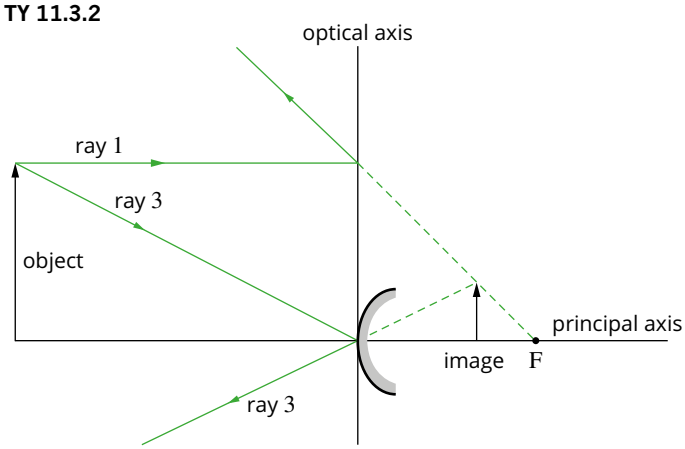
11.3 Reflection of light

TY 11.3.1 **a**



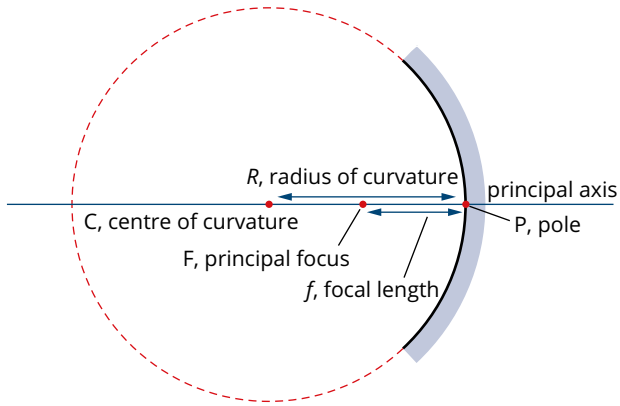
b The image will be virtual, upright and magnified.

TY 11.3.2



11.3 KEY QUESTIONS

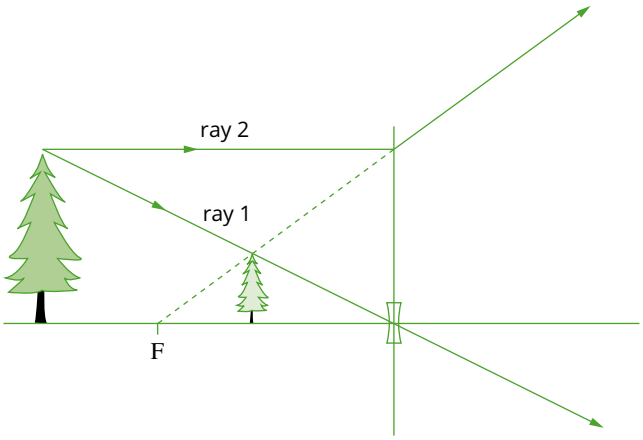
1 An image in a plane mirror is always virtual, upright and the same size as the object.
2 The mirrors are a part of a sphere. The radius of curvature is the radius of this sphere.
3



4 A convex mirror would be used if a wide field of view is required. Both mirrors produce upright and virtual images. The image in the convex mirror will always be a diminished image ($M < 1$).
5 Reflected rays always diverge in a convex mirror.
6 Nature: real or virtual
Orientation: upright or inverted
Position: depends upon position of the object relative to the mirror and the mirrors focal length
Size: magnified or reduced
7 Both mirrors are curved, usually spherical.
Concave mirrors are like the inside of a spoon (e.g. make-up mirrors).
Convex mirrors are like the back of a spoon (e.g. security mirrors).
8 The image is between the focal point and the pole of the mirror so it will be virtual, upright and enlarged.
9 **a** The image will be upright, virtual and diminished.
b As the object gets closer to the mirror, its image increases in size, but it will never be the same size as the object. So at 15 m the image will be larger than at 30 m but it is still upright, virtual and diminished.

1.4 Refraction of light and image formation with lenses

TY 11.4.1 $n = 1.52$
TY 11.4.2 $1.62 \times 10^8\,\text{m s}^{-1}$
TY 11.4.3 28.2°
TY 11.4.4 24.4°
TY 11.4.5 The image is virtual, upright and diminished.

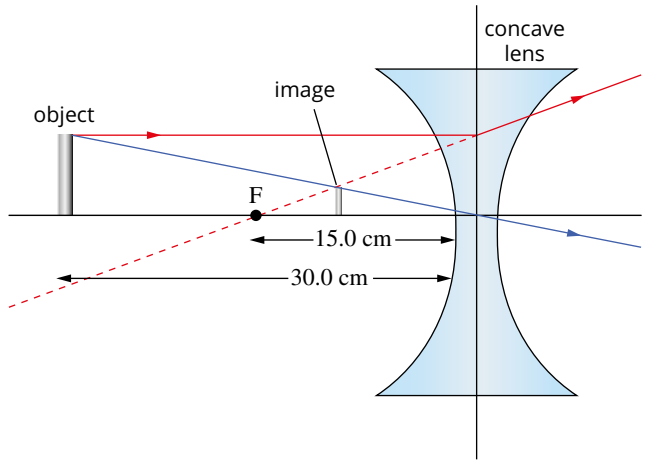


11.4 KEY QUESTIONS

1

boundary between two media	D
normal	B
incident ray	A
refracted ray	E
reflected ray	C

2 The ray will bend towards the normal.
3 The parallel rays of light will converge.
4 The ray travels in a straight line and passes through the lens undeviated.
5 A, C, as the ray diffracts towards the normal.
6 B, D **7** C
8 A
9 As the direction of travel of the wavefront is from the normal, medium D must be a less dense medium than glass, and so the speed of light increases.
10 Rays must intersect to form a real image. A single concave lens causes light to diverge, so a virtual, reduced image is always formed.
11 **a** lens B **b** lens A
12 $n = 1.50$ **13** $n_2 = 2.4$ **14** 35° **15** 24.4°
16 The image is virtual, upright and reduced.



17 The focal length will increase because the relative refractive index between water and the lens is less than that for air to lens.

11.5 Interference and diffraction of light

11.5 KEY QUESTIONS

1 It is a result of diffraction of the incident light on the etched surface.
2 A crest meeting a crest or a trough meeting a trough.
3 Increasing the wavelength (decreasing the frequency), increasing the distance, L, and decreasing the distance between the slits would all increase the fringe spacing.
4 The spacing of the interference fringes is decreased.
5 When there are two slits, the fringes are produced by interference. The colours are seen because of the different wavelengths included in white light.
6 $\lambda \geq w$
7 Laser light is better. It meets the special conditions of being monochromatic, and producing a narrow beam with the waves from the incoming beam in phase. Monochromatic light will result in constructive and destructive interference effects in a regular pattern of bright and dark fringes.
8 **a** The fringe spacing decreases.
b Using light of a longer wavelength and lower frequency can increase the fringe spacing of an interference pattern. The frequency of the new light was decreased.
9 Significant diffraction is observed when $\lambda \geq w$. The gap must be less than or equal to the wavelength of yellow light, which is 580 nm. So the maximum width of the gap is approximately 580 nm

11.6 Intensity

TY 11.6.1 $0.40\,\text{W m}^{-2}$
TY 11.6.2 $I_2 = 25I_1$, i.e. 25 times brighter at new position

11.6 KEY QUESTIONS

1 W m^{-2}
2 Wave sources such as sound are observed to follow this same relationship. Waves spread in two dimensions as they travel from the source, hence $I \propto \frac{1}{r^2}$. Light follows the same relationship, which provides further evidence of the wave nature of light.
3 $\frac{I_1}{I_0} = \frac{1}{25}$
4 $\frac{I_1}{I_0} = \frac{1}{100}$
5 The intensity seen by observer B will be $\frac{1}{9}$ that seen by observer A.
6 Intensity reduces to 0.16 times that at the source.

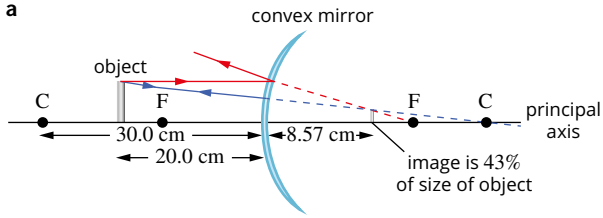
11.7 Polarisation

11.7 KEY QUESTIONS

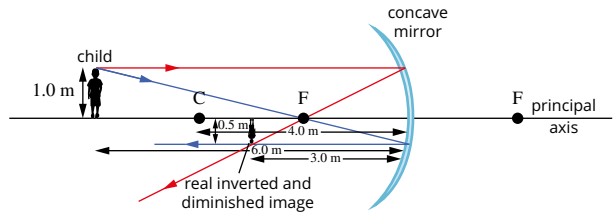
1 About half of the light from any light source will be vertically polarised, the other half will be horizontally polarised.
2 100%: The light incident on the second polaroid will be polarised by the first at angle of 90° and will be completely blocked by the second.
3 There would be very little change. If the second polaroid was rotated 180°, then it would be aligned along the same plane as the first. A small amount would be absorbed as the light passes through the material.
4 Plane polarised means aligned to one plane.
5 Only light that has its electric field aligned with the filter will be able to pass through, therefore polarised light emerges from the filter.
6 Polarisation only affects transverse waves. If light only had particle-like properties, it wouldn't be affected.
7 The first filter reduces the intensity by half. The second filter will reduce the intensity further, but will not completely block the light.
8 Violet light corresponds to very short wavelengths. These short wavelengths may be able to pass through the width of the polarising slits without being polarised.

Chapter 11 review

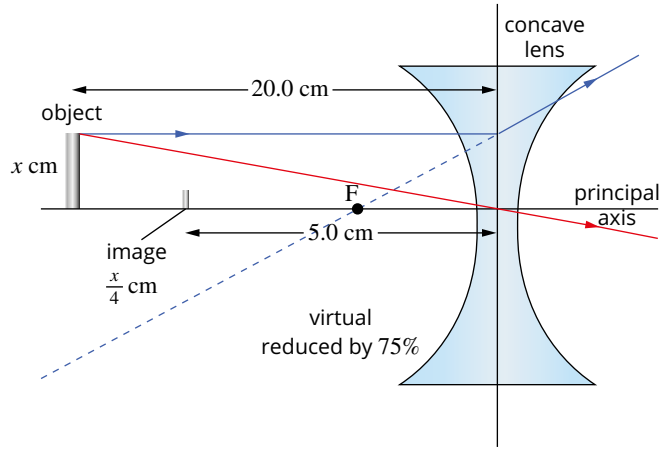
1 A
2 radio waves, microwaves, visible light, X-rays
3 D
4 C
5 Parallel rays of light converge at the focal point.
6 **a** ray model and waves
b waves (only way of explaining change of speed)
c waves
d electromagnetic waves
7 The intensity will be 4 times greater.
8 6 m: the image is the same distance behind as you are in front.
9 Black: no colours of light are reflected.
Grey: all colours are partially reflected.
10 Michelson and Morley placed the interferometer in the direction of the proposed aether and obtained an interference pattern. When they placed the interferometer at right angles to the proposed aether there was no difference in the interference pattern. Therefore there was no medium and so light was not a mechanical wave.
11 Medium 1: Light bends towards the normal in the slower, more optically dense medium.
12 Light is refracted by the layers of the atmosphere (different densities and temperatures) causing light from the star to refract over the horizon and towards the observer.
13 All images are virtual and upright but diminished in size. The mirror will give a very wide field of view.
14 The radius of curvature and refractive index.
15 White light would contain all component wavelengths of visible light and would not necessarily be in phase when it is incident on the slits. The resulting interference pattern would produce an interference pattern with coloured bands merging into each other.
16 Significant diffraction is observable when $\lambda \geq w$, so diffraction is more likely to be seen with a smaller gap.
17 Light reflected from horizontal surfaces is plane polarised, so the polarised sunglasses would filter out a large proportion of the reflected light.
18 Mechanical waves need a medium in which to travel. The aether was proposed as a theoretical substance that provided the medium for a mechanical wave model of light. Michelson and Morley demonstrated that a theoretical aether didn't exist and established that light was not a mechanical wave.
19 It is not impossible, but it would be extremely difficult because two coherent source vibrating in the same phase are required. Independent light sources would almost certainly be out of phase.
20 Laminated windscreens display stress patterns due to photoelasticity, which are distracting when driving. Light reflected off flat surfaces is plane polarised. Polarised sunglasses will reduce this glare substantially by only allowing vertically polarised light through.
21 between 7.5×10^{14} Hz and 3.0×10^{16} Hz
22 An object is placed 20 cm in front of a convex mirror with a radius of curvature of 30 cm.
a



b The image is upright, virtual and diminished.
23 **a**



b The image is real, inverted and diminished.
24 2.10×10^8 m s^{-1}
25 $r_{red} = 19.5°$, $r_{violet} = 19.1°$
26 24.4°
27 **a** virtual, upright
b The image is 5 cm from the lens.



28 13.5 W m^{-2}
29 0.192 W m^{-2}
30 It is refracted twice by the same amount, first towards the normal on entering the glass and then away from the normal on exiting the glass. The amount of refraction is the same, as the changes in medium are the same but reversed. The ray will emerge parallel to its original direction of travel but not along the same path as it would if the plate glass was not there.
31 The human eye perceives an equal proportion of each colour in the visible spectrum as white light. For a top to be perceived as being white when it's spinning, the proportion of each colour must be the same. The first top has an equal proportion of each colour. The second top has a greater proportion of colours towards the red end of the spectrum.
32 Shaving and make-up mirror: concave for magnification, *f* approximately 50 cm.
Shop security mirror: convex for wide field of view, *f* approximately 70 cm.
Rear-view mirror: convex for wide field of view.
33 Refractive indexes that are more similar (closer together) result in a larger critical angle.

34 She is hypermetropic or long sighted. A +30 cm focal length corresponds to a convex lens converging the light slightly earlier and so focusing on the retina rather than behind.

35 Holding the lenses parallel to one another and rotating one lens 90° relative to the other.

- If they are both polarising, then all light will be blocked out.
- If only one is polarising, then an illuminated clear surface under stress would show patterns due to photoelasticity.
- If they are both non-polarised, then no illumination will appear.

Unit 2 Review: Worked solutions

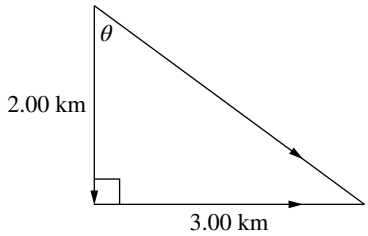
Topic 1: Linear motion and force

Multiple choice

1	A	**2**	C	**3**	D	**4**	A
5	B	**6**	A	**7**	B	**8**	A
9	C	**10**	D				

Short answer

1 **a** $s = 2.00$ km south **b** $s = 3.00$ km east
c $s_R = 3.61$ km S56.3°E



2 **a** Displacement is the change in position.
Average velocity is the rate of change in position between two times: $v_{av} = \frac{s_2 - s_1}{t_2 - t_1}$
Instantaneous velocity is the rate of change of position at an instant. It can be calculated using the gradient at that point in time.
b average velocity = 1 cm s^{-1}, instantaneous velocity = 1 cm s^{-1}
c average velocity = 0.3 cm s^{-1}, instantaneous velocity = –2 cm^{-1}
d Average velocity and instantaneous velocity are only equal when the velocity is constant for the whole time period in question, in other words when the acceleration = 0 during the entire time period.

3 $v = 125.2$ m s^{-1}, $t = 12.8$ s

4 **a** $F_{\text{on balloon by air}} = -F_{\text{on air by balloon}}$
b $F_{\text{on chair by girl}} = -F_{\text{on girl by chair}}$

5 **a** $u_b = 505$ m s^{-1} **b** $I = 5.00$ N s

6 **a** $v = 1.4$ m s^{-1} in the direction in which the dog was running originally.
b E_k before = 490 J, E_k after = 98 J
Kinetic energy is not conserved, so it is an inelastic collision.

7 The marble in initially travelling at 2 m s^{-1} in the positive direction. In the first 0.9 seconds the acceleration is constant.

$$\text{acceleration} = \frac{\text{rise}}{\text{run}} = \frac{7}{0.9} = 7.8\,\text{m s}^{-2}.$$

The marble travels a distance of

$$\text{area} = \frac{1}{2}(2 + 9) \times 0.9 = 4.95\,\text{m}$$

The marble then travels with a constant velocity of 9 m s^{-1} in the positive direction for 0.3 seconds, travelling a further 2.7 m.
At 1.2 s the marble rapidly decelerates at a rate of

$$\text{acceleration} = \frac{\text{rise}}{\text{run}} = \frac{-5}{0.2} = -25\,\text{m s}^{-2} \text{ for 0.2 seconds.}$$

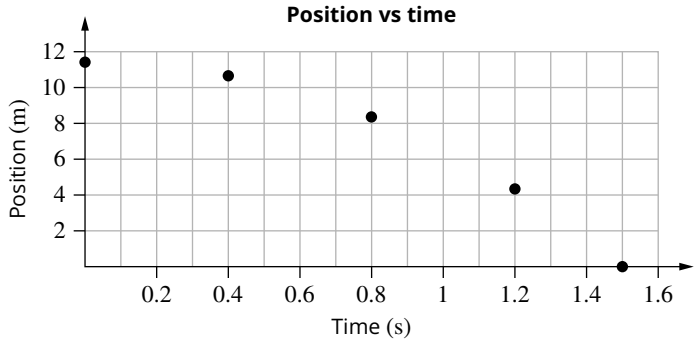
The deceleration then decreases to

$$\text{acceleration} = \frac{\text{rise}}{\text{run}} = \frac{-3 - 2}{2.5 - 1.6} = -5.6\,\text{m s}^{-2}$$

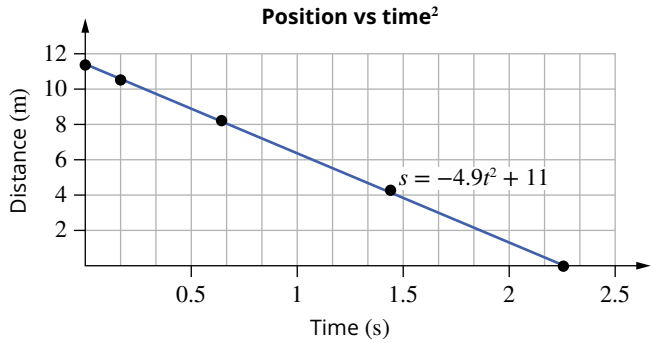
At 1.9 seconds the marble is momentarily stationary, before moving in the negative direction. The acceleration is still –5.6 m s^{-2}. Between 1.9 s and 2.5 s the marble travels

$$\text{area} = \frac{1}{2}(2.5 - 1.9)3 = 0.9\,\text{m}$$ in the negative direction.

8 **a** Shape indicates the position is related to time squared, or that the square root of the position is related to the time.



b, c



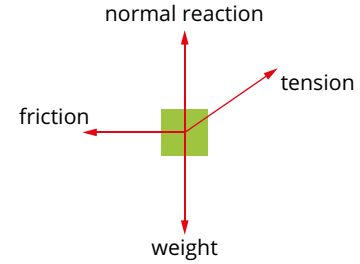
d Various answers are possible. Conclusion should include the value of acceleration due to gravity found (approximately 9.8, depending on the line of best fit drawn).

9 **a** $v = 4.4$ m s^{-1} in the same direction
b $v = 39.8$ m s^{-1}
c Impulse is the change in momentum.
$F = 66$ N
d Conservation of momentum is the principle that says the total momentum in a closed (or isolated) system is constant. In this case, the momentum of the fish and the water before the collision is equal to the momentum of the fish and the water after the collision. Momentum from the fish is transferred to the water.

10 **a** $E_p = 34.3$ kJ **b** $E_k = 0$ J
c $\Delta E_k = -\Delta E_p = 34.3$ kJ **d** $v = 14$ m s^{-1}
e $v = 6.3$ m s^{-1} **f** $v = 8.85$ m s^{-1}

11 **a** According to Newton's first law, an object will continue with its motion unless acted upon by an unbalanced, external force.
A driver's head will continue to move at the velocity of the car until it hits the airbag instead of the dashboard.
b The change in momentum of the driver's head will be the same if the head hits the dashboard or the airbag.
With the same impulse, a larger period of time results in less force acting on the driver's head.

12 **a**



b $W = 45\,\text{J}$
c Possible answers:
- A smaller surface area leads to smaller frictional forces.
- More weight of surfboard is supported by the surfer, so the board would not push into the sand as much.

d Area under graph = 25 J
e Many possible answers. Some include:
- Reduce the friction force between the board and the sand by changing the surfaces (wax on the board, wet/dry sand)
- Reduce the friction between the board and the sand by using wheels under the board.

If the answer suggests carrying the board, it must mention that the force required to overcome gravity is perpendicular to the motion, and hence does not contribute to the work required.

Topic 2: Waves

Multiple choice

1	B	**2**	C	**3**	C	**4**	C	**5**	D	**6**	A
7	B	**8**	A	**9**	D	**10**	B				

Short answer

1 Longitudinal waves displace media in the same direction as the wave's direction of propagation (e.g. sound). Transverse waves produce a displacement of particles at right angles to the direction of propagation (e.g. water ripples, string vibrations).

2 **a** $T = 0.4\,\text{s}$ (for example, the points at 0.1 s and 0.5 s are in phase)
b Speed $= 5\,\text{m s}^{-1}$

3 $\lambda = 4\,\text{cm}$, $A = 2\,\text{cm}$

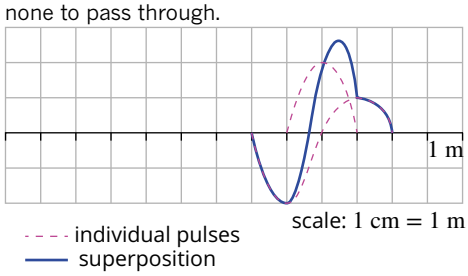
4 Once the person on the swing is moving, the swing must be pushed with a frequency equal to the resonant frequency of the swing. Then there can be an efficient transfer of energy to the swing and the amplitude of swing can increase.

5 Medium B has the highest refractive index, then medium A; medium C has the lowest index.

6 **a** $\theta_2 = 11.92°$
b $v_2 = 1.24 \times 10^8\,\text{m s}^{-1}$

7 The original white light is unpolarised. The first polarising sheet polarises the light by allowing only light in one plane of polarisation to pass through and so reduces the brightness by about half. The second polarising sheet has the same orientation as the polarising material in the first sheet and so the same amount of light passes through. Thus, brightness is unaffected. When the second polarising sheet is rotated 90°, its polarising material is now orientated at 90° to that of the polarising material in the first sheet so it blocks the remaining light, allowing almost none to pass through.

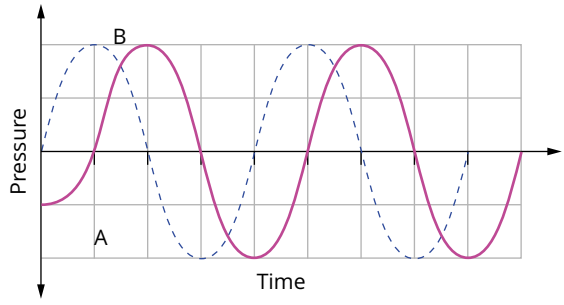
8



a Correct amplitude and position of the two pulses shown after 2 seconds (dotted lines).
b Correct shape/amplitude of superposition shown (solid line).

9 Intensity is the measure of the rate of energy transfer through a square metre in one second, or the power transfer through $1\,\text{m}^2$. Waves in three dimensions, such as light or sound through the air, radiate in all directions. As the energy travels it spreads out along the surface of a sphere. Hence the intensity is proportional to the inverse of the square of the radius: $I \propto \frac{1}{r^2}$

10 **a** Amplitude, period and shape remain the same.

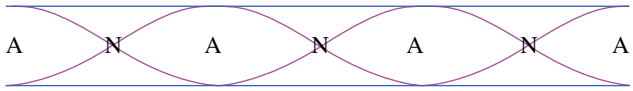


b $\lambda = 1.0\,\text{m}$ **c** $f = 340\,\text{Hz}$

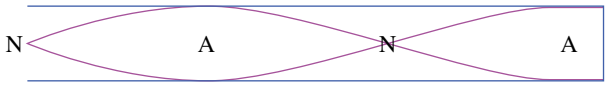
11 **a** Destructive interference occurs when a crest and a trough meet. The water will appear flat when complete destructive interference occurs.
b Constructive interference will occur.
c $\lambda = 0.012\,\text{m}$ or $1.2\,\text{cm}$
d Destructive interference means that a node is occurring. The second non-central node means that $n = 2$: path difference $= 0.018\,\text{m}$ or $1.8\,\text{cm}$.

12 **a** The natural frequency is the frequency at which the string will vibrate when a plucked once, without repeated input.
b $f_1 = 110\,\text{Hz}$ **c** $f_3 = 330\,\text{Hz}$ **d** $f_5 = 550\,\text{Hz}$

13 **a** A standing wave is created when the wave reflects at the end of the pipe, and interferes with the incoming wave.
b Third harmonic for the flute:



Third harmonic for the clarinet:



c The flute. The fundamental frequency of a pipe open at both ends occurs when the wavelength is twice the length, whereas a pipe closed at one end has a fundamental frequency with a wavelength 4 times the length.
d The energy transfer is very efficient in a resonating system. When a standing wave is created, the interference creates a wave with twice the amplitude, hence it is louder. Frequencies that do not create a resonance interfere to create a wave with a reduced amplitude.

14 **a** Light as a wave is a transverse wave for which the magnetic and electric components are perpendicular to the propagation of energy. Sound is a longitudinal wave for which the direction of motion of the particles is parallel to the energy propagation. Sound is a mechanical wave, requiring a medium through which to propagate. Light can travel through a vacuum, so it is not a mechanical wave.
Light travels at $3.0 \times 10^8\,\text{m s}^{-1}$ in a vacuum whereas sound travels at $340\,\text{m s}^{-1}$ through air at 25°C.
b Refraction is caused when the speed of the light changes as it enters a different medium. When the waves slow down or speed up it causes a change in the direction of wave.
c Snell's law is relationship between the angles of incidence (θ_i) and refraction (θ_r) and the indices of refraction of the two materials (n_1 and n_2).
$n_1 \sin\theta_1 = n_2 \sin\theta_2$
The refractive index of air is 1.00.
By measuring the angle of refraction at different angles of incidence, the ratio of refractive indices can be found.
To reduce experimental uncertainties, the ratio of the refractive indices should be found from the gradient of a $\sin\theta_1$ vs $\sin\theta_2$ graph.
d Unknown is quartz.

Glossary

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A

aberration A distortion of an image due to a physical property of the image-forming apparatus.

absolute refractive index An index or number that is equal to the ratio of the speed of light in a vacuum compared with the speed of light in a medium.

absolute zero The coldest possible temperature (0 K, −273.15°C).

absorption The taking up and storing of energy, such as radiation, light or sound, without it being reflected or transmitted. During absorption, the energy may change from one form into another. When radiation strikes the electrons in an atom, the electrons move to a higher orbit or state of excitement by absorbing the energy of the radiation.

acceleration The rate at which an object's velocity changes (symbol, a; SI unit m/s^2).

aether The theoretical medium that was once supposed to fill space to support the propagation of light modelled as a wave.

air resistance The frictional force that acts against moving objects as they travel through the air. Air resistance always acts in the opposite direction to the motion of an object.

alpha particle The composite particle consisting of two protons and two neutrons tightly bounded together, emitted from the nuclei of some radionuclides. Its symbol is ${}^4_2\text{He}$ or ${}^4_2\alpha$.

alpha radiation The composite particle consisting of two protons and two neutrons tightly bounded together, emitted from the nucleus of some radionuclides (symbol, α or ${}^4_2\text{He}$)

ammeter An instrument that measures electric current flowing through a circuit, in amperes.

amplitude The distance from the rest position of a wave (equilibrium position) to the crest position, which is half the vertical distance from a trough to a crest.

angle of incidence The angle measured between the incident ray and the normal to the surface that it strikes.

angle of reflection The angle between the reflected ray and the normal to the surface that it strikes.

antineutrino An almost massless particle associated with beta negative decay.

antinode The midway point between each pair of nodes where there is maximum amplitude of vibration.

aperture A very narrow opening or gap.

apparent depth The apparent distance of the virtual image from the surface of the water.

artificial transmutation The process in which an isotope is intentionally caused to change by nuclear processes into an isotope of another element (distinct from natural radioactivity) (e.g. neutron bombardment of ${}^{235}\text{U}$).

atom The smallest unit of matter that still behaves as a chemical element. It consists of a positively charged nucleus, comprised of positively charged protons and neutral neutrons, surrounded by negatively charged electrons.

atomic number The number of protons in an element's nucleus, Z; in a neutral atom, the number of protons will be equal to the number of electrons orbiting the nucleus.

B

beta particle A particle emitted during beta negative or beta positive decay. It is an electron in beta negative decay, and a positron in beta positive decay.

beta negative radiation A type of radioactive decay in which an energetic electron (${}^0_{-1}\text{e}$) and associated antineutrino (${}^0_0\overline{\nu}$) are emitted from an atomic nucleus (symbol β^-).

beta positive radiation A type of radioactive decay in which an energetic positron (${}^0_1\text{e}$) and associated neutrino (${}^0_0\nu$) are emitted from an atomic nucleus (symbol β^+).

binding energy The mechanical work that must be done against the forces holding a nucleus together to disassemble it into component parts.

binding energy per nucleon The binding energy divided by the number of nucleons in the nucleus of an atom.

C

calorimetry The science of measuring amounts of heat.

centre of curvature The centre of the spherical mirror from which the mirror is assumed to have been made.

centre of mass Point at which the mass of an object is considered to be concentrated for the purpose of analysing motion.

chain reaction A single nuclear reaction that causes a rapid increase in the number of subsequent reactions.

charge A characteristic of a unit of matter that refers to the extent to which a particle has fewer or more electrons than protons.

collinear Lying on the same straight line.

collision A collision occurs when two or more objects hit each other due to forces acting on them, resulting in an exchange of energy or momentum.

compression A region in a longitudinal wave where the particles are closest together.

concave A shape that is inwardly curved.

conduction The process by which heat or electricity is directly transferred or transmitted through the material of a substance when there is a difference of temperature or of electrical potential between adjoining regions, without movement of the material.

conductor A substance, body or system that readily conducts heat, electricity, sound or light. A material that allows the flow of electric charge.

conserved When a quantity that exists before an interaction is exactly equal to the quantity that exists after the interaction.

constructive interference The interference of two or more waves of the same, or almost the same, frequency and in phase with each other, superposing to produce an observable pattern in intensity.

contact forces The forces that exist when one object or material is touching another. Friction, drag and normal reaction forces are contact forces.

convection The movement caused within a fluid by the tendency of hotter and therefore less dense material to rise, and colder, denser material to sink under the influence of gravity, which consequently results in transfer of heat.

conventional current The current that moves in the same direction as positive charge flow.

convex A shape that is outwardly curved.

corpuscular Particle-like in nature.

coulomb The SI unit of electric charge.

coulomb force The attractive (for particles of opposite charge) or repulsive (for particles of the same charge) force that exists between charged particles over a distance.

crest The highest part or point of a wave.

critical angle The angle of incidence that produces an angle of refraction of 90°.

current The flow of electric charge.

D

daughter nucleus The resulting nuclide formed after the parent nucleus has decayed.

decay The spontaneous emission of radiation from a nucleus via alpha, beta or gamma radiation. It is distinct from nuclear fission.

decay series The successive decay products of daughter nuclides produced until a final stable nuclide is formed.

destructive interference The interference of two or more waves of the same, or almost the same, frequency and 180° out of phase with each other, superposing to produce a resultant wave with reduced amplitude.

diffraction A phenomenon in which waves either bend behind a barrier or the wavefront is broken up into many small sources.

diffuse reflection When light is reflected from a rough or uneven surface and is scattered in all directions.

dimension Space can be considered to consist of three length dimensions. The position of an object can be defined in relation to its position along each of the three dimensions. Typically, these three dimensions are labelled x, y and z. However, up–down, left–right and backwards–forwards are also appropriate.

dimensional analysis The use of the units in a graph or formula to check that the derived term is correct.

direction conventions Direction conventions are standardised systems for describing the direction in which an object is travelling. The use of cardinal points of a compass (N, S, E and W) is an example of a direction convention.

dispersion (of light) On refraction, different colours of light will take slightly different paths. This results in the spreading out of white light into its component colours. This is known as dispersion.

displacement A vector quantity representing the location of the destination relative to the origin of motion only, irrespective of the path actually taken between the two points (symbol, s; SI unit, m).

dissipate To lose or waste something, to melt away or to cause it to disappear.

distance travelled How far an object travels during a particular motion or journey between the origin and the destination point. Distance is a scalar value. Direction is not required when expressing magnitude (symbol, d; SI unit, m).

drift velocity The average velocity of an electron in a material through which it is travelling.

E

efficiency The ratio of useful work performed by a machine or in a process, to total energy expended or heat taken in.

elastic collision A collision in which both momentum and kinetic energy are conserved.

elastic modulus The resistance of a material to being deformed elastically; the stiffer a material, the higher its elastic modulus.

electrical circuit A path in which electrons form a voltage or current source flow.

electrical potential energy The capacity of electric charge carriers to do work due to their position in an electric circuit.

electricity The energy that results from the movement of charged particles.

electromagnetic radiation Radiant energy consisting of synchronised oscillations of electric and magnetic fields, or electromagnetic waves, propagated at the speed of light in a vacuum.

electromagnetic spectrum The family of electromagnetic radiations consisting of radio waves, microwaves, infrared radiation, visible light, ultraviolet radiation, X-rays and gamma rays. All electromagnetic radiations travel at $3.00 \times 10^8\,\text{m}\,\text{s}^{-1}$ in a vacuum.

electromagnetic waves Produced by an oscillating charge resulting in mutually perpendicular electric and magnetic fields.

electron The negatively charged subatomic particle (symbol is ${}^{0}_{-1}\text{e}$ or ${}^{0}_{-1}\beta$).

electron volt A unit of energy equal to the work done on an electron in accelerating it through a potential difference of one volt (unit, eV).

electrostatic attraction Occurs when unlike charged particles attract; or example, when the positively charged proton is attracted to the negatively charged electron.

electrostatic force See *coulomb force*.

electrostatic repulsion Occurs when like charged particles repel; for example, when a positively charged proton repels another positively charged proton.

elementary charge The charge carried by one electron or one proton.

emission Something that is emitted or given out.

emit To give out. For example, energy can be emitted in the form of heat, light, radio waves etc.

energy conservation A principle in physics that states that the total energy in an isolated system remains constant. Energy cannot be lost or removed but it can transform from one type of energy to another; for example, from mechanical energy to heat and/or sound energy.

equilibrium The condition of equal balance between opposing forces acting on each other; so that a static or balanced situation results.

equivalent resistance A single resistance that could be used to replace a number of individual resistors for the purpose of circuit analysis.

evaporation The changing of a liquid into a gas, often under the influence of heat (as in the boiling of water) but not necessarily requiring heating.

explosion In an explosion, an object will break apart into multiple fragments, each with their own momentum.

extend In science, to extend an experiment is to modify the methodology to overcome limitation of the scope or applicability of the data.

F

fission fragments The nuclides that are formed via the process of nuclear fission.

focal length The distance from a lens or mirror at which a parallel beam of light is brought to a focus.

force A push or pull between objects that may cause one or both objects to change speed and/or the direction of their motion (i.e. accelerate) or change their shape. Scientists identify four fundamental forces: gravitational, electromagnetic (involving both electrostatic and magnetic forces), the weak nuclear force and the strong nuclear force; all interactions between matter can be explained as the action of one, or a combination, of the four fundamental forces.

free-fall The motion of a falling body under the effect of gravity only; no air resistance or propulsive forces are acting.

frequency Equal to the number of waves that move past a given point in one second (symbol, *f*; SI unit, Hz).

fundamental Forming a necessary base or core; of central importance; affecting or relating to the essential nature of something; part of a foundation or basis.

G

gamma radiation Extremely high-frequency electromagnetic radiation (high-frequency photons) emitted from the nucleus of some radionuclides (symbol is γ).

gamma ray See *gamma radiation*.

geometrical optics The branch of optics that models the path of light using straight rays.

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

H

half-life The time taken for half of the atoms in a sample of a material to undergo radioactive decay.

harmonic A frequency that is a whole number multiple of the same basic frequency.

heat The energy transferred from one system to another because of a difference in temperature.

Huygens' principle States that every point on a wavefront is a source of secondary wavelets. These wavelets spread out in the forward direction at the same speed as the source wave. The new wavefront is a line that is a tangent to all of these wavelets.

I

image The location in space from which all the reflected light appears to diverge. An optically formed reproduction of an object by using a lens or a mirror.

impulse The change in momentum of an object; equals the product of a force and the time interval over which the force acts.

in phase Two points within a wave that are simultaneously experiencing the same displacement and velocity and are, therefore, moving in the same direction.

incident To arrive at or strike a surface, especially a beam of light or radiation, or particles.

incident ray A ray of light that hits a surface of any material.

induction The process by which an object becomes electrically charged by being exposed to another object with an excess of either positive or negative charge.

inelastic collision A collision in which kinetic energy is not conserved.

inertia A property of an object, related to its mass, that opposes changes in motion.

insulator A material or an object that does not easily allow heat, electricity, light or sound to pass through it. Air, cloth and rubber are good electrical insulators. Feathers and wool are good thermal insulators.

intensity The average rate of flow of energy per unit area.

intensity (of a wave) The average rate of flow of energy per unit area.

interference The combination of two or more waves to form a resultant wave.

interference pattern The pattern due to light (or fast-moving particles) from two or more sources arriving at the one location.

internal energy The total potential energy and kinetic energy of the particles in a system.

internal resistance The resistance of a component in a circuit such as a battery, voltmeter or ammeter. For Physics Units 1 and 2 this is usually assumed to be ideal.

inverse square law A mathematical pattern expressing a relationship in which one quantity decreases with the square of another; e.g. if the first doubles, the second decreases to one-quarter, and so on.

ion An atom with unbalanced charges, making it either more positive or more negative.

ionisation The process by which an atom acquires a negative or positive charge by gaining or losing electrons.

ionised An atom or molecule becomes electrically charged.

ionising radiation Radiation that is energetic enough to cause ionisation. Examples include ultraviolet light, X-rays, gamma rays, alpha particles, beta particles and neutrons.

isotope A chemical element that has the same atomic number but different neutron number.

J

junction A point in an electric circuit that current can flow into or out of from more than one direction.

K

kelvin The SI unit of temperature measurement on the absolute temperature scale based on the triple point of water.

kinetic energy The energy resulting from the movement of an object. When associated with temperature, kinetic energy is associated with the motion of particles in a substance (symbol, E_k; SI unit, J).

kinetic particle model A model in which matter is made up of particles that are constantly moving.

Kirchhoff's current law At any node in an electrical circuit, electric charge is conserved such that the sum of the electric currents flowing into a node is equal to the sum of electric currents flowing out of that node.

Kirchhoff's voltage law The energy inputs in a circuit equal the sum of energy output from loads in the circuit such that the directed sum of the electrical potential differences around any closed network is zero.

L

latent heat The 'hidden' energy used to change the state of a substance at the same temperature; the energy is not seen as a change in temperature.

latent heat of fusion The energy required to change 1 kg of solid to a liquid at its melting point.

latent heat of vaporisation The energy required to change 1 kg of liquid to a gas at its boiling point.

law A statement describing invariable relationships between phenomena in specified conditions, frequently expressed mathematically.

law of conservation of electric charge The total electric charge of an isolated system remains constant regardless of changes within the system.

law of conservation of energy The total energy of a system remains constant; energy can neither be created nor destroyed, rather, it transforms from one form to another.

law of reflection States that the angle of reflection, measured from the normal, equals the angle of incidence measured from the normal.

longitudinal wave A wave where the direction of oscillation of particles is parallel to the direction of energy transfer or wave movement.

M

magnification The factor by which the size of an image has changed from the size of the original.

magnitude The size or extent of something. In physics, this is usually a quantitative measure expressed as a number of a standard unit.

mass defect The difference between the mass of an intact nucleus and the sum of the masses of the individual nucleons of which it is made.

mass number The total number of nucleons in an element's nucleus, A, i.e. the number of protons plus the number of neutrons.

Maxwell Boltzmann distribution A graph of kinetic energy against number of particles that shows the range of energies in a sample of a gas or a liquid at a given temperature.

mechanical energy The sum of the kinetic energy of an object and all potential energies available to it (e.g. gravitational, spring, chemical).

mechanical wave A wave that requires a medium to propagate; mechanical waves may oscillate the medium or oscillate the pressure within the medium.

mechanical work The transfer of energy to or from an object by the action of a force over a distance.

medium A physical substance, such as air or water, through which a mechanical wave is propagated and energy is transmitted.

metal A material made up entirely of metal atoms and is electrically conductive.

model In science, a representation that describes, simplifies, clarifies or provides an explanation of the workings, structure or relationships within an object, system or idea.

modify Change the form or qualities of; make partial or minor changes to something.

momentum The product of an object's mass and velocity.

multimeter A meter than can be used in an electrical circuit as either an ammeter or a voltmeter, depending on how it is wired.

N

net charge The total number of positive and negative charges in an atom or molecule.

net force The vector sum of all the individual forces acting on a body. This is also known as the resultant force.

neutral The state of having no charge.

neutrino An almost massless particle associated with beta positive decay.

neutron A subatomic particle with neutral electric charge.

neutron number The number of neutrons in a nucleus (symbol, N).

newton The SI unit for force (N).

Newton's first law States that an object will maintain a constant velocity unless an unbalanced, external force acts on it.

Newton's second law States that force is equal to the rate of change of momentum. This can be processed mathematically to: the acceleration of an object is directly proportional to the force on the object and inversely proportional to the mass of the object.

Newton's third law States that for every action (force), there is an equal and opposite reaction (force).

node The point in a medium that is not displaced as a wave is propagated through it.

non-contact forces The forces that act at a distance and do not require the bodies to touch each other. Gravitational, magnetic and electric forces are non-contact forces.

non-metal A material made up entirely of non-metal atoms and is electrically insulative.

non-ohmic A conductor that does not follow Ohm's law; the relationship between voltage and current is non-linear.

normal An artificially constructed dashed line drawn perpendicularly from the boundary surface.

nuclear fission The process in which a large unstable nucleus splits, forming two (or more) smaller, more stable nuclei and releasing neutrons and energy.

nuclear fusion A nuclear reaction in which two or more atomic nuclei combine to form one or more different, heavier atomic nuclei and subatomic particles.

nuclear reaction An interaction where a target nucleus and a smaller particle collide.

nuclear reactor A device used to start and continue a nuclear reaction.

nuclear transmutation The process by which a nuclide changes its atomic number; that is, changes into a different element.

nucleon The particles (protons and neutrons) that make up the nucleus of an atom.

nucleus The central part of an atom.

nuclide The range of atomic nuclei associated with a particular atom, which is defined by its atomic number and the various isotopes of that atom as identified by the mass number.

O

object A point or source of outgoing rays.

ohmic A conductor that follows Ohm's law; the relationship between voltage and current is linear.

optical density A measure of the speed at which light is able to travel through a substance.

P

P-wave A longitudinal seismic wave, also called a primary wave.

parallel circuit A circuit that contains junctions; the current drawn from the battery, cell or electricity supply splits before it reaches the components and re-joins afterwards.

parent nucleus The radionuclide that undergoes decay.

particle accelerator A device used to accelerate and hold charged particles at high speed, usually using electric and magnetic fields. The particles are then typically smashed together.

particles A small portion, or piece, of matter.

path difference The difference in distance travelled by two waves. This is useful in determining the phase difference between two waves travelling at the same velocity with the same frequency.

penetrating ability The distance that radiation can travel into a substance before being absorbed into the substance.

period The amount of time one cycle or one event takes to occur; the length of time taken for one wavelength to pass a given point; in circular motion, period refers to the time taken to complete one revolution (symbol, T; SI unit, s).

phase A particular point in time of a wave. Points on the wave separated by 360°, or a complete cycle, are in phase. Points on a wave separated by 180° are out of phase.

phase change Occurs when waves that reflect off fixed barriers are inverted, or have a 180° phase change.

phenomenon An event that is not artificial and can be observed through the senses or can be scientifically described or explained.

plane polarised Polarisation in which the electric vector of waves of light or other electromagnetic radiation is restricted to vibration in one plane.

plane wave A wave of constant frequency and amplitude with wavefronts that are long straight lines.

polarised light Light waves that have their electric fields aligned, i.e. varying in the same plane as one another.

polarising filters A filter that is able to convert unpolarised light into polarised light.

position The location of an object with respect to a reference point. Position is a vector quantity.

positron A positively charged electron.

potential difference The difference of electric potential between two points; measured in volts.

potential energy Energy that can be considered to be 'stored' within a body due to its position, composition or molecular arrangement.

power The rate at which work is done or the rate at which energy is transferred or transformed (symbol, P; SI unit, W).

principal axis The line drawn through both the optical centre and the centre of the curvature of a lens.

principal focus (principal focus point) The point of a convex lens at which the rays parallel to the principal axis converge (are brought together) to a focus.

principle of superposition The resultant displacement is the sum of the individual wave displacements at a point.

propagation The motion of waves through or along a medium.

proton A subatomic particle with a positive electric charge.

pulse A single disturbance moving through a medium from one point to the next.

R

radiation The emission of energy as electromagnetic waves or as moving subatomic particles, especially high-energy particles, which cause ionisation.

radioactive A nucleus with excess energy that must be relieved by emitting the excess energy.

radioactivity The process by which an unstable nucleus with excess energy loses some of that energy by emitting radiation in the form of electromagnetic waves or moving subatomic particles.

radioisotope A radioactive isotope.

radionuclide A radioactive nuclide.

radius of curvature The radius of the sphere from which a mirror has been cut.

rarefaction A region in a longitudinal wave where the particles are furthest apart.

ray An artificially constructed line, drawn perpendicular to the wavefront, in the direction of energy transmission or transfer.

ray tracing The process of using known pathways of light to model image formation on a scaled, two-dimensional diagram.

Rayleigh wave A seismic surface wave causing the ground to shake in an elliptical motion.

real depth The actual distance of an object beneath the surface of the water, as would be measured by submerging a ruler along with it.

real image An image that is formed at the point of intersection of light from a common point of origin.

real position The actual position of an object.

rectilinear The description of motion in a straight line.

rectilinear propagation The property of waves to move in a straight line through a uniform medium.

redirect In science, to redirect an experiment is to modify the methodology to gain further insight into the phenomena observed in the original experiment.

refine In science, to refine an experiment is to modify the methodology to obtain more accurate or precise data.

reflection When incident waves at a boundary change direction returning into the same medium according to the law of reflection.

refracted ray A ray of light that has entered a medium and either bent towards or away from the normal, depending on the density of the new medium.

refraction When incident waves at a boundary change direction and speed when passing into another medium according to Snell's law of refraction.

relative refractive index An index or number that is allocated to each pair of substances indicating their relative optical densities.

resistance The ratio of the voltage applied to the electric current that flows through a component in an electrical circuit.

resistor A component that restricts or impedes the flow of electric current.

resolution The measure of an instrument's ability to separate two points. It is called the resolving power of an instrument.

resonance When a vibrating system or external force drives another system to oscillate with greater energy at a particular frequency; resonance occurs when a system is forced to vibrate at one of its natural frequencies.

resonant frequency A natural frequency of vibration determined by the physical parameters of the vibrating object.

resultant One vector that is the sum of two or more vectors.

resultant force A force that is also known as the net force.

S

S-wave A transverse seismic wave, also called a secondary wave.

scalar A quantity that has a magnitude but no direction.

scientific journal A book containing the entire collection of work related to an experiment or investigation.

Segre plot A graph showing how the neutron number of nuclides changes with atomic number. It shows stable nuclides and radioactive nuclides and is useful in determining how a nuclide will react.

series circuit A circuit in which the components are connected one after another in a continuous loop so that the same current passes through each component.

sinusoidal oscillation A disturbance with a period oscillation and a fixed frequency. The term comes from the mathematical sine function.

specific heat capacity The amount of thermal energy transfer necessary to raise the temperature of one kilogram of a substance with no change in its temperature (symbol, c; SI unit, $\mathrm{J\,kg^{-1}\,K^{-1}}$).

speed The ratio of distance travelled to time taken. Speed is a scalar quantity.

spherical mirror A mirror that has a specially shaped surface such that it could have formed part of the surface of a sphere.

standing wave Waves with stationary vibration pattern formed due to the superposition of waves with particular frequencies.

strong nuclear force One of the four fundamental forces; the strong nuclear force that acts over small distances in the nucleus to hold the nucleons together against the repulsive electrostatic forces exerted between the protons.

subatomic A scale smaller than the atom.

superposition When two or more waves overlap in space, the resultant wave is the algebraic sum of the individual waves.

surface waves A seismic wave that travels across the surface of the Earth as opposed to through it.

T

temperature The degree or intensity of heat present in a substance or object, especially as expressed according to a comparative scale, e.g. the Celsius temperature scale.

theory In science, a set of concepts, claims and/or laws that can be used to explain and predict a wide range of related observed or observable phenomena; theories are typically founded on clearly identified assumptions, are testable, produce reproducible results and have explanatory power.

thermal contact When two objects are in contact so that energy exchange via heat transfer is possible.

thermal energy The internal energy present in a system due to its temperature (symbol, U; SI unit, J); transfer of thermal energy when heating or cooling a substance has the symbol Q in the equation $Q = m\Delta T$.

thermal equilibrium The condition of a system in which there is no net heat exchange between any of its components, i.e. the components have the same temperature and the average kinetic energy of their particles is equal; this relates to the zeroth law of thermodynamics.

thermal inversion A situation in which a layer of warm air lies over a layer of cool air in the Earth's atmosphere.

thermodynamics The study of heating processes and their relationships with various forms of energy and work; concerned with characteristics of energy such as temperature, entropy and pressure and their interrelationships.

torsional wave A twisting type of wave.

total internal reflection The phenomenon whereby all energy is reflected inside a medium due to the incident angle of the wave being greater than the critical angle.

transfer The movement of energy from one place to another.

transform To change energy from one form to another (e.g. from gravitational potential to kinetic).

transmitted A wave or pulse carries energy through a medium from one location to another.

transmutation The process in which an isotope changes into an isotope of another element (usually from natural decay).

transverse wave A wave where the direction of oscillation of particles is perpendicular to the direction of energy transfer.

travelling wave A wave in which its maxima and minima are moving through the medium in which the wave is travelling.

trough The lowest part or point of a wave.

tsunami A large wave on the ocean caused by an undersea earthquake, or a volcanic eruption, or a coastal landslide.

U

unified atomic mass unit A unit of mass used for very small masses (unit, u) equal to 1.66×10^{-27} kg.

units The properties related to physical measurements. Units can be fundamental, such as metres (m), seconds (s) or kilograms (kg). Units can also be derived by combining fundamental units such as metres per second ($\mathrm{m\,s^{-1}}$).

unpolarised light The light waves that have electric field variations that are not aligned with one another.

V

vector A quantity that has both magnitude and direction; a vector may be represented pictorially by an arrowed line segment (→) and symbolically as $\vec{a}$ or $\underline{a}$.

vector diagram A diagram that depicts the direction and relative magnitude of a vector quantity by a vector arrow.

velocity The rate of change of displacement of an object (symbol, v; SI unit, m/s); if the rate of change is measured at an instant in time, then this is an instantaneous velocity; if the rate of change is calculated using the formula velocity $= \frac{\text{displacement}}{\text{time}}$, then this is average velocity.

virtual image An image formed when light rays that originate from a common point on an object are diverged by a mirror or lens and appear to have come from a common image point.

visible light The range of electromagnetic radiation frequencies to which the cells in human eyes can respond.

volatile The liquids that have weak surface bonds and so evaporate rapidly.

voltmeter An instrument that measures potential difference, which is the voltage change between two points in a circuit in volts.

volt The SI unit of potential difference or voltage.

W

wavefront A continuous line or surface that includes all the points reached by a wave or vibration at the same instant as it travels through a medium.

wavelength The distance between corresponding points on successive waves (symbol, λ; SI unit, m).

work A concept that relates force to energy; defined as the product of a force and the displacement of an object on which it acts.

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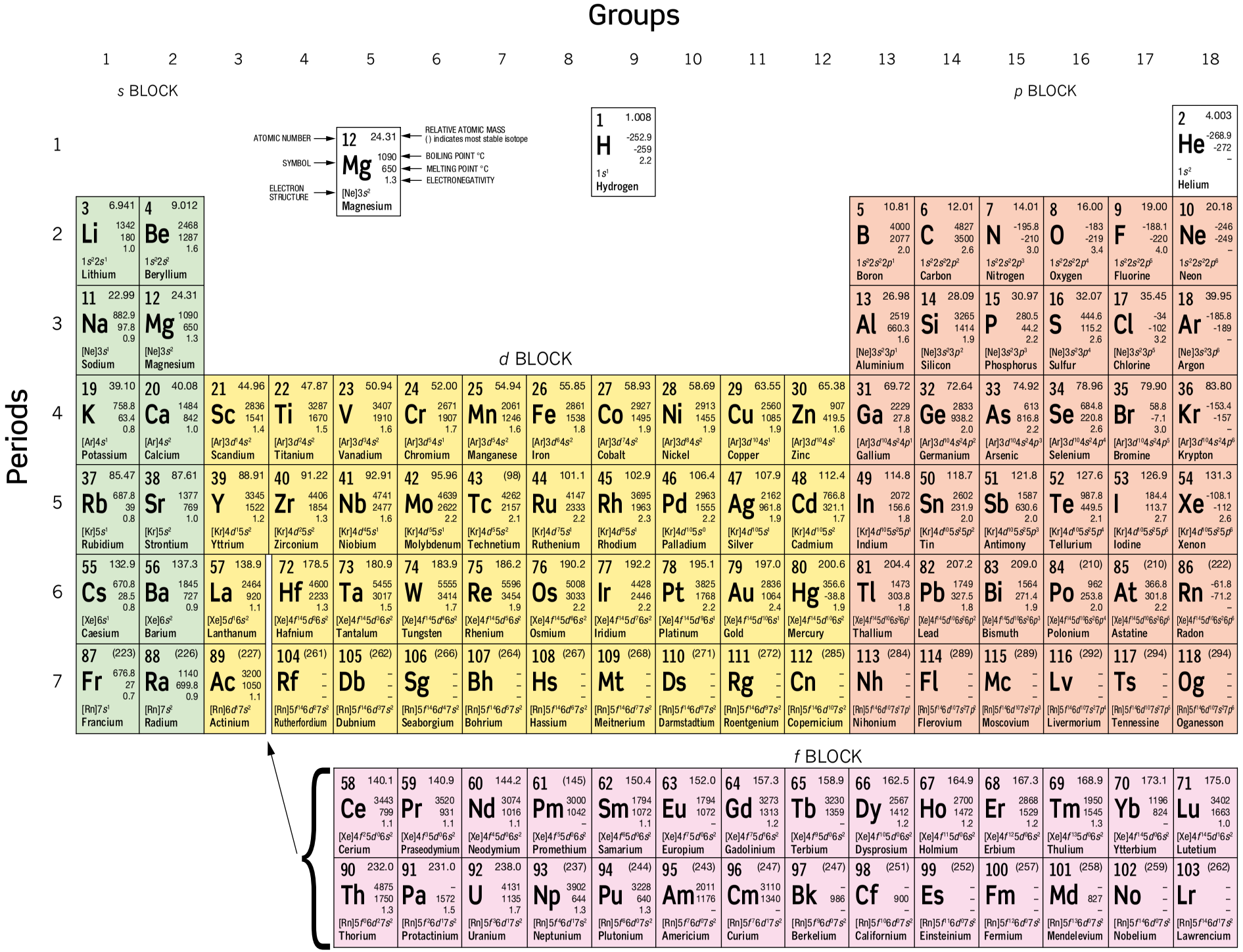
Groups
1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16 17 18
s BLOCK
p BLOCK
d BLOCK
f BLOCK
Periods
1 2 3 4 5 6 7
ATOMIC NUMBER
SYMBOL
ELECTRON STRUCTURE
RELATIVE ATOMIC MASS
( ) indicates most stable isotope
BOILING POINT °C
MELTING POINT °C
ELECTRONEGATIVITY
12 24.31 Mg 1090 650 1.3 [Ne]3s² Magnesium
1 1.008 H -252.9 -259 2.2 1s¹ Hydrogen
2 4.003 He -268.9 -272 – 1s² Helium
3 6.941 Li 1342 180 1.0 1s²2s¹ Lithium
4 9.012 Be 2468 1287 1.6 1s²2s² Beryllium
5 10.81 B 4000 2077 2.0 1s²2s²2p¹ Boron
6 12.01 C 4827 3500 2.6 1s²2s²2p² Carbon
7 14.01 N -195.8 -210 3.0 1s²2s²2p³ Nitrogen
8 16.00 O -183 -219 3.4 1s²2s²2p⁴ Oxygen
9 19.00 F -188.1 -220 4.0 1s²2s²2p⁵ Fluorine
10 20.18 Ne -246 -249 – 1s²2s²2p⁶ Neon
11 22.99 Na 882.9 97.8 0.9 [Ne]3s¹ Sodium
12 24.31 Mg 1090 650 1.3 [Ne]3s² Magnesium
13 26.98 Al 2519 660.3 1.6 [Ne]3s²3p¹ Aluminium
14 28.09 Si 3265 1414 1.9 [Ne]3s²3p² Silicon
15 30.97 P 280.5 44.2 2.2 [Ne]3s²3p³ Phosphorus
16 32.07 S 444.6 115.2 2.6 [Ne]3s²3p⁴ Sulfur
17 35.45 Cl -34 -102 3.2 [Ne]3s²3p⁵ Chlorine
18 39.95 Ar -185.8 -189 – [Ne]3s²3p⁶ Argon
19 39.10 K 758.8 63.4 0.8 [Ar]4s¹ Potassium
20 40.08 Ca 1484 842 1.0 [Ar]4s² Calcium
21 44.96 Sc 2836 1541 1.4 [Ar]3d¹4s² Scandium
22 47.87 Ti 3287 1670 1.5 [Ar]3d²4s² Titanium
23 50.94 V 3407 1910 1.6 [Ar]3d³4s² Vanadium
24 52.00 Cr 2671 1907 1.7 [Ar]3d⁵4s¹ Chromium
25 54.94 Mn 2061 1246 1.6 [Ar]3d⁵4s² Manganese
26 55.85 Fe 2861 1538 1.8 [Ar]3d⁶4s² Iron
27 58.93 Co 2927 1495 1.9 [Ar]3d⁷4s² Cobalt
28 58.69 Ni 2913 1455 1.9 [Ar]3d⁸4s² Nickel
29 63.55 Cu 2560 1085 1.9 [Ar]3d¹⁰4s¹ Copper
30 65.38 Zn 907 419.5 1.6 [Ar]3d¹⁰4s² Zinc
31 69.72 Ga 2229 27.8 1.8 [Ar]3d¹⁰4s²4p¹ Gallium
32 72.64 Ge 2833 938.2 2.0 [Ar]3d¹⁰4s²4p² Germanium
33 74.92 As 613 816.8 2.2 [Ar]3d¹⁰4s²4p³ Arsenic
34 78.96 Se 684.8 220.8 2.6 [Ar]3d¹⁰4s²4p⁴ Selenium
35 79.90 Br 58.8 -7.1 3.0 [Ar]3d¹⁰4s²4p⁵ Bromine
36 83.80 Kr -153.4 -157 – [Ar]3d¹⁰4s²4p⁶ Krypton
37 85.47 Rb 687.8 39 0.8 [Kr]5s¹ Rubidium
38 87.61 Sr 1377 769 1.0 [Kr]5s² Strontium
39 88.91 Y 3345 1522 1.2 [Kr]4d¹5s² Yttrium
40 91.22 Zr 4406 1854 1.3 [Kr]4d²5s² Zirconium
41 92.91 Nb 4741 2477 1.6 [Kr]4d⁴5s¹ Niobium
42 95.96 Mo 4639 2622 2.2 [Kr]4d⁵5s¹ Molybdenum
43 (98) Tc 4262 2157 2.1 [Kr]4d⁵5s² Technetium
44 101.1 Ru 4147 2333 2.2 [Kr]4d⁷5s¹ Ruthenium
45 102.9 Rh 3695 1963 2.3 [Kr]4d⁸5s¹ Rhodium
46 106.4 Pd 2963 1555 2.2 [Kr]4d¹⁰5s⁰ Palladium
47 107.9 Ag 2162 961.8 1.9 [Kr]4d¹⁰5s¹ Silver
48 112.4 Cd 766.8 321.1 1.7 [Kr]4d¹⁰5s² Cadmium
49 114.8 In 2072 156.6 1.8 [Kr]4d¹⁰5s²5p¹ Indium
50 118.7 Sn 2602 231.9 2.0 [Kr]4d¹⁰5s²5p² Tin
51 121.8 Sb 1587 630.6 2.0 [Kr]4d¹⁰5s²5p³ Antimony
52 127.6 Te 987.8 449.5 2.1 [Kr]4d¹⁰5s²5p⁴ Tellurium
53 126.9 I 184.4 113.7 2.7 [Kr]4d¹⁰5s²5p⁵ Iodine
54 131.3 Xe -108.1 -112 2.6 [Kr]4d¹⁰5s²5p⁶ Xenon
55 132.9 Cs 670.8 28.5 0.8 [Xe]6s¹ Caesium
56 137.3 Ba 1845 727 0.9 [Xe]6s² Barium
57 138.9 La 2464 920 1.1 [Xe]5d¹6s² Lanthanum
72 178.5 Hf 4600 2233 1.3 [Xe]4f¹⁴5d²6s² Hafnium
73 180.9 Ta 5455 3017 1.5 [Xe]4f¹⁴5d³6s² Tantalum
74 183.9 W 5555 3414 1.7 [Xe]4f¹⁴5d⁴6s² Tungsten
75 186.2 Re 5596 3454 1.9 [Xe]4f¹⁴5d⁵6s² Rhenium
76 190.2 Os 5008 3033 2.2 [Xe]4f¹⁴5d⁶6s² Osmium
77 192.2 Ir 4428 2446 2.2 [Xe]4f¹⁴5d⁷6s² Iridium
78 195.1 Pt 3825 1768 2.2 [Xe]4f¹⁴5d⁹6s¹ Platinum
79 197.0 Au 2836 1064 2.4 [Xe]4f¹⁴5d¹⁰6s¹ Gold
80 200.6 Hg 356.6 -38.8 1.9 [Xe]4f¹⁴5d¹⁰6s² Mercury
81 204.4 Tl 1473 303.8 1.8 [Xe]4f¹⁴5d¹⁰6s²6p¹ Thallium
82 207.2 Pb 1749 327.5 1.8 [Xe]4f¹⁴5d¹⁰6s²6p² Lead
83 209.0 Bi 1564 271.4 1.9 [Xe]4f¹⁴5d¹⁰6s²6p³ Bismuth
84 (210) Po 962 253.8 2.0 [Xe]4f¹⁴5d¹⁰6s²6p⁴ Polonium
85 (210) At 366.8 301.8 2.2 [Xe]4f¹⁴5d¹⁰6s²6p⁵ Astatine
86 (222) Rn -61.8 -71.2 – [Xe]4f¹⁴5d¹⁰6s²6p⁶ Radon
87 (223) Fr 676.8 27 0.7 [Rn]7s¹ Francium
88 (226) Ra 1140 699.8 0.9 [Rn]7s² Radium
89 (227) Ac 3200 1050 1.1 [Rn]6d¹7s² Actinium
104 (261) Rf – – – [Rn]5f¹⁴6d²7s² Rutherfordium
105 (262) Db – – – [Rn]5f¹⁴6d³7s² Dubnium
106 (266) Sg – – – [Rn]5f¹⁴6d⁴7s² Seaborgium
107 (264) Bh – – – [Rn]5f¹⁴6d⁵7s² Bohrium
108 (267) Hs – – – [Rn]5f¹⁴6d⁶7s² Hassium
109 (268) Mt – – – [Rn]5f¹⁴6d⁷7s² Meitnerium
110 (271) Ds – – – [Rn]5f¹⁴6d⁸7s² Darmstadtium
111 (272) Rg – – – [Rn]5f¹⁴6d⁹7s² Roentgenium
112 (285) Cn – – – [Rn]5f¹⁴6d¹⁰7s² Copernicium
113 (284) Nh – – – [Rn]5f¹⁴6d¹⁰7s²7p¹ Nihonium
114 (289) Fl – – – [Rn]5f¹⁴6d¹⁰7s²7p² Flerovium
115 (289) Mc – – – [Rn]5f¹⁴6d¹⁰7s²7p³ Moscovium
116 (292) Lv – – – [Rn]5f¹⁴6d¹⁰7s²7p⁴ Livermorium
117 (294) Ts – – – [Rn]5f¹⁴6d¹⁰7s²7p⁵ Tennessine
118 (294) Og – – – [Rn]5f¹⁴6d¹⁰7s²7p⁶ Oganesson
58 140.1 Ce 3443 799 1.1 [Xe]4f²5d⁰6s² Cerium
59 140.9 Pr 3520 931 1.1 [Xe]4f³5d⁰6s² Praseodymium
60 144.2 Nd 3074 1016 1.1 [Xe]4f⁴5d⁰6s² Neodymium
61 (145) Pm 3000 1042 – [Xe]4f⁵5d⁰6s² Promethium
62 150.4 Sm 1794 1072 1.1 [Xe]4f⁶5d⁰6s² Samarium
63 152.0 Eu 1794 1072 – [Xe]4f⁷5d⁰6s² Europium
64 157.3 Gd 3273 1313 1.2 [Xe]4f⁷5d¹6s² Gadolinium
65 158.9 Tb 3230 1359 – [Xe]4f⁹5d⁰6s² Terbium
66 162.5 Dy 2567 1412 1.2 [Xe]4f¹⁰5d⁰6s² Dysprosium
67 164.9 Ho 2700 1472 1.2 [Xe]4f¹¹5d⁰6s² Holmium
68 167.3 Er 2868 1529 1.2 [Xe]4f¹²5d⁰6s² Erbium
69 168.9 Tm 1950 1545 1.3 [Xe]4f¹³5d⁰6s² Thulium
70 173.1 Yb 1196 824 – [Xe]4f¹⁴5d⁰6s² Ytterbium
71 175.0 Lu 3402 1663 1.0 [Xe]4f¹⁴5d¹6s² Lutetium
90 232.0 Th 4875 1750 1.3 [Rn]5f⁰6d²7s² Thorium
91 231.0 Pa – 1572 1.5 [Rn]5f²6d¹7s² Protactinium
92 238.0 U 4131 1135 1.7 [Rn]5f³6d¹7s² Uranium
93 (237) Np 3902 644 1.3 [Rn]5f⁴6d¹7s² Neptunium
94 (244) Pu 3228 640 1.3 [Rn]5f⁶6d⁰7s² Plutonium
95 (243) Am 2011 1176 – [Rn]5f⁷6d⁰7s² Americium
96 (247) Cm 3110 1340 – [Rn]5f⁷6d¹7s² Curium
97 (247) Bk – 986 – [Rn]5f⁹6d⁰7s² Berkelium
98 (251) Cf – 900 – [Rn]5f¹⁰6d⁰7s² Californium
99 (252) Es – – – [Rn]5f¹¹6d⁰7s² Einsteinium
100 (257) Fm – – – [Rn]5f¹²6d⁰7s² Fermium
101 (258) Md – 827 – [Rn]5f¹³6d⁰7s² Mendelevium
102 (259) No – – – [Rn]5f¹⁴6d⁰7s² Nobelium
103 (262) Lr – – – [Rn]5f¹⁴6d¹7s² Lawrencium

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